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Summary

Municipalities in Germany develop policy plans referred to as ‘Energetische Quartierskonzepte’ (EQ, pl. EQs) to lower and decarbonize the energy consumption of existing buildings in whole city districts. These EQs describe the status-quo, a strategy, and measures for the energy-related improvement of a district based on an initial analysis of the buildings in the considered area. We study 25 publicly available reports of German EQs to identify common state-of-the-art approaches for the analysis of buildings on district scale, summarizing their strengths and weaknesses. We extract ten approaches that are currently applied in practice. Overall, we could not find any connection between the year of the EQ publication, the district size, and the type and quantity of analysis approaches used. The most common approaches for obtaining data for building analyses are the use of representative building typologies, on-site inspections of buildings, datasets from network-operators, and citizen surveys. The main weaknesses of the assessed approaches are for example inaccuracies due to simplifying assumptions, inconsistent data formats from different data sources, and problems due to data protection restrictions. The standardization, combination, and further development of the assessed approaches are recommended.

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Keywords: heating, building retrofits, urban transition, district analysis, building inspection, neighborhood

1. Introduction

The Paris agreement of 2015 obliges the signing nations to restrict the rise in global average temperature well below 2°C compared to pre-industrial levels and to pursue efforts to limit it to 1.5°C [1]. To achieve such goals, urban areas play a key role. Today, more than half of the world's population lives in urban areas that contain the majority of the world's built assets and economic entities [2].

In 2018, the building sector accounted for the largest share of both global final energy use (36%) and energy-related CO_2 emissions (39%), and thus possesses a high potential for energy savings [3]. The Intergovernmental Panel on Climate Change (IPCC) summary for urban policy makers highlights the key role of the transformation and retrofitting of building stocks in urban areas for the achievement of climate goals [2]. This role is also emphasized by the New Urban Agenda [4], envisaging cities as part of the solution for sustainable development and climate protection. A part of this agenda focuses on the renewal, regeneration, and retrofitting of urban areas, and the provision of "high-quality buildings and public spaces, promoting integrated and participatory approaches involving all relevant stakeholders and inhabitants and avoiding spatial and socioeconomic segregation and gentrification".

To push a sustainable urban transition in the building sector, there are three main levels of action: the city scale, the district scale, and the building scale [5]. The district scale (neighborhood/ community scale) is the intermediate level between the city and the building scale, a spatially narrow area consisting of several private and/or public buildings, including public infrastructure [6, 7].

The district scale has certain advantages for the development of energy improvement approaches and their implementation and is also emphasized by the New Urban Agenda [4]. Riechel [5] summarizes different advantages of the district scale: Compared to action plans for single buildings, plans on district scale provide the possibility of cost digressions and other economies of scale for procurement, installation, or energy improvements. The closeness between inhabitants and other stakeholders in a neighborhood is an advantage compared to the development of strategies on city scale. Communication in a district takes place with its own dynamics: for example, informal communication among neighbors ("neighborhood gossip") or copying of building modernization in the neighborhood by other owners. Moreover, approaches on district scale do not only focus on buildings, but also on framework conditions of a district such as the optimization of infrastructure in a district. When planning building retrofits and the optimization of a district heating network there can be relevant efficiencies which can't be taken into account in practicable way at the city- or building scale [8]. Approaches on district scale can also take into account the local stakeholders (e.g. inhabitants and building owners) and their individual preferences in a more targeted way than on city scale. This is relevant, for example, when retrofitting multi-occupancy residential buildings with multi-property ownerships, which often requires special efforts for the coordination and participation of owners [9].

In order to systematically use the advantages of the district scale for the energy retrofit of buildings, there are various standardized approaches that are supported and funded by governments. Examples are the Community Energy Strategic Planning (CESP) in the USA [10], Community Energy Planning (CEP) in Canada [11], Positive Energy Districts (PED, pl. PEDs) in Europe [12] and "energetische Quartierskonzepte" (EQ, pl. EQs) in Germany [7]. CESP, CEP and EQs intend to reduce the energy use and increase the use of renewable, low carbon energy sources of buildings [7, 10, 11]. PEDs are energy-efficient and energy-flexible urban areas or groups of buildings which have net zero greenhouse gas emissions and contribute to a surplus production of renewable energy [12]. Moreover, there are countries (e.g. China) where district energy planning is not established yet, primarily because there are no clear standards and specifications for these plans, but emphasized as beneficial in future by researchers [13].

While the development of 100 total PEDs is targeted by 2050 [12], already 150 CEP projects have been developed as of 2015 [11], and even 850 EQs in Germany as of 2019 [14]. For the USA, the authors could not find any official figures on the progress of the development of CESP.

There is no generic approach for the improvement of existing building stocks on district scale known to the authors that has been performed as frequently and has a broad, often publicly accessible reporting system as German EQs. EQ reports are documents that are authored by energy agencies, universities and scientific research institutions and are usually commissioned and published by municipalities. They describe the process and the results of an EQ development. The German government supports municipalities in developing EQs with financial incentives by Kreditanstalt für Wiederaufbau[1] (KfW). KfW offers financial support via its program 432 for energy-focused city district optimization. The amount of the financial support of the KfW bank is between 5,000 euros and 350,000 euros per EQ and includes personnel and material costs for the development of an EQ and its implementation for the duration of maximum 5 years. [7]

KfW defines minimum requirements, procedures, and standards for the development of an EQ. Following the KfW definition [7], an EQ has to include six planning steps to receive funding, shown in Figure 1. The first step is the initial analysis of the district, its buildings, and infrastructure to identify large energy consumers and potential for energy savings. The second step is the development of an action plan, including specific measures and goals for the reduction and decarbonization of energy consumption in the district. An effective and efficient action plan depends significantly on a well-founded analysis of the initial state. The third step includes a plan for financing all planned actions. It must be clarified how much the municipalities pay themselves or through third parties and how much funding from KfW is needed. The fourth step targets the stakeholders (e.g. inhabitants, building owners, and local business people) of the district. With public participation measures and active energy consulting, the aim is to address and motivate these stakeholders to participate in the EQ process. This is a key step for the success of an EQ as the implementation of all measures depends on the participation of the stakeholders, especially the building owners and their willingness to invest own money, time, and effort. Concrete analysis results and the clarification of identified weak points in the individual buildings of the district can help for the mobilization of building owners. The fifth step is an implementation strategy, including a timetable and priorities for the implementation of actions. The final step is a plan for the long-term evaluation, performance monitoring, and assessment of success during the implementation of the EQ. [7,15]

[1] (engl. German Reconstruction Loan Corporation)

The specifics of individual steps are largely not specified by the KfW. Each municipality can/must find its own ways of designing them in the context of each individual district.

Figure 1. Planning steps of an EQ as outlined by KfW [7, 15]

The initial analysis of the district's buildings is the first step in the development of an EQ and the basis for all further steps. It is also the most resource-intensive step. Riechel and Koritkowski [16] state that the time required for collection of the data of a district can account for up to 65% of the total EQ development. On average, they estimate that the time share of this step is about 40%. For the pilot projects of the KfW program 432, Neußer [17] shows that a major share of 50% to 80% of the funding amount and time is spent for the analysis of the initial energy situation of buildings and facilities. This shows that the analysis step is decisive in order to reduce costs and time required for the development of EQs which could lower barriers for municipalities to invest in EQs and push climate protection measures for buildings on the district scale.

In this study, we address the following research questions on the analysis of districts for the development of EQs: Which approaches form the current practices for the analysis of districts in EQs? What are the strengths and weaknesses of current analysis approaches to analyze buildings on a district scale? What improvements of current approaches are possible and necessary for increasing EQ uptake?

2. Related work

In Germany, many recent publications and guidelines deal with the development of EQs and the initial analysis of a district. Early research goes back to the research program ExWoSt[2] dealing with innovative housing and urban development of the Federal Ministry of Transport, Building, and Urban Affairs [18]. Numerous projects in the field of the energy-related optimization of districts, such as "Energetische Stadterneuerung"[3], "EnEff:Stadt"[4], "Anforderungen an energieeffiziente und klimaneutrale Quartiere"[5] (EQ-project), as well as guidelines at state level have emerged from this program [18-21].

The EQ-project deals with requirements for energy-efficient and climate-neutral districts on the basis of five sample districts that were among the first EQs in Germany following the KfW standards [18, 21]. The EQ-project investigates EQs and evaluates them with a view to their components and instruments for the climate-friendly improvement of urban districts. The research approach uses a qualitative analysis of impact relationships and a quantitative evaluation of energy saving measures. It focuses on the energy performance of buildings as well as in the transport sector of a district. For the initial analysis of a district, it highlights that good ways of aggregation (e.g. via building typologies) help keep initial data collection to a reasonable level of effort. This study is a good first approach to evaluating EQ practices, but is superficial regarding the initial district analysis and is based on only five early EQs.

More recent research on the quality of EQs is currently done by the BES project[6] [22]. It evaluates EQs supported by the KfW program 432 with different subprojects and approaches to improve the program in line with practical needs, as well as to support the targeted knowledge transfer and the public communication of results. Up to 70 reference EQs are being examined within the framework of the research project. Final results are not available yet. So far, the BES project provides a short overview of planning tools for district analysis [23]. A more in-depth examination of current district analysis approaches in EQs and a consideration of their strengths and weaknesses are missing.

Neußer [17], who also takes part in the BES project, deals among other topics with the quality of databases for the analysis of districts. He criticizes the lack of standards for the collection and use of basic information in EQs, and thus the lack of comparability between EQs. Neußer also mentions the heterogeneity of districts as a challenge for the development of EQs, but neither specifies his critique nor proposes solutions.

The project "TransStadt" examines 15 districts that developed EQs with respect to local transformation paths in the context of a strategically oriented integrated urban development mix [5, 16, 24]. Riechel and Koritowski [16] focus on the obstacles and conflicts at municipal level that make it difficult or impossible to achieve national climate protection goals. Moreover, they identify the weaknesses of several components of existing EQs. For the initial analysis, Riechel and Koritowski state difficulties in collecting heat data in districts due to data protection regulations, and criticize the inconsistency of data used in the developed EQs such as CO_2 equivalents or the share of renewable energies in the electricity mix. The "TransStadt" project also developed a guideline to municipal transformation management for local heat transition [24]. This guideline includes advice on collecting technical data for the heating system and thermal

[2] ExWoSt: Experimenteller Wohnungs- und Städtebau (engl. Experimental urban development)

[3] (engl. Energy renewal of cities)

[4] EnEff:Stadt: Energieeffiziente Stadt (engl. Energy efficient city)

[5] (engl. Requirements for energy-efficient and climate-neutral districts)

[6] BES: Begleitforschung zur Energetischen Stadtsanierung (engl. Accompanying research on urban energy renewal)

quality of a district. It also mentions some weaknesses of current analysis tools, data protection requirements, and the integration of different data formats.

International research on the energy performance analysis of districts is summarized by Aghamolaei et al. [25]. They reviewed approaches in three sections: (1) approaches defining district energy performance, (2) approaches to and methodologies for district energy performance evaluation, and (3) system interactions between district entities. They state that few of the reviewed studies investigated the challenges in the initial stages of designing different steps of energy performance analysis in districts. However, inaccurate or imprecise assumptions in the basic steps of energy performance analysis can lead to expensive and irreversible consequences such as waste of project resources or unreliable results and solutions.

This literature overview shows that, particularly for German EQs, there is already research covering the topic of the analysis of city districts. However, there is no publication providing a comprehensive list of current approaches and focusing on their quality for the energy analysis of buildings in a structured way. So far, it has not been possible to conclude from existing publications what the reasons for the enormous resource consumption in the analysis step of the EQ development are and how in the future the use of time and costs can be reduced in order to make EQs more practicable in Germany.

3. Materials and methods

In this study, we summarize how EQs deal with the initial analysis of city districts and identify strengths and weaknesses as well as potential improvements of these approaches.

For this, we work with information that we gain from the comprehensive database of existing EQ reports. We first search for publicly available EQ reports in Google, Google Scholar, and on official websites of German municipalities and of local energy agencies. The reports we find, we sort according to their year of publication, the geographical location, and size of the investigated district. For this study we selected 25 EQ reports that attempt to balance the distribution of these three characteristics. We preference districts with a heterogeneous building stock, as a large diversity of buildings complicates analysis on district scale. The building stock heterogeneity includes the aesthetic, physical, and thermal quality of buildings with features like year of construction, building materials, size, restoration and maintenance quality including quality of thermal building envelopes, as well as heating systems and energy sources. There is also a broad heterogeneity of usage. Besides housing, most urban districts also include public buildings, such as schools or hospitals, and commercial buildings, such as offices, stores/trades, and different forms of handicraft and industry. In addition, we ensure that the reports are detailed enough to obtain information on the applied building analysis approaches.

When studying the selected EQ reports, we first examine the role of residential and non-residential buildings in the analysis of the district's building stocks. We look for information in the reports on whether the EQs differentiate between residential and non-residential buildings and whether special approaches are used for the analysis of non-residential buildings. We summarize all approaches mentioned in the reports for the acquisition of building data and the energy analysis of buildings on district scale. To investigate strengths, weaknesses, and potential improvements of building analysis approaches on district scale, we provide short SWOT[7] analyses for each approach mentioned in the studied reports. In this context we consider strengths as enhancers of an effective and efficient building energy analysis and weaknesses as inhibitors leading to high costs, analysis times, and inaccurate results of a building energy analysis.

[7] SWOT: Strengths, Weaknesses, Opportunities, and Threats

Opportunities are possible ways of mitigating weaknesses. Threats are risks having to be considered when improving analysis approaches. To find strengths and weaknesses, we extract know-how from the experiences described in the 25 EQ reports on the used building analysis approaches and point out opportunities and threats.

All results in Section 4 rely exclusively on information extracted from the analysis of the 25 EQ reports. Additional literature used for more precise explanations is explicitly indicated.

The research approach of this study is illustrated and summarized in the flowchart in Figure 2.

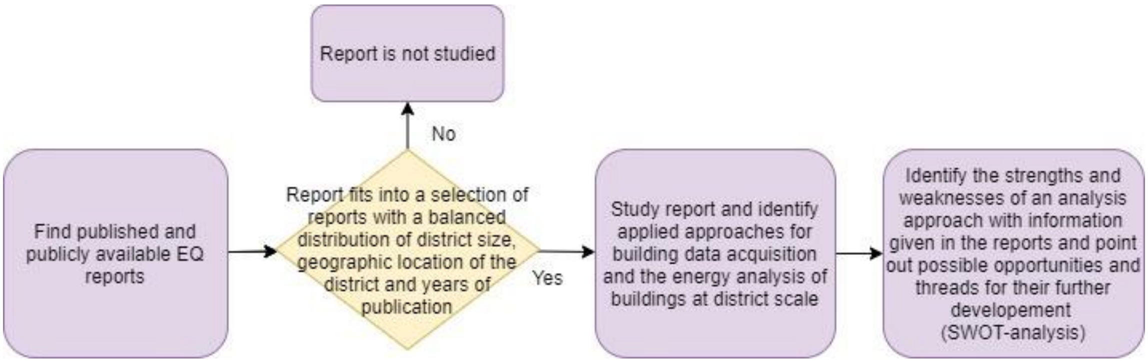

Figure 2. Flowchart for the study design

4. Review results

4.1. Database

Of the existing 850 German EQs as of 2019 [14], we found around 50 publicly accessible EQ reports that were published between 2013 and 2018 and do not violate data protection requirements. During our investigation, we could not find any reports published before 2013. All EQs fulfill the German "standards" (funding requirements of the KfW bank) and thus follow the same structure as described in Section 1. Of these 50 EQ reports, we selected 25 reports that correspond to as balanced a distribution as possible of the characteristics outlined in the beginning of Section 3, namely the geographical, temporal, and district size features of the considered districts (Figure 3, Figure 4, and Figure 5).

Since an EQ is often developed by local or regional stakeholders, such as local energy agencies, the selection process of the reviewed EQs was designed to cover as best as possible all federal states of Germany. Except for the federal states of Bremen, Saxony-Anhalt, and Mecklenburg-Western Pomerania, we found publicly accessible reports in all states. We selected a widespread geographical distribution of the considered EQs between Northern and Southern Germany as well as laterally and of districts of different sizes. The sizes of the districts' covered areas vary between 4.6 ha and 235.5 ha, with an approximately balanced distribution between the sizes in the range between 4.6 ha and 100 ha, excluding two large outliers with 173 ha and 235.5 ha (Figure 5a). The number of district inhabitants varies between 393 and 12,440 with an approximately balanced distribution in the range of 393 to 8,900, excluding a slightly larger outlier with 12,440 (Figure 5b). The number of considered buildings in the reviewed EQs varies between 20 and 1,135, with an approximately balanced distribution in the range of 20 to 900, excluding one outlier with 1,135 (Figure 5c).

A detailed overview of the considered EQ reports shows information about the area size, number of inhabitants, and number of buildings (Table 1).

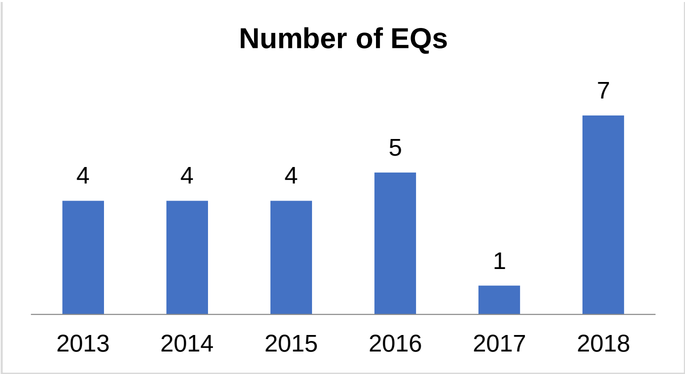

Figure 3. Number of reviewed and analyzed EQs according to their years of issue in the period of 2013 to 2018

Figure 4. Distribution of selected and reviewed EQs in Germany (created with Google Maps [26])

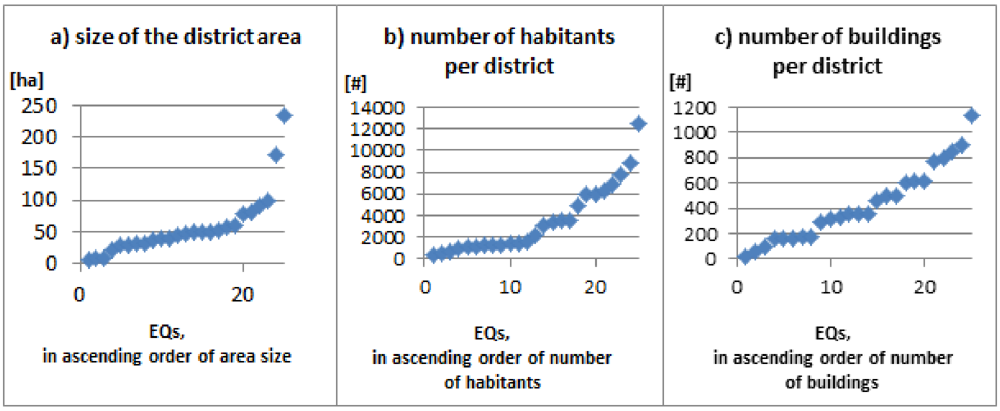

Figure 5. Selected and reviewed EQs sorted according to their characteristics of the considered EQs in ascending order: (a) Size of the district area, (b) Number of citizens, (c) Number of buildings in the district

Table 1. Overview of the considered plans for the energy improvement of districts (EQ) with Information about the area size, number of inhabitants, and number of buildings

District	Municipality	State	Year	Area [ha]	Inhabitants [#]	Buildings [#]	Area-related population density [inhabitants/ha]	Building-related population density [inhabitants/building]	Area-related building density [buildings/ha]	Remarks
Altchemnitz	Chemnitz	Saxony	2018	80	6003	460	75	13.1	5.8	*** [27]
Eichkamp und Heerstr	Berlin	Berlin	2016	60	3090	767	51.5	4	12.8	* [28]
Engeo	Bremervörde	Lower Saxony	2014	50	1272	350	25.4	3.6	7	** [29]
Gartenberg	Sömmerda	Thuringia	2013	37	894	320	24.2	2.8	8.6	[30]
Gibitzenhof	Nuremberg	Bavaria	2018	79	12440	800	157.5	15.6	10.1	** [31]
Hainholz	Hannover	Lower Saxony	2015	173	6821	850	39.4	8	4.9	** [32]
Hillscheid	Höhr-Grenzhausen	Rhineland-Palatinate	2014	47	1312	500	27.9	2.6	10.6	** [33]
Historische Innenstadt	Neuruppin	Brandenburg	2015	100	4933	900	49.3	5.5	9	[34]
Innenstadt	Nord Völkingen	Saarland	2017	32	3600	618	112.5	5.8	19.3	[35]
Innenstadt	Geldern	North Rhine-Westphalia	2016	40	2208	609	55.2	3.6	15.2	* [36]
Innenstadt	Baunatal	Hessen	2016	50	3450	285	69	12.1	5.7	[37]
Lerchenberg	Mainz	Rhineland-Palatinate	2014	235.5	6305	1135	26.8	5.6	4.8	[38]
Moabit-West	Berlin	Berlin	2013	8.3	8900	500	1072.3	17.8	60.2	** [39]
Mollerstadt	Darmstadt	Hessen	2013	30	3500	325	116.7	10.8	10.8	[40]
Nettersheim	Nettersheim	North Rhine-Westphalia	2018	50	393	155	7.9	2.5	3.1	* [41]
Neue Mitte	Grenzach-Whylen	Baden-Württemberg	2018	90	1431	163	15.9	8.8	1.8	[42]
Neumünden Fuldablick	Hann Münden	Lower Saxony	2018	52	1609	350	30.9	4.6	6.7	[43]
Nörd. Festplatz	Mörfelden-Walldorf	Hessen	2015	32.4	1157	176	35.7	6.6	5.4	[44]
Ostrow	Cottbus	Brandenburg	2016	40	1192	167	29.8	7.1	4.2	[45]
Schilksee	Kiel	Schleswig-Holstein	2018	8	5907	20	738.4	295.4	2.5	** [46]
südöstliches Eisendorf und Bremerstr	Hamburg	Hamburg	2018	58	7800	600	134.5	13	10.3	[47]
Unsere Stadt	Altensteig	Baden-Württemberg	2016	22	616	162	28	3.8	7.4	* [48]
Weinberg-Dichterviertel	Roßleben	Thuringia	2015	28	1152	101	41.1	11.4	3.6	[49]
Wengenviertel	Ulm	Baden-Württemberg	2013	4.6	480	60	104.3	8	13	** [50]
Weststadt	Steinheim	Baden-Württemberg	2014	45	1400	349	31.1	4	7.8	[51]

Data sources:
(-): data explicitly mentioned in the EQ reports
*: area size approximately calculated with Google Maps [26],
**: number of buildings approximately estimated on the basis of maps shown in the EQ reports;
***: number of inhabitants in 2016 according to information by the city of Chemnitz and its districts [52]

4.2. Study of applied building analysis approaches

4.2.1. Preliminary remarks for dealing with residential and nonresidential buildings

The studied EQ reports refer to districts that have mixed types of buildings with a large share of residential buildings, as well as nonresidential buildings such as commerce, offices, industry, and schools. In the initial analysis, the majority of 16 EQs focus almost exclusively or exclusively on residential buildings. Seven EQs consider the analysis of residential and nonresidential buildings in the reports equally or in a close to equal way. Only two EQs put nonresidential buildings in the focus of the analysis.

With regard to different building types, 15 EQ reports describe the use of analysis tools that differ from the standard analysis tools which are especially suitable for residential buildings described in the following subsection (4.2.2). These differing tools are, for example, transferable industrial value estimates, comparative values for nonresidential buildings of the German energy saving guideline (Energieeinsparverordnung, EnEV), or other scientific indicators for nonresidential buildings. For public buildings, ten EQs work with consumption data and building information collected and provided by municipalities.

An overview of this subsection on the single EQ reports is summarized in the Appendix Table 3.

4.2.2. Overview of building analysis approaches

In the 25 EQ reports, ten approaches for analyzing buildings on district scale are mentioned (Figure 6).

19 EQs describe on-site inspections to analyze the considered area and buildings. This involves recording basic building information such as the size dimensions of buildings, along with structural conditions of buildings such as the visible thermal quality of building envelopes or of individual envelope components. In most cases, on-site inspections are limited exclusively to inspections from the outdoor perspective. Also concerning the inspection of buildings from the outside (envelope qualities and size dimensions), eight EQs work with aerial images from Google Maps or other image data providers.

19 EQs work with consumption data obtained from the local network operator for heating (gas, district heating). Nine EQs mention the possibility of working with data from the district chimney sweep association. These datasets often contain additional information on the age of heating systems that are mentioned in some EQ reports. Another way of collecting real consumption data is to work with citizen surveys, which are performed in 19 EQ reports. Some survey sheets are provided as additional material in the EQ reports. These surveys not only include questions concerning energy consumption data, but also the size and shape of the buildings and their parts, current restoration and reconstruction information, the building architecture, the year of construction, the energy system and energy source of the building, as well as personal data of the building owners and tenants. In the EQs, these data are partly used directly and partly for post-survey calculations of the theoretical energy demands of buildings (if the consumption values are not specified) and for identification of the structural weaknesses of a building. The surveys are usually addressed to the building owners, but sometimes also to the tenants. Expert interviews are mentioned in four EQ reports. Experts mentioned in the studied EQ reports are for example important stakeholders in a district with a large property portfolio or stakeholders who combine building knowledge with local knowledge, such as local planning offices.

In order to calculate the theoretical demand for the heating of buildings, 21 EQs use existing or self-made building typologies and standard energy demand values per occupant, residential unit, building, or square meter heated area. The use of building typologies is the most common analysis approach across all studied EQ reports. Typologies define representative buildings for specific years of construction, refurbishment statuses, as well as form and design characteristics. The theoretical thermal energy demand for such representative buildings can be derived in relation to parameters such as the building size (mostly depending on the number of floors, the number of residential units, and the living area size). A popular building typology for the German building stock named TABULA combines the fields of housing and urban development with energy efficiency and climate protection [53].

17 EQs work with information from building-related data sources and documents, often stored in GIS formats. Such databases are monument protection documents, energy performance certificates, construction files, development plans, real estate registers, or other databases such as destruction maps from World War II or previous energy analyses of buildings. To detect the structural weaknesses of a building envelope, four EQs work with thermal images of buildings from the inside and/or outside.

A holistic approach is the analysis of homogeneous sub-districts. This approach is mentioned in six EQ reports. The entire district can be divided into homogeneous small areas, for which individual representative buildings are then analyzed.

An overview of this subsection on the single EQ reports is summarized in the Appendix in Table 4.

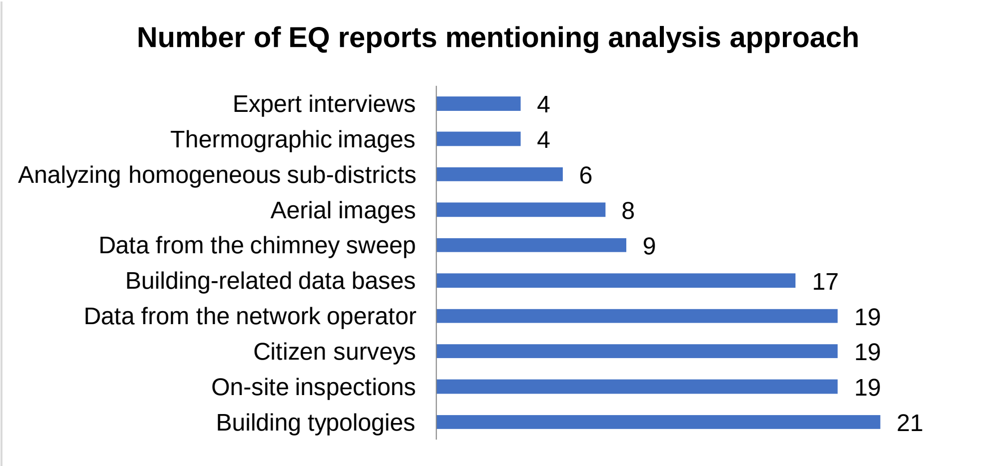

Figure 6. Frequency of used analysis approaches in the studied EQs

4.2.3. Evaluation of common analysis approaches in EQs

The advantage of building typologies is that they do not need much specific data or detailed calculations for each individual building to approximate the energy demand of a whole building stock [e.g. 47, p. 24]. For a very heterogeneous building stock, however, the limited number of building classes in a typology can lead to a problematic simplification. For example, the EQ report of Nord Völkingen criticizes the most frequently used TABULA typology. It states that the building classes of the typology, which are based on the year of construction, allow only limited conclusions about the current thermal quality of a building. Neither retrofits and reconstructions nor extensions of buildings are included in the cataloging [35, p. 21]. The extent to which the use of building typologies leads to a false description of the building stock depends on the used typology and the difference between real buildings and building class typologies. Better analysis results can be achieved with the detailing and expansion of typologies, with the trade-off of increased analysis effort.

On-site inspections can consider the individuality of each building and the heterogeneity of districts. Inspections are particularly suitable for analyzing complex and highly specific buildings with significant energy consumption. In Nuremberg, a production plant [31, p. 74] and in Hannover, important architectural monuments [32, p. 45] are on-site-inspected in depth. The more detailed on-site inspections are, the more complex they become which is why they can often not be carried out for a whole district. For example, Hamburg’s EQ report states that a detailed inspection of all buildings in the district (over 500) would have required a considerable amount of time (the amount of time is not specified in the report). Thus, they just limited on-site inspections to the documentation of a few criteria [47, p.30]. The accessibility of properties is also usually limited due to property rights. Inspections are therefore often limited to the perspective from the street if no agreements have been arranged with building owners and tenants beforehand [37, p. 49]. In order to keep the inspection effort of a district low, inspections can only be limited to special buildings that are difficult to analyze with other approaches.

To detect structural weaknesses of building envelopes in detail, thermal images of buildings provide timely and high-quality information. As part of on-site inspections these are usually also just recorded for individual complex buildings and/or limited to the street perspective. The analysis of roofs from the ground perspective is often limited by conventional thermographic recordings [28, p. 33]. For the EQ of Cottbus, for example, aerial thermographic images are taken into account [45].

Aerial images from providers like Google are easily accessible and can be used to supplement missing information from on-site inspections [40, p. 51]. All sides of the buildings and roofs are visible. Nevertheless, in contrast to on-site inspections, up to date images and high image quality are not always available.

In order to increase the quality and timeliness of aerial images, and to extend inspections and thermographs to all building perspectives, drones could be used in the future. With programmed flight routes and automated image processing, the effort of collecting high-resolution and timely drone images would be manageable. Nevertheless, data protection must be taken into account when recording images with high resolution.

Citizen surveys allow responding to the heterogeneity of buildings in a district and can also be used to collect information about the heating technology of buildings. However, problems arise in the activation of participants at the beginning and during the EQ development. Different response rates have shown that not all EQs have been successful with activating participants. Ten of the 19 EQs describe the response rate of surveys in more detail. They state response rates between 3% up to a peak value of 50%.[8] Potential reasons for the different rates are not explained in the reports. Another possible obstacle for the use of questionnaires is that building owners and tenants need to be well informed about their buildings. In some cases, the questionnaires ask very detailed information concerning the thermal quality of buildings and use technical terms. For example, the survey of Altensteig asks for the wattage of the heating system and the thickness of building components such as the floor slab [48, p.109]. Another citizen survey in Chemnitz asked for the usable building area ("Nutzfläche"[9]) [27]. It is unlikely that all participants have sufficient knowledge to answer such questionnaires correctly and in a consistent way. A simplification of questionnaires could increase the response rate and the correctness of information, but it is questionable to what extent simplified surveys are helpful for a meaningful analysis.

Like surveys, expert interviews can also provide detailed information. Compared to surveys, more detailed, extensive, and targeted questions are possible in direct interviews. However, organizing and conducting expert interviews can require significant effort. Therefore, they can be seen as a targeted supplement to information gaps [35, p. 41].

[8] Response rates of citizen surveys: Ulm (Wengenviertel): 50%, Höhr-Grenzhausen (Hillscheid): 50%, Steinheim (Weststadt): 43%, Grenzach-Whylen (Neue Mitte): 42%, Berlin (Eichkamp und Heerstr.): 25%, Hannover (Hainholz): 15%, Chemnitz (Altchemnitz): 13%, Nord Völkingen (Innenstadt): 12%, Hann Münden (Neumünden Fuldablick): 3%

[9] The "Nutzfläche" of a building is the proportion of the floor area that is used in accordance with its intended purpose. Traffic areas (e.g. entrances, stairwells, lifts, corridors) and functional areas (heating room, machine rooms, technical operating rooms) are not included in the usable area [54].

Data provided by network operators and chimney sweeps have the same strengths and weaknesses. These data can have a high value for the analysis of individual heterogeneous buildings, they provide an indication of the thermal quality of a building without further building information. However, these approaches bring up the topic of data protection. In many districts, network operators and chimney sweep associations do not cooperate or just provide incomplete data about heating technologies and/or consumption data. Usually, suppliers in Germany are only allowed to provide consumption data on an aggregated scale like from distribution points at street level, building block level, or just for the whole district [43, p. 21; 40, p. 56; 27, p. 36; 36, p. 10]. Due to the high aggregation levels of data on block or street levels, statements for individual buildings become difficult if buildings within the aggregation differ from one another. A relaxation of data protection guidelines could be helpful for scientific or EQ development purposes, but conflicts with individual data rights and the developers of EQs have no influence on this. Furthermore, aggregated consumption data does not provide any information on the reason for energy consumption. High consumption can be attributed either to the thermal weaknesses of the building or to specific user behavior. Thus, the comparability of consumption data with calculated demand values must be taken into account when comparing different analysis approaches. Experience mentioned in the EQ report of Darmstadt has shown that consumption in buildings with poor energy performance is usually lower than the calculated energy demand, as people seem to be aware of it and aim to save heating costs [40, p. 68].

Building-related databases have the advantage that they are usually already available to EQ developers and do not have to be collected separately for the EQ development. However, the data is often not up-to-date due to the high effort of maintaining databases [45, p. 132]. Generalizable statements about the data quality of such databases are also difficult. The quality of data varies a lot between different sources and can only be checked in each individual case. When integrating various sources, problems with different standards and calculation databases can arise. Municipalities should have an interest in using uniform formats and standards for all processes and documentations. The goal to standardize data formats for a better integration and the reuse of data is, for example, explicitly mentioned in the EQ report of Cottbus [45, p. 139].

The holistic approach to define and then analyze homogeneous sub-districts of a district simplifies the analysis of complex heterogeneous structures. In the EQ report of Baunatal, neighboring buildings with a similar structure were clustered. Individual clusters were examined independently and with specific approaches (e.g. different approaches and responsibilities for residential and commercial clusters) [37, p. 50]. The division into homogeneous sub-districts can be very detailed, for example in Hann Münden with 37 clusters [43, p. 29]. The division into homogeneous sub-districts does not always make sense and depends highly on the degree of heterogeneity and the layout of a district.

Table 2 summarizes the described strengths, weaknesses, opportunities, and threats of the common district analysis approaches.

Table 2. SWOT analyses for common thermal analysis approaches for buildings on district scale

Building typologies:

Strengths (+): Small amount of data required to model many different kinds of buildings; Suitable for homogeneous buildings with properties in accordance with common typological characteristics and few special design features

Weaknesses (-): Simplification of the approach makes it difficult to include all kinds of specific characteristics of buildings like extensions and retrofit modifications

Opportunities (↑): Typologies with many modifications and options to take into account many specific characteristics of buildings and the considered district

Threats (↓): The advantage of small effort due to the simplicity of the approach can be lost with too many modifications and options to include specific characteristics of buildings

On-site inspections:

Strengths (+): Any kind of specific characteristic of buildings can be taken into account

Weaknesses (-): Property rights restrict the access and visibility of buildings and building parts

Opportunities (↑): Limitation of detailed inspections to special buildings which are difficult to determine with other analytical approaches

Threats (↓): High efforts for the EQ developers which increase when asking stakeholders for cooperation and access

Terrestrial thermographic images:

Strengths (+): Provide detailed information on the thermal quality of building envelopes

Weaknesses (-): High effort; For images from the inside, cooperation with building stakeholders is necessary

Opportunities (↑): New technologies like drones can help to collect images of many buildings from the outside with lower effort

Threats (↓): Thermographic images only from the outside provide less information than detailed thermographic analyses; Lower image qualities due to a higher distance between the camera and buildings when using drones

Aerial photographic images:

Strengths (+): Inspections from all sides are possible with less effort than in the case of on-site inspections

Weaknesses (-): Aerial satellite images have a too low resolution to see details; Partly outdated databases

Opportunities (↑): New technologies like drones can help to collect aerial images with a high quality and timeliness

Threats (↓): Collecting images of buildings with a high resolution could be a problem for data protection and privacy; Increased effort in collecting data compared to existing databases

Citizen surveys:

Strengths (+): Any kind of specific characteristic of buildings can be taken into account

Weaknesses (-): Difficulties of motivating stakeholders to participate in surveys; stakeholders should be well informed about their buildings and technically understand the questions asked

Opportunities (↑): Social science research can provide better strategies for motivating stakeholders to participate; Development of simple and easily understandable surveys

Threats (↓): Increasing effort to activate stakeholders; Too simple surveys do not provide good data

Expert interviews:

Strengths (+): Targeted, extensive, and detailed questions are possible

Weaknesses (-): High effort for organizing and conducting high-quality expert interviews

Opportunities (↑): Focusing on the possibility to complement specific missing information

Threats (↓): Depending on the availability, willingness to cooperate and quality of experts in individual districts

Data from network operators and chimney sweeps: Strengths (+): Simple indicator of the thermal quality of a building without many further building data Weaknesses (-): Data protection regulations prevent building-specific use of data; Limited comparability of consumption data and calculated energy needs; Network operators must be willing to cooperate Opportunities (↑): Relaxed data protection regulations for research purposes can increase the quality of available data Threats (↓): The willingness of network operators to cooperate and the relaxation of data protection conditions are difficult to influence by EQ developers; Individual data rights conflict with relaxed data protection requirements
Building-related databases: Strengths (+): No additional effort of data collection if data sources already exist Weaknesses (-): Depending on the quality of the individual database Opportunities (↑): Uniform data standards across different data sources simplify cross-project data processing also for EQs Threats (↓): The effort/possibility for the unification of data depends on the individual processes of municipalities
Analyzing homogeneous sub-districts: Strengths (+): Simplifies the analysis of heterogeneous structures Weaknesses (-): Not suitable for very heterogeneous districts; Practicability depending on the district layout Opportunities (↑): Smaller sub-districts for more detailed analysis results; Clustering only for very homogeneous parts of the district Threats (↓): A greater level of detail increasingly reduces the benefit of this approach

5. Results and discussion

In order to answer the research questions of our work and investigate current building analysis approaches on district scale, their strengths, weaknesses, and potential for improvement, our most important findings based on the analysis of 25 EQ reports are:

- Currently ten analysis approaches for the thermal quality of buildings in a district are frequently used in EQ practice. The most frequently applied approaches in our study for obtaining data for building analyses are: the use of representative building typologies, on-site inspections of buildings, datasets from network-operators and citizen surveys. Overall, we could not find any connection between the year of the publication of the EQ report and the type and quantity of analysis approaches used. We compared the approaches used for all newer EQs (2016-2018) and older EQs (2013-2015) and did not identify any significant differences in this regard. Furthermore, we could not find a connection between the size of the districts and the types of the used approaches.
- In order to compensate for weaknesses in the individual analysis approaches, EQs commonly rely on a combination of multiple approaches and accept deficits in the analysis. There are approaches that are well suited for the analysis of buildings with typical and recurring characteristics such as the use of building typologies and the analysis of homogeneous sub-districts. Other, more resource-intensive approaches are suitable for the detailed analysis of buildings that are individual in their design and use, such as expert interviews or thermography. For practical purposes, detailed analyses should only be carried out for special buildings without reference values and large energy consumers in a district. In addition, there are approaches that are generally suitable for obtaining building data, such as the use of existing building databases, energy consumption values from municipal utilities or chimney sweep associations, and the use of aerial photographs to measure building and component dimensions.
- Current analysis approaches for districts are resource-intensive and complicated for many reasons. Existing databases including information on the thermal quality of buildings are often subject to strict data protection requirements and not always accessible. Well-informed and participating building stakeholders are needed for data collection at early stages of the EQ development. Different file formats make it

difficult to combine different data sources, and for adequately modeling buildings (e.g. according to building typologies) lots of data is necessary. The more precise and usable analysis results should be, the more complex the data acquisition becomes.

• To improve building analyses on district scale for the development of EQs to make them faster, cheaper, and more accurate in the future, we see a need for action in two main areas: (1) the research and further development of existing approaches, and (2) the improvement of legal and organizational framework conditions at the state and municipality level.

Research to improve analytical approaches can lead to better analysis tools such as more detailed building typologies, but should consider the trade-off between better results and more complex analyses or data demand. In some cases, new technologies offer the possibility of improvement without additional effort, such as the use of drones to obtain thermographic aerial images of buildings and automated image processing/assessment or other data analytics approaches.

Further improvement of such approaches is also dependent on external factors that cannot be influenced by EQ developers, but by state governments and municipalities, such as relaxed data protection guidelines for energy consumption data from network operators and chimney sweep associations. Governments that want to push energy retrofits on district scale already (e.g. Germany) or pondering introducing retrofit plans on district scale (e.g. China) could rethink data protection standards for research purposes. Also, the inconsistency of data formats of existing databases in municipalities (e.g. of property land registers, monument protection catalogs, district heating maps) hampers exchanges between individual databases and complicates analysis processes of districts. Uniform data structures and/or open-source software in administrations is a necessity for simple data processing in future.

We also note a distinct lack of uniform standards regarding the procedure for developing EQs and the structure of reports, complicating the comparability of the results of different EQ reports. In Germany, clear instructions should be defined in the KfW funding conditions for this purpose regarding a clear and uniform presentation of the results of the initial analysis of buildings in EQ reports. It should contain information on basic characteristics of the district, such as the number of residents, the number of residential units, the number of owners, the energy demand/energy consumption of the entire district and the individual buildings and the types of heating systems used. It should be shown clearly and transparently how the energy requirements of the individual buildings and the district were calculated, and, if possible, a uniform method should be chosen for all EQs.

Finally, we would like to discuss possible criticisms of our research approach:

First, the major drawback of this study is the limited availability and the limited number of studied EQs. Like all literature-based research, we cannot guarantee to have identified all relevant publicly available EQ reports as well as all strengths or weaknesses in the analysis. However, with our analysis we provide a first comparative insight into these reports. Seeing 850 EQ as the population, 63 randomly sampled EQs would have been a representative sample (with confidence level: 90%, margin error: 10%). However, as the analysis of EQ reports is very complex and we only found around 50 publicly available EQ reports in our extensive research, we studied a sample of 25 appropriate reports taking into account as best as possible a mix of size, geographical aspects, and year of publication. We see this method as suitable and regard the added benefit of examining a higher number of EQ reports as small for answering our research questions. With a higher number of analyzed EQ reports the results about the frequency of applied analysis approaches would, however, become more reliable.

Second, we would like to point out that we used only published EQ reports as the basis for our research approach. To a large extent, the information provided in the 25 analyzed EQ reports regarding the used analysis approaches is not detailed. EQ reports focus more on the presentation of the analysis results and less on the procedure or quality of used approaches. We also see that the analysis of the initial state of a district is often not a structurally delimited unit in the reports and sometimes merges into other parts of the EQ, such as the sections for the action plan or for the public participation process. This makes it more difficult to identify the used approaches and to analyze how they are implemented in the individual EQs.

Third, we want to emphasize that there are ways for improving the methodology of our SWOT analyses. For more results with further details of the SWOT analyses, expert interviews with the developers of EQs, such as local energy agencies, would be suitable. The use of supplementary literature, e.g. scientific publications on building typologies or guidelines for creating expert interviews for EQs, would also be beneficial and provide additional information.

Nevertheless, we believe that our study was able to identify the main analysis approaches used in practice in Germany to gain information on the thermal quality of buildings on district scale and gave insight into some of their essential shortcomings, and strengths for the development of EQs.

6. Conclusions

The district scale (neighborhood/ community scale) has many advantages for the energy retrofit of buildings. It does not focus on buildings as individual, independent objects, but rather in their urban context. In this way, for example, local social dynamics can be specifically addressed when motivating building stakeholders in the planning and implementation of retrofit measures. Economies of scale can be realized when retrofitting many buildings in a small area at the same time, while the district scale is smaller and easier to coordinate than the higher-level city scale. We thus expect that the district scale will gain in importance in the next years worldwide.

In Germany, the development and implementation of EQs is already a popular instrument for decreasing and decarbonizing the energy consumption of existing buildings in urban areas, and is readily funded by the German government. EQs have been very frequently applied already and EQ reports are documented for each individual district. However, a holistic and comprehensive evaluation of the long-term benefits of EQs after the implementation of developed measures with regard to ecological, social, and emission-related criteria has been lacking so far in research. It is necessary for urban policy makers to invest high costs and effort for analysing buildings and developing appropriate retrofit strategies for whole districts. The actual participation of the various different district stakeholders in the implementation process, however, is essential for the success of EQs and cannot be precisely quantified in the planning process.

To reduce the time and costs of retrofit plans on district scale we have identified a need for more research in the field of energy building analysis. We see our work as a basic overview of current building analysis on district scale with the intention of motivating further research in this field, especially to develop energy improvement strategies in urban areas.

With regard to EQs, we see a need for action for standardizations in Germany on the national level. To deal with different forms of buildings, uniform guidelines (both in data collection, assessment, and reference values) would be beneficial for analyses on district scale and lead to a better comparability of EQ report analysis and implementation results.

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Appendix

Table 3. Overview for dealing with residential and nonresidential buildings (1: used in EQ, 0: not used in EQ)

District		Specific analysis tools for nonresidential buildings	Data of public buildings from local administration	Focus on residential buildings	Focus roughly equally on residential and nonresidential buildings	Focus on nonresidential buildings
Eichkamp und Heerstr	Berlin	0	0	1	0	0
Moabit-West	Berlin	1	0	0	0	1
Ostrow	Cottbus	0	0	1	0	0
Historische Innenstadt	Neuruppin	0	0	1	0	0
sö Eisendorf und Bremerstr	Hamburg	1	1	1	0	0
Mollerstadt	Darmstadt	1	0	0	1	0
Innenstadt	Baunatal	1	0	1	0	0
Nettersheim	Nettersheim	0	1	1	0	0
Altchemnitz	Chemnitz	1	0	0	1	0
Neumünden Fuldablick	Hann Münden	1	0	1	0	0
Innenstadt	Nord Völkingen	1	0	1	0	0
Gartenberg	Sömmerda	0	0	1	0	0
Enego	Bremervörde	0	1	1	0	0
Schilksee	Kiel	0	1	0	1	0
Lerchenberg	Mainz	1	1	1	0	0
Gibitzenhof	Nuremberg	1	1	0	0	1
Weststadt	Steinheim	1	0	0	1	0
Wengenviertel	Ulm	0	0	1	0	0
Neue Mitte	Grenzach-Whylen	0	1	1	0	0
Unsere Stadt	Altensteig	1	1	0	1	0
Innenstadt	Geldern	0	0	1	0	0
Nörd. Festplatz	Mörfelden-Walldorf	1	1	0	1	0
Weinberg-Dichterviertel	Roßleben	1	0	1	0	0
Hainholz	Hannover	1	0	0	1	0
Hillscheid	Höhr-Grenzhausen	1	1	1	0	0
	Total	**15**	**10**	**16**	**7**	**2**

Table 4. Overview for analysis approaches for the building stock (1: used in EQ, 0: not used in EQ)

District		Building typologies	On-site inspections	Citizen surveys	Data from the network operator	Building-related databases	Data from the chim-ney sweep	Aerial images	Analyzing homogeneous sub-districts	Thermographic images	Expert interviews
Eichkamp und Heerstr	Berlin	1	0	1	0	1	0	0	0	1	0
Moabit-West	Berlin	0	0	1	1	1	0	1	0	0	0
Ostrow	Cottbus	1	1	1	1	1	0	1	0	1	0
Historische Innenstadt	Neuruppin	1	0	0	1	0	0	0	1	0	0
sö Eisendorf und Bremerstr	Hamburg	1	1	0	1	1	0	0	0	0	0
Mollerstadt	Darmstadt	1	1	1	1	1	0	1	0	0	0
Innenstadt	Baunatal	1	1	1	0	0	0	1	1	0	0
Nettersheim	Nettersheim	1	1	0	1	1	0	1	0	0	0
Altchemnitz	Chemnitz	0	1	1	1	0	1	0	0	0	0
Neumünden Fuldablick	Hann Mün-den	1	1	1	1	1	0	1	0	0	0
Innenstadt	Nord Völk-ingen	0	1	1	1	0	1	0	0	0	1
Gartenberg	Sömmerda	1	1	1	1	0	1	0	0	1	0
Enego	Bremervörde	1	0	1	1	0	0	0	0	0	0
Schilksee	Kiel	1	1	0	0	1	0	0	0	0	0
Lerchenberg	Mainz	1	1	1	1	1	1	1	0	0	0
Gibitzenhof	Nuremberg	1	1	1	1	1	0	0	0	0	1
Weststadt	Steinheim	1	1	1	1	0	1	0	0	0	0
Wengenviertel	Ulm	0	0	1	1	0	0	0	0	0	0
Neue Mitte	Grenzach-Whylen	1	1	1	0	1	0	0	0	0	0
Unsere Stadt	Altensteig	1	1	1	0	1	0	0	0	0	1
Innenstadt	Geldern	1	1	1	1	1	0	0	1	0	1
Nörd. Fest-platz	Mörfelden-Walldorf	1	0	0	1	1	1	0	1	1	0
Weinberg-Dichterviertel	Roßleben	1	1	1	0	1	1	1	0	0	0
Hainholz	Hannover	1	1	0	1	1	1	0	1	0	0
Hillscheid	Höhr-Grenzhausen	1	1	1	1	1	1	0	1	0	0
	Total	**21**	**19**	**19**	**19**	**17**	**9**	**8**	**6**	**4**	**4**

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