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Fifty years after the Schelling's Models of Segregation: Bibliometric analysis of the legacy of Schelling and the future directions of segregation research

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ABSTRACT

In 1969 Thomas C. Schelling published his paper "Models of Segregation" and in 1971 he published a follow-up paper introducing "Dynamic Models of Segregation". Schelling's papers developed the theoretical models of interactive dynamics of individual residential choices, resulting in pronounced patterns of residential segregation at the city level. Even after 50+ years, the topic of residential segregation and sorting remains as relevant as when Schelling published his papers. The two Schelling papers have been cited more than 8000 times together, and have made a strong impact on the residential segregation literature and beyond. In this paper, we examine how Schelling's ideas have impacted empirical research on residential segregation, and thus contributed to a greater understanding of urban processes. We find that few empirical papers explicitly test the Schelling models in residential segregation studies, and there are a growing number of influential papers in the field of segregation that do not reference Schelling. However, the papers by Schelling have served as a source of inspiration for a diverse set of empirical studies, new ways of defining neighbourhoods and developing more comprehensive theories of segregation.

1. Introduction

It has been more than 50 years since Thomas Schelling (1921–2016) developed theoretical models explaining the dynamics of residential segregation. Today, the Schelling models of residential segregation have become one of the most cited models in the urban research literature. According to Google Scholar, Schelling's seminal papers have been cited more than 8000 times together. Schelling was primarily an economist, and he was awarded the 2005 Nobel Memorial Prize in Economic sciences (shared with Robert Aumann), but the impact of his work was way beyond economics. Papers referring to the Schelling models come from a great diversity of disciplines, ranging from urban studies to computer science and from economics to medicine. This is a testimony of the wide influence of the Schelling models for different disciplines. While there is a surge in studies focusing on segregation, an expanding body of research is also exploring alternative frameworks.

Schelling had originally developed his theoretical models of segregation with an example of the residential sorting of members of two different population groups. This model, according to Schelling (Aydinonat, 2005; Schelling, 2006), was born unexpectedly while he was flying in an airplane and had nothing to read. To amuse himself, he started to experiment with pencil and paper. After he noticed that interesting patterns started to emerge, he continued to develop the model at home in a form of a game with his twelve-year-old son and his son's coin collection. Soon he realized that something important had emerged and he started experimenting on a computer, which lead to the publication of the two seminal papers (Schelling, 1969, 1971). Schelling's work received little attention at the time of publication. It was twenty-five years later, together with the rapid development of computer sciences, that the scientific community rediscovered that Schelling

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has done some pioneering work in the fields of game theory, agent-based modelling and in simulating human behaviour.[1] As a result, a significant proportion of publications referring to Schelling's papers are from the computational and modelling literature. Of course, the Schelling models also had a major impact on residential segregation research, which is the primary focus of this paper.

The aim of this paper is to better understand the impact that the Schelling papers have made on empirical studies of residential segregation. Our paper is specifically focused on the empirical studies of segregation in the real urban environment and using real-world data that explicitly cite the original papers of Schelling (1969, 1971), although we also acknowledge that a large body of the literature using Schellings' ideas deals with simulated environments and "artificial" data (e.g., studies of Fossett (2006), Clark and Fossett (2008), Zhang (2011)). In this paper, we first provide a bibliometric overview of the 50+ years (from 1969 to 2022) of scholarly literature referring to the Schelling models. Following this, we broaden our focus to explore empirical literature on residential segregation, with more emphasis on recent contributions and an outlook towards the future of segregation research. More specifically, we start with conducting a bibliometric study of the full body of literature that has referenced the Schelling models of residential segregation to understand the contribution of the Shelling's models to different fields of research; and from this full body of the "Schelling literature", we select studies that empirically test Schelling's models in the context of residential segregation using real-world data, and we examine this specific literature to understand the extent to which the Schelling's models have been empirically validated in the real urban environment. The bibliographic analysis brings out three important contributions of the empirical papers citing Schelling's original work, including (a) a better understanding of both moving desires and preferences as well as actual moves, (b) new ways of defining neighbourhoods (e.g., bespoke neighbourhoods), and (c) the development of more comprehensive theories of segregation that extend research on residential segregation to segregation in schools, workplaces, and leisure time activity sites. However, we also observe that an increasing amount of research does not reference Schelling's papers, and there has been growth in both conceptual and methodological diversity within segregation research (Müürisepp et al., 2022). Therefore, we touch upon the critique as well as some of these new avenues of segregation research.

The rest of this paper is organized as follows. Section two provides a summary of the Schelling models. Section three presents the findings of the bibliometric analysis of the full body of the literature that references the Schelling papers followed by a more specific examination of empirical studies of residential segregation (in the appendix, we provide a detailed explanation of how the selection of literature was carried out). Section four goes beyond the Schelling's legacy to uncover the current state of the art and future challenges in empirical residential segregation research. Section five introduces a multi-domain extension of the Schelling models, and Section six offers final conclusions.

2. Summary of the Schelling models

The literature often refers to 'Schelling's model of segregation', but to be precise, the plural form – models – should be used. Thomas Schelling developed three types of models: A linear-distribution model, an area-

distribution model, and a bounded-neighbourhood model, each of them having somewhat different rules and applications. These models are one of the earliest agent-based simulations in the social sciences (Hatna & Benenson, 2012), offering an explanation of how patterns of residential segregation form as people move around in a city. In Schelling's models, agents – members of any two distinguishable population groups – move around in urban space, following a few simple rules, and eventually settle in spatially segregated residential clusters. In the models, the residential arrangement of the two population groups is determined solely by the preferences of individuals.

Schelling (1971) started from a linear-distribution model by arranging population groups into lines. The initial state of the model assumes a random distribution of two groups across residential neighbourhoods of a city. This linear model is essentially aspatial with eight nearest neighbours representing the "neighbourhood". Some people are satisfied while others are dissatisfied with their nearest neighbours, based on the balance of own-group and out-group members among their eight closest neighbours. Residentially satisfied people are those who live in neighbourhoods where own-group members out-number out-group members. Even a slight over-representation is enough for being residentially satisfied, meaning that the share of own-group and out-group neighbours (4/4) can be equal since ones' own presence would shift the overall balance of the two groups in favour of own-group.

Residentially dissatisfied people are those who have more out-group neighbours among the eight nearest neighbours than their own-group members. Residential dissatisfaction is related to the neighbour preference; having too few own-group neighbours is a trigger for moving. The model moves people back and forth along the line in ways that people get satisfied with their nearest neighbours. However, as people start to move to become more satisfied with the balance of own-group and out-group neighbours, they also affect the neighbour satisfaction of other people. Other people may either become more satisfied (if members of the other group leave and members of their own group arrive), or more dissatisfied (if members of the other group arrive and members of their own group leave) with the composition of their nearest neighbours. Thus, an iterative process of residential moves starts, and it lasts until the moment that all people living in the city are satisfied with their neighbour composition.

As a next step, Schelling introduced the notion of geographical space into the area-distribution and bounded-neighbourhood models. For this purpose, a theoretical city is divided into small spots (grids, squares or housing units) like a checkerboard. The area distribution model is based on the idea of ego-centric neighbourhoods, and the eight closest spots form a neighbourhood for any person in the area-distribution model. In other word, Schelling was the first to introduce the concept of 'ego-centric neighbourhoods' in his area-distribution model. In the bounded-neighbourhood model, neighbourhoods have fixed borders. It is especially noteworthy that according to Schelling, it is not only residential neighbourhoods which are bounded, but also schools, workplaces, and leisure time activity sites. These are all fixed spatial units, and any person can be inside or outside of them. In these models the term 'tolerance' is related to insiders (neighbours, co-workers, schoolmates). For example, members of one group could tolerate a certain percentage of the other group in each of these spatial units.

In both area-distribution and bounded-neighbourhood models, members of the two population groups are then randomly distributed across the grids, one person per grid, and a fair number of randomly chosen grids (25 to 30 %) are left vacant to allow for a relatively free moving around. In the models, people can only move into the vacant spots on the checkerboard, and each move also creates vacancies in the spots from where people leave. The rules are similar to the linear-distribution model. In the area-distribution model, residentially dissatisfied people are those who have more out-group members in their ego-centric residential neighbourhood than own-group members. Dissatisfied people move to the closest spot in a neighbourhood where their own-group members out-number out-group members. In the bounded-

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[1] There has been some controversy over whether Schelling's models were actually the first examples of agent-based modelling in the social sciences. In fact, James Sakoda developed similar models of social interactions in his PhD thesis submitted in 1949, thus 20 years before Schelling's first seminal paper (Hegselmann, 2017). According to Hegselmann (2017), at the time J. Sakoda published his ideas, there were no skills and technical equipment to realize his model, and later his work was simply forgotten. Schelling had never heard of Sakoda's model, but his contribution was timely and led to success (Aydinonat, 2005).

neighbourhood model, the mechanisms of moving are slightly more complex, as Schelling introduces the concept of 'tolerance' to set additional rules in this model. In a nutshell, people who are less tolerant towards out-group members move to another neighbourhood with a higher share of own-group members. Again, as people start to move to become satisfied with their residential neighbourhood, they also affect the neighbourhood satisfaction of other people.

All three models predict that the 'interactive dynamics of discriminatory individual choices' are guided by the aim to achieve a slight over-representation of own-group members by each dissatisfied move. And that this leads to high levels of residential segregation between the two groups across the neighbourhoods. Based on the three simulation models that follow a few simple rules, Schelling (1971: 146) found that 'In some cases small incentives, almost imperceptible differentials, can lead to strikingly polarized results'. Schelling himself focussed on racial residential segregation. It is important to note that the models exclusively focus on the patterns of residential segregation that emerge from the preference-based sorting of individual group members who are dissatisfied with their neighbours. The simulation models do not take into account collectively enforced and economically induced mechanisms of residential segregation, nor do they take into account organized discrimination, despite acknowledging their existence. For Schelling (1971: 145), these 'are very different mechanisms and have to be separately understood.' Hence, Schelling's models explain residential segregation that result only from individual discriminatory choices, and the models provide insights in how individual choices, and related residential sorting, shape the aggregate distribution of different population groups across urban neighbourhoods.

The Schelling models were very innovative at the time that they were developed, and they have made a significant impact in different fields of research in the social and computer sciences over the last 50+ years. Since Schelling originally developed his models with the example of racial segregation, his work continues to inspire research on racial/ethnic residential segregation. The following section of this paper will investigate to what extent empirical papers have been able to validate the purely theoretical models of Schelling. We are especially interested in how empirical studies have isolated the role of residential satisfaction and preferences from other mechanisms leading to segregation. We will seek to understand how preferences compare to, and interact with, economic, institutional, and other factors, such as discrimination, that collectively leads to segregation.

3. Literature analysis

3.1. Bibliometric analysis of the "Schelling literature"

In this section, we present the results of a detailed bibliometric analysis of the research publications that have referenced the Schelling models of segregation, the so-called "Schelling literature". This analysis is based on 2787 unique source documents published over a 50+ year period, 1969–2022 (see appendix on how the selection of the literature was done). It should be noted that our bibliometric analysis has an obvious limitation – it does not capture those studies on segregation that do not reference Schelling. Thus, many papers that empirically analyse residential segregation and individual preferences are excluded from this literature review. We address this additional literature in the later part of the paper.

When reviewing the "Schelling literature", it becomes clear that the Schelling papers have made an impact on a very wide range of disciplines, including urban studies, computer sciences, economics, sociology, political science, ecology, and medicine. For example, the Schelling segregation models have been used to evaluate the COVID-19 transmission risks (Cuevas, 2020), to simulate processes of opinion dynamics (Feliciani et al., 2017), to predict the location of cultural conflicts (Lim et al., 2007), to simulate the competition of gangs for urban territory (Alsenafi & Barbaro, 2018), to model the incident rate of children's lead

poisoning (Shao et al., 2017), or to investigate the effect of air pollution on residential property values (Anderson Jr & Crocker, 1971).

To better understand the influence and circulation of the Shelling models in different disciplines, we have classified the "Schelling literature" (2787 unique source documents) into several research areas (Fig. 1). The classification was done by searching for keywords in the source title (the title of the journal or book), and the title of the publication. Although such classification may not be absolutely accurate, the results shown in Fig. 1 illustrate the wide applicability of the Schelling's models, the extent of their use in different research areas and the interdisciplinary nature of the research. It is important to note that many publications, referring to Schelling's seminal papers, are interdisciplinary, e.g., the book chapter by Edmonds (2006) is at the intersection of four research areas: sociology, computer sciences, economics and nature sciences. Broadly speaking, the bulk of the "Schelling literature" can be categorized into two research areas: computer sciences/math and social sciences. Thomas Schelling originally developed his models with an example of racial/ethnic segregation, thus eventually these models have made a great impact on social sciences and specifically on research on residential segregation. Schelling's influence on computer sciences is very important too, he is even considered to be one of the pioneers of game theory, and his models are seen as early examples of agent-based simulations. Nowadays, agent-based simulations are a powerful tool for examining residential segregation and have been widely used in the literature on this topic, building on the pioneering work of Schelling (see e.g., The Journal of Mathematical Sociology, Volume 35, 2011 Special Issue 1–3; Olteanu et al., 2020). In addition, the "Schelling literature" also covers studies that we have broken down into spatial sciences (i.e., studies that emphasize the spatial dimension, such as urban studies, regional planning, etc.), economics, physics, biology and other nature and environmental sciences, law and politics, transport and communication as well as medicine and health.

Fig. 2 illustrates the evolution of the dissemination and application of the Schelling models in different disciplines. The number of publications citing Schelling's papers remained relatively stable from 1970 to 1995, with a subsequent rapid increase, reaching its peak in 2017 with 216 new publications citing the Schelling models. Since then, the annual number of citations to Schelling's models appears to be gradually decreasing, despite the ongoing growth of the entire body of research on residential segregation since the 1970s. Moreover, initially, Schelling was predominantly cited in the social sciences, with fewer citations in the computer sciences/math literature, but since around 2005, however, the influence of Schelling's ideas in this field has rapidly gained prominence. Research combining the social and computer sciences also became popular at the same time. Interestingly, for many years now, the proportions between different research areas have been very similar from year to year.

Additionally, to visually illustrate the relationships between different research areas that refer to the Schelling models, we used the VOSviewer software tool (van Eck & Waltman, 2011). Using this tool, we generated a semantic map as shown in Fig. 3. This map is based on the bibliographic data extracted from the Scopus database.[2] The units of analysis are the keywords specified in the publications that refer to Schellings' work. In Fig. 3, the size of the circles indicates the number of publications in which these keywords occur. Thus, the semantic map depicts the most frequently used keywords, and the adjacent keywords tend to recur in the same publication. High frequency of occurrence and similarity of keywords form clusters, and these clusters represent

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[2] We were not able to perform this analysis using the dataset that we compiled ourselves by the selection of literature, because VOSviewer supports specific data formats. Although, both Scopus and Web of Science can be used for such analysis, Scopus is found to have a better coverage of citations (Martín-Martín et al., 2018). Analogous analysis with the Web of Science database yielded a very similar result.
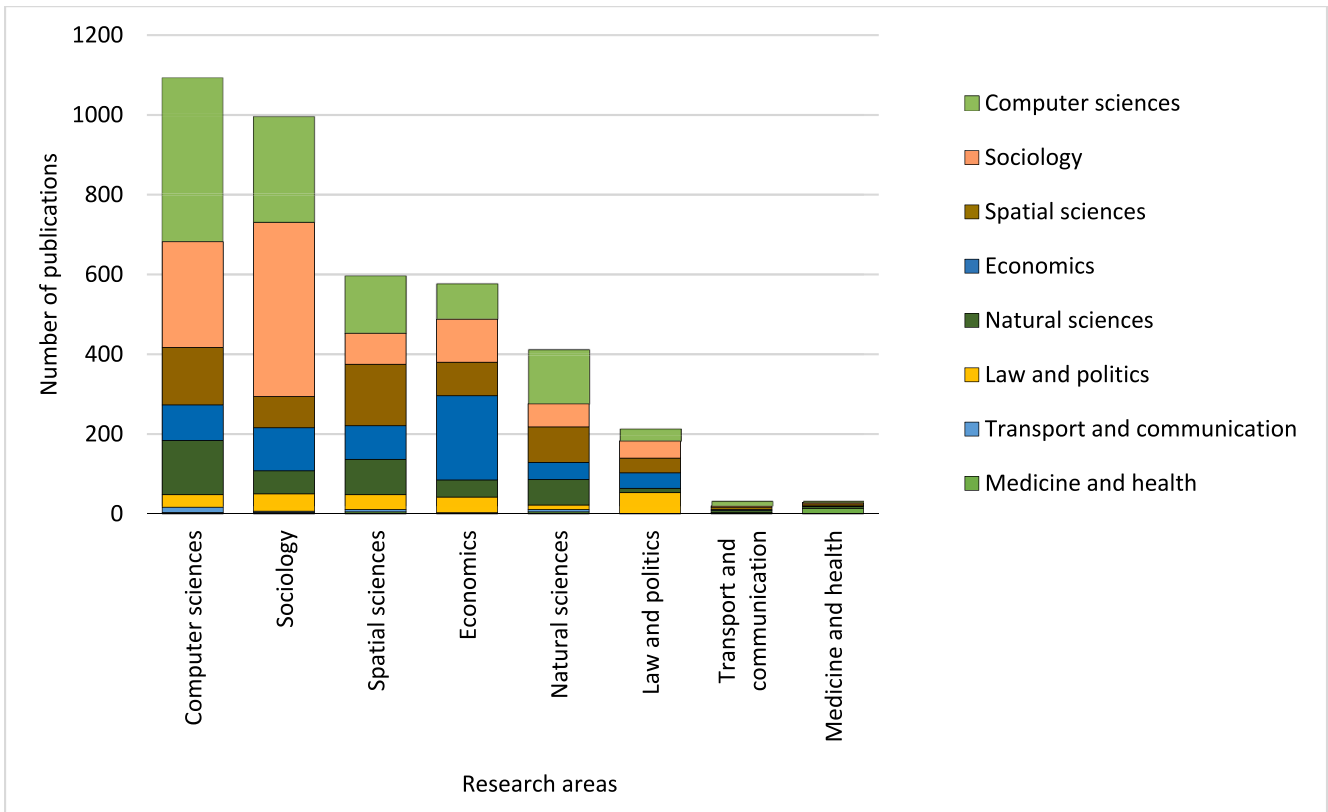
Fig. 1. Classification of the "Schelling literature" by research areas (authors' calculations).
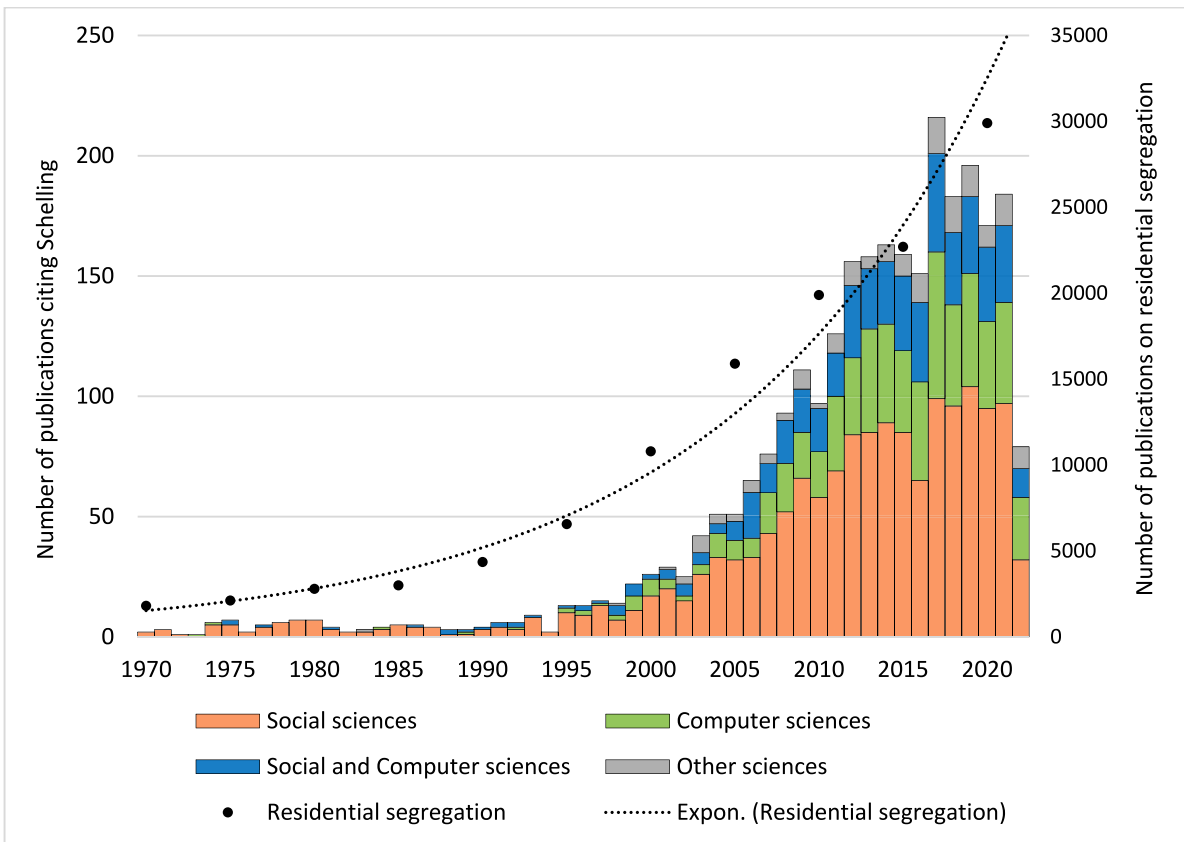

Fig. 2. The yearly number of new publications citing Schelling's papers (authors' calculations).
Note: The statistics on the number of publications on residential segregation have been collected from Google Scholar.
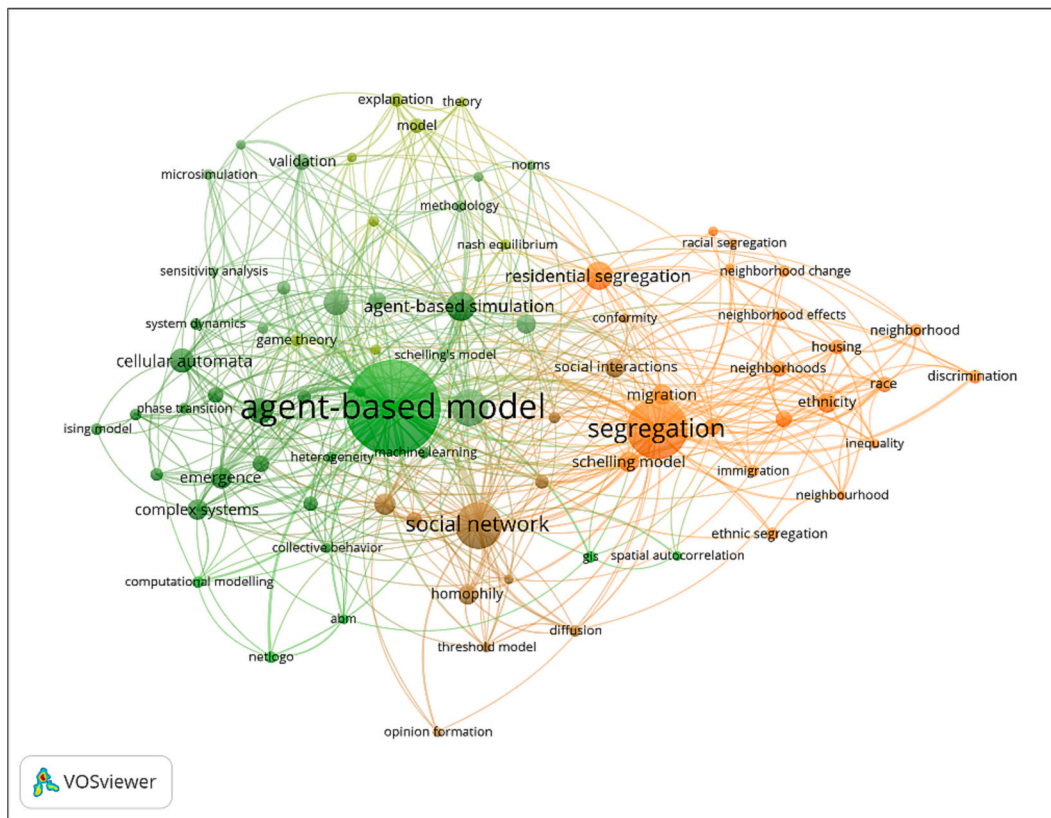
Fig. 3. Semantic map of co-occurrences of the keywords in the research that cite Schelling (extracted from 2258 source documents from Scopus database, on March 2022).

Note: Data cleaning was performed; terms of the same meaning have been merged, e.g., agent-based model, agent-based models, agent-based modelling, agent-based modelling, agent-based model, agent-based models, agent-based modelling and agent-based modelling – all of these are called "agent-based model" in our semantic maps.

research areas. In Fig. 3, we can clearly identify two broad research areas: social sciences and computer sciences. Basically, the orange cluster – social sciences – includes research related to various forms of residential segregation, housing, migration, and inequality. The green cluster – computer sciences – includes research related to modelling and simulation. Between these two clusters, a research field dedicated to social networks emerges.

Overall, our bibliometric analysis presented in this section illustrates that the application of the Schelling models is extremely diverse and is equally important and widespread in the computer and social sciences. This can be considered a rather unique convergence of two sciences. We acknowledge the wide influence of the Schelling models on different disciplines, including the strand of mathematical simulations where "artificial" data are often used, but the rest of this paper is focused on residential segregation literature that originates from the social sciences.

3.2. Residential segregation through the lens of Schelling

We found that there are 1100 publications dealing with residential segregation that reference the Schelling models (see appendix on how the selection of the literature was done). These publications can be categorized into three (often overlapping) groups: (a) contextual studies providing a literature review; (b) studies using a theoretical model and artificial data and simulations; (c) studies that empirically investigate (aspects of) segregation using real population data (see Fig. 4). By our estimation, all three groups are of similar size in terms of the number of publications that could be attributed to them. In this paper, we are mainly interested in the last group of publications that empirically test (parts of) the Schelling models of residential segregation. In order to select the most relevant studies for further analysis, we applied a
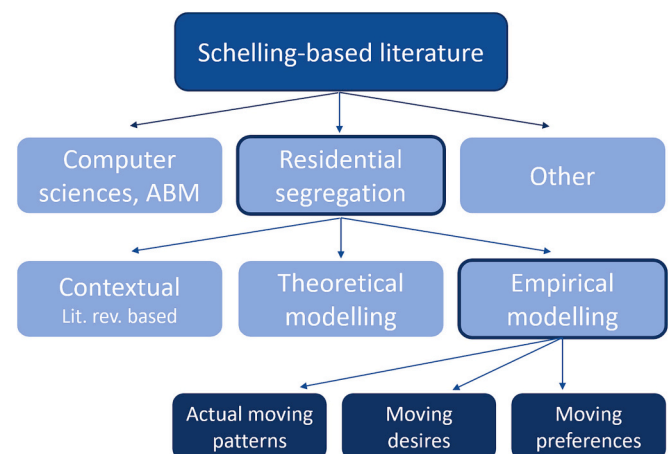

Fig. 4. Classification of Schelling-based literature (author's elaboration).

criterion (filter) measuring the impact of publications, which is based on the number of their own citations (see appendix for more details on the selection criteria). We then performed a content analysis of each remaining publication, focusing on the research data and methods. As a result, we have selected 60 empirical studies for further analysis. We conducted a thorough review of these publications to better understand their contribution to the validation of Schelling's segregation models. We were particularly interested in papers that sought to find evidence that individual preferences can lead to city-wide patterns of residential segregation. We noticed that the 60 publications can be divided into

three categories depending on their focus: studies focussing on actual moving patterns, on moving desires, and on moving preferences. Next, we will analyse the three types of studies in greater detail.

3.2.1. Actual moving patterns

These studies usually aim to identify patterns of residential mobility of different ethnic groups (e.g., Alba & Logan, 1993; Quillian, 2002), often in the context of the White flight hypothesis (Boustan, 2010; Crowder, 2000; Pais et al., 2009; Shertzer & Walsh, 2019; Wessel & Nordvik, 2019). The White Flight hypothesis is related to the concept of tipping points (see e.g., Card et al., 2008 for tipping points) in the Schelling models, indicating that members of the majority population start to leave their neighbourhood once the share of the minority groups in a neighbourhood exceeds a certain level or 'tipping point'. Research on actual moves aims to capture mechanisms of residential sorting (Sampson & Sharkey, 2008), and neighbourhood composition effects on intergenerational residential mobility (Sharkey, 2008). In general, these studies investigate whether people actually move to neighbourhoods dominated by their own-group (or leave neighbourhoods dominated by the other group), sometimes with a specific focus on the transmission of neighbourhood disadvantage over the life course or across generations. This research utilizes individual level data on residential moves, and contextual data that characterizes the racial/ethnic composition of neighbourhoods, obtained from censuses (e.g., Alba & Logan, 1993; Sampson & Sharkey, 2008), panel studies (e.g., Harris, 1999; Sharkey, 2008), population registers (e.g., Hedman et al., 2011; Musterd et al., 2016; van Gent et al., 2019; Wessel & Nordvik, 2019) or a combination of different large-scale data-sets (e.g., Crowder, 2000; Massey et al., 1994; Pais et al., 2009; Quillian, 2002; Vogiazides, 2018).

The main finding of these studies is that racial/ethnic homophily is a strong factor that affects actual moves. The studies indicate a preference towards own-group neighbours, which shapes the residential sorting of both members of the minority and majority population. Although these studies do not explicitly look at preferences, the findings are often interpreted as confirming that individual preferences in terms of ethnic/racial composition of residential neighbourhoods are a trigger for moves that ultimately lead to ethnic/racial residential segregation on the aggregate level of a city. However, Harris (1999) warns that evidence of the importance of preferences in explaining actual moving patterns that lead to new patterns of residential segregation is not conclusive.

Research on actual moving patterns thus usually makes indirect assumptions about individual preferences in shaping residential mobility. Such studies hypothesize that the change of racial/ethnic composition of the neighbourhoods as a result of moving is driven by individual preferences, and eventually leads to aggregate segregation patterns. For example, Iceland (2004) tracked racial and ethnic residential segregation over the 1980–2000 period and examined the association between growing ethnic diversity and trends in ethnic residential segregation in the United States. Similarly, Denton and Massey (1991: 60) analysed patterns of racial and ethnic neighbourhood change in the US, and they were interested in 'whether the concentration of minorities demand for housing – especially black demand – in neighbourhoods close to minority enclaves represents a pattern of voluntary action or an involuntary outcome of institutional and individual discrimination'.

Explicit attempts to test Schelling's hypotheses on the role of the presence of out-group members in residential neighbourhoods on residential moves are rare. One of the few exceptions is a study by Bakens and Pryce (2019) who use a Schelling-type theoretical model to construct a simplified 'minority-mover' model. The results of their empirical study provide evidence on the importance of homophily in explaining mover flows; the results show that as the horizon of homophily increases, the rate at which the Schelling-type model approaches a high level of segregation also increases. However, the explicit role of preferences as isolated from other factors such as discrimination has yet to be established in studies on actual moving patterns. For example, Alba and Logan (1993), find that residential sorting is different for different

ethnic groups, but they remain sceptical about to what degree these patterns can be explained by preferences alone. Hence, other strands of research have focussed on studying the role of moving desires and residential preferences rather than actual moves in understanding segregation.

3.2.2. Moving desires

The strand of research on moving desires focusses on the question whether the population composition, e.g., the ethnic or racial composition in origin and destination neighbourhoods, influences the desire to move. Such studies are based on surveys with questions on moving intentions such as: 'If possible, would you like to leave the neighbourhood?' (Feijten & Van Ham, 2009; van Ham & Feijten, 2008) or on questions on residential satisfaction such as: 'How satisfied or dissatisfied you are with your neighbourhood as a place to live?' (Harris, 2001). These studies – in contrast to the first type, where the actual moving patterns are analysed, – come closer to understanding the role of preferences in residential decision-making.

In general, the results of research investigating people's desires to move provide support to the Schelling models. When people's characteristics match the characteristics of their neighbours, their desire to leave their neighbourhood is lower compared to the situation where people's characteristics do not match the characteristics of their neighbours. From this it can be deducted that if people are able to fulfil their desires when it comes to the similarity of neighbour characteristics to their own characteristics, the aggregate level of segregation will increase. From the opposite perspective, van Ham and Feijten (2008) conclude that mixed neighbourhoods are often the result of people not being able to realize their moving desires.

It is worth noting that several studies suggest that ethnic minorities are less sensitive to neighbour characteristics than the majority population, and they are less likely to materialize their moving desires into actual residential moves (Boschman et al., 2017; Crowder, 2001; Freeman, 2000).[3] Furthermore, minorities who desire to live together with out-group neighbours may face constrains for realizing such desires. For example, the analysis of Freeman (2000) shows that African Americans are more segregated from whites than other minorities, and they have greater difficulties entering white neighbourhoods even if they wish so. In other words, the residential desires of the majority population to live together with the own-group members may be key for understanding how aggregate level patterns of ethnic/racial residential segregation are produced and reproduced. However, an important limitation of the 'moving desires' studies is that intentions and willingness to move do not always translate into actual moving behaviour.

3.2.3. Moving preferences

The idea behind this type of studies is directly related to the identification of people's preferences for the neighbourhood, usually by measuring the ethnic or racial makeup of the neighbourhood population composition. The most common data used comes from surveys. In contrast to the 'desire to move' literature, this type of studies does not delve into the intentions to move or into the neighbour characteristics in the current neighbourhood of residence. Rather, people are asked to imagine and evaluate hypothetical residential neighbourhood contexts. For example, respondents are asked questions such as: 'What mixture of people would you prefer?' (Clark, 1991: 9, 1992: 454), or: "Which neighbourhoods would you 'seriously consider' looking for a house or apartment, and which neighbourhoods you would 'never consider' looking for a house or apartment" (Krysan & Bader, 2007: 708). In general, these studies aim to find out who are the neighbours people (do not) want to live with.

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[3] Papers of Crowder (2001) and Boschman et al. (2017) where not among the selected papers for this examination, but are important to refer to in this context.

The main findings of this literature indicate that in general people prefer to live among their own-group members, and it is suggested that this individual preference is the key for understanding aggregate level segregation patterns. For example, Clark (1992: 463) states that: 'Although a study of preferences cannot answer all the questions about ethnic and racial separation in the city, preferences clearly are relevant in generating and maintaining separate ethnic residential areas' Some authors are somewhat more cautious about the role of preferences in shaping segregation. Bruch and Mare (2006) combine survey data with agent-based modelling to analyse the role of preferences in residential segregation. The authors find that 'Race preferences alone may be insufficient to account for the high levels of segregation observed in American cities', and that 'residential sorting by both race and income may produce higher levels of racial segregation than either factor alone' (Bruch & Mare, 2006: 667).[4]

Emerson et al. (2001) also try to isolate the role of racial preferences from other factors in residential segregation. They find that race shapes residential patterns and that there are clear differences among racial/ethnic groups, with preferences being less important for minorities. Many other studies also report differences in preferences (so-called preference gap) between racial/ethnic groups (e.g., Clark, 1991, 1992; Farley et al., 1997; Ihlanfeldt & Scafidi, 2002; Krysan & Farley, 2002; Lewis et al., 2011). Although, studies analysing moving preferences aim to explicitly test the Schelling models, the limitation of these studies is similar to studies on moving desires, i.e., the stated residential preferences do not necessarily lead to actual moves and actual patterns of segregation in cities.

To conclude, of the large body of residential segregation literature that references the work of Schelling, only a small proportion of research actually empirically tests (part of) the models and explores the interactions between residential satisfaction and moving. Studies that do empirically test Schelling's models in the context of residential segregation examine the relationships between individual preferences, residential choices, and aggregate segregation patterns. In doing this, different studies use different approaches and different sources of data. Most of the studies use individual level data: nearly half of them are based on survey/interview data, one third uses census or register data, and the rest of the studies combine the results of surveys and censuses. The majority of the research focusses on racial/ethnic segregation in the US, and some research has been undertaken in Europe. Around 50 % of the publications clearly state that they test the Schelling models (e.g., Harris, 1999, 2001; Krysan, 2002; Krysan & Bader, 2007; Vogiazides, 2018), while the rest of the papers have received inspiration from the Schelling models. The majority of the papers confirm the outcomes expected by Schelling's theoretical models that individual-level residential preferences are related to city-level patterns of residential segregation, although it is acknowledged that in reality the process leading to segregation is more complex than preferences alone. Moreover, we were interested in how empirical studies have isolated the role of individual preferences from other mechanisms leading to segregation. Isolating preferences is a critical requirement for studies based on the Schelling models. Our analysis revealed that many empirical studies either neglect or are not able to distinguish preferences from other mechanisms, despite being inspired by Schelling segregation models. This finding encourages future empirical studies to device new methods that can effectively isolate the role of preferences in shaping segregation patterns from other mechanisms.

4. Moving beyond Schelling's legacy: new directions of segregation research

The 1969 and 1971 papers of Schelling have triggered an extensive

body of research on residential segregation over the past 50+ years, leaving a long-lasting effect on urban research. The ideas of Schelling have served as a source of inspiration for urban scholars and especially segregation scholars. While the body of research on residential segregation, and consequently our understanding of it, has expanded significantly over the decades (see Fig. 2), an increasing number of influential papers in segregation studies now do not reference Schelling. Therefore, the results of our bibliometric analysis provide a limited view of the progress in segregation research. Many empirical studies, whether drawing inspiration directly from Schelling's models or indirectly from other sources, have made a noteworthy contribution towards a greater understanding of urban processes and the advancement of methodological approaches. For example, the paper by Olteanu et al. (2019), introduces a mathematical framework for analysing multi-scalar and multi-group segregation. In this study, the proposed method is applied to illustrate multi-group ethnic segregation in Los Angeles. While ideologically resembling Schelling models, this paper does not explicitly reference Schelling. Moreover, various recent publications (e.g., Dimou et al., 2020; Owens, 2019; Vogiazides & Chihaya, 2020) can be found explicitly examining residential segregation resulting from preference-based sorting of individuals, yet they make no reference to Schellings' papers.

While the reasons for citing or not citing Schelling might be intentional or non-intentional, there is a growing perception that Schelling models are overly simplistic because of (a) agents making binary decisions on residential relocations based on a single criterion of neighbour race/ethnicity, (b) fixed neighbour preferences of individuals, (c) homogeneity of preferences within the studied groups, (d) oversimplified neighbourhood structures in cities, and (e) lack of consideration for connections between residential decision-making and decision-making regarding other activity places (schools, workplaces, leisure time) within the social and spatial structures of each city. Such oversimplifications neglect the complexity of residential decision-making and real-world spatial arrangements, making researchers to seek new approaches and methods to better capture these complexities of segregation (such as by Olteanu et al., 2019; Crowell & Fossett, 2023). Ultimately, there are also studies that are highly critical with regard to Schelling's model, and even reject them. For example, Batty and Torrens (2001) highlight challenges encountered by models of complex systems, like the Schelling models, referring to limited observations on how individuals express preferences for segregation as well as inadequacy of available data for testing. Similarly, Silverman (2018) raises concern that Schelling's models lack a solid foundation in real-world data, creating a disconnect between the simulated scenarios and the actual social phenomena they aim to represent. This is exemplified in the findings of Tsvetkova et al.'s (2016) experiment, which revealed that minor distinctions between human behaviour and simulated agents led to segregation patterns different than expected, thus challenging previously drawn conclusions about segregation derived from these models.

Next, we will discuss what we see as some of the main lessons learned from examining empirical studies on segregation, regardless of whether they reference Schelling or not, and outline the challenges for the future. We distinguish five discussion topics:

a) methodological dilemmas for the joint studying of moving preferences and actual moving;
b) challenges of neighbourhood and group definitions as outlined in Schelling's area-distribution and bounded-neighbourhood models;
c) isolation of the effects of individual-level preference from structure of discrimination in housing markets;
d) intersectionality of residential segregation, making it difficult to isolate the forces that shape ethnic residential segregation from residential segregation based on class, income or occupation, and;
e) recognition that focussing on residential segregation alone falls short in understanding the complex mechanisms that produce and reproduce spatial separation of population groups in different life

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[4] See also the follow-up debate on the results of the publication by Van de Rijt et al. (2009) and Bruch and Mare (2009).

domains: at residential neighbourhoods, at schools, at workplaces and at leisure time activity sites.

4.1. Methodological dilemmas

Research that has been inspired by Schelling segregation models faces a methodological dilemma. A full study would proceed in three steps, starting with clarifying individual neighbour preferences, proceed with how neighbour preferences shape actual moves to neighbourhoods with different neighbour compositions and, finally, reveal the residential segregation patterns that emerge as a result of these moves. Most of the research to date has focussed on step one or two, making assumptions with regard to step three. The first methodological approach relates to studying actual moves, and it relates these actual moves directly with existing segregation patterns and, indirectly, to preferences without being able to isolate preferences from other factors related to residential mobility. The second methodological approach relates to studying moving desires and preferences, and it relates these moving desires and preferences directly to the residential context, but indirectly to actual moves. It is possible to overcome such methodological dilemmas by utilizing panel data that follows people over time, asking both questions on moving desires and preferences as well as on actual moving and neighbour characteristics in neighbourhoods of origin and destination. Data for such studies do exist, but has not been used to test the Schelling models. For example, Coulter et al. (2011) use British Household Panel Survey that includes information on moving desires, expectations and actual moving behaviour, and find that although the desires and expectations to move are strongly associated with subsequent mobility, only 55 % of the individuals reporting this combination actually move over the next year.

4.2. Neighbourhood and population categories

A major element of the Schelling models is to provide two alternative conceptual approaches for defining a neighbourhood that he called bounded-neighbourhood and area-distribution approaches. In the bounded-neighbourhood approach, a city is divided into small predefined small-scale spatial units like a checkerboard to represent neighbourhoods. Most of the studies use census blocks (e.g., Bayer et al., 2004; Dmowska & Stepinski, 2021), census tracts (e.g., Trounstine, 2020; Wessel & Nordvik, 2019) or similar small-scale spatial planning units (e.g., van Ham & Feijten, 2008) for studying residential segregation. A growing body of research, however, highlights that ego-centric neighbourhoods represent a better way for characterizing neighbour composition in the vicinity of people (e.g., Easton & Pryce, 2019). Schelling introduced the concept 'ego-centric neighbourhoods' in the area-distribution model but, interestingly, research that is based on ego-centric or bespoke neighbourhoods seldom cites Schelling (e.g. not cited by Olteanu et al., 2019; Petrović et al., 2022). In addition to the characteristics of neighbours, the body of research on bespoke neighbourhoods is also investigating the spatial reach of neighbour effects, represented by studies that try to find out at what spatial scale neighbourhoods matter (Marcińczak et al., 2021; Petrović et al., 2022). In the bounded-neighbourhood model, neighbourhoods have fixed spatial borders. It is especially noteworthy that according to Schelling, it is not only residential neighbourhoods that are bounded, but also schools, workplaces, and leisure time activity sites. People can be inside or outside of these spatial units, while the bespoke neighbourhoods relax this assumption. This way, bespoke neighbourhoods emerge as a significant innovation in measuring the spatial dimension of segregation. They contribute to a more relational understanding of segregation, wherein not only spatial but also social units/categories are viewed as fluid and evolutionary, as highlighted by Fiel (2021). Unlike Schelling's models that begin with predefined categories, there is a growing recognition that these categories are, to some extent, fluid and

constructed through what is referred to as an alliance-formation mechanism (Pietraszewski, 2021). This recognition suggests that using preexisting classifications may (a) overlook the diverse ways in which segregation is both created and overcome by a complex web of power relations and social ties as people engage in various social interactions in their daily activities (Fiel, 2021) and (b) conceal, reflect, and perpetuate social and spatial inequalities in multiple ways (Hochschild & Weaver, 2007; Strader et al., 2023).

4.3. Preference and discrimination

Much of the research that is inspired by Schelling is based on large-scale individual-level census and register data. These studies are able to control for a host of factors that shape residential mobility both when it comes to individual as well as neighbourhood characteristics. It is often assumed that the remaining differences in actual moving that are not captured by the variables included in the models relate to preferences or discrimination. For example, Krysan and Crowder (2017) show that the differences in perceived discrimination in different urban neighbourhoods and communities shape the neighbourhood choice-set and residential preferences of members of the minority population. Likewise, it is often difficult to relate the ethnic composition of the origin and destination neighbourhoods with neighbour preference. For example, migrants who adapt to the host society and aim to improve their residential outcomes often favour housing characteristics over neighbourhood characteristics (Torpan et al., 2020). For example, migrants who exit from the rental sector or social housing to become home-owners, often find the most affordable housing in neighbourhoods with a high share of the minority population.

4.4. Intersectional residential segregation

Schelling started his 1969 paper with the observation that people get separated along different lines and in different ways – by sex, age, income, language, race and ethnicity (referred to as colour by Schelling), taste, etc. Since Schelling himself provided examples of his simulation based on two racial groups (blacks and whites), much of the research has been dealing with ethnic/racial residential segregation as well. However, it is noted in many papers that ethnic and socioeconomic segregation are strongly related. Andersson and Kährik (2016) introduce the concept of "eth-class segregation" to characterize the overlap between these two dimensions of segregation. Because of this intersectional nature of segregation, it is difficult to reduce research on residential preferences towards certain neighbour characteristics as well. Residential preferences may further depend on the context of each city when it comes to the formation of the ethnic minority population, as well as structures of social and spatial inequalities (Tammaru et al., 2016). For example, the preferences towards neighbour ethnicity and socioeconomic status, and how these two dimensions interact with each other may fundamentally differ in US and European cities. Malmberg and Clark (2021) explores the interplay between ethnic and economic segregation in Sweden, and how they affect segregation outcomes, showing that the combination of preferences and budget constraints contributes to continued immigrant clustering. While Sampson (2019) shows that ethnicity trumps class in understanding residential segregation in the US cities, global comparative studies reveal that in tandem with the rise of income inequalities, levels of residential segregation by socio-economic status have grown as well (van Ham et al., 2021).

4.5. Segregation as a multi-domain phenomenon

The most recent advancement of segregation research argues for the need to extend the Schelling model of residential segregation to other important domains of daily life in order to understand the ways in which spatial separation of population groups is produced and reproduced (Tammaru et al., 2021). The Schelling bounded-neighbourhood model

claimed that not only residential neighbourhoods are bounded but also schools, workplace, and leisure time activity sites. This has served as an inspiration for new and recent conceptual thinking in segregation research. Tammaru et al. (2010) proposed the term "domains" for studying segregation in residential neighbourhoods and workplaces. Silm and Ahas (2014) introduced an "activity space approach" for analysing links between residential neighbourhoods and other out-of-home leisure-time activities. Park and Kwan (2017) advanced the conceptual thinking by proposing the term "multi-contextual segregation" for understanding how immigrants and members of the host population sort into various daily activity sites, anchored around home and work. Finally, Tammaru et al. (2021) developed the "vicious circles of segregation" framework to show how segregation is transmitted from one activity site (e.g., residential neighbourhood) to another activity site (e. g., school) as a result of sorting and contextual effects experienced in these different activity sites.

5. Discussion and moving forward

The key advancement in the conceptual thinking about segregation as inspired by Schelling relates to the understanding that spatial segregation is a multi-domain or multi-contextual phenomenon. The most comprehensive account of these complexities has been developed in the concept of vicious circles of segregation (Tammaru et al., 2021; van Ham et al., 2018). According to the vicious circle of segregation model, segregation is correlated in different domains. From a spatial perspective, domains comprise all activity sites in a given urban region; all residential neighbourhoods form the residential domain, all workplaces form the work domain, all schools form the school domain, and all leisure time activity sites form the leisure domain. Hence, segregation is not only a characteristic of residential neighbourhoods but also of all other activity sites and domains of life (Tammaru et al., 2021; van Ham et al., 2018).

Segregation is triggered both by the mobility of people as they sort into residential neighbourhoods, schools, workplaces and leisure time activity sites, as well as by in situ changes caused by the mobility of other people (Finney & Simpson, 2009). More specifically, aggregate patterns of segregation emerge as a result of (a) the sorting of individuals with particular characteristics into certain activity sites, and (b) contextual effects because people are exposed to and interact with other people (neighbours, friends, colleagues, classmates, etc.) in these activity sites (van Ham et al., 2018). In each activity site, people experience contextual effects (also called neighbourhood effects), that, in turn, are related to the future sorting of people into activity sites. Hence, segregation could be seen as a dynamic and co-evolutionary loop of sorting and contextual effects. Individual preferences and resources, constraints and discrimination – all serve to affect the sorting processes into activity sites, and hence segregation in different life domains. Sorting into concrete neighbourhoods leads to city-level patterns of residential segregation, sorting into concrete schools leads to city-level patterns of school segregation, sorting into concrete workplaces leads to city-level patterns of work segregation and sorting into concrete leisure time activity sites leads to city-level patterns of segregation during the leisure time. Policies that are related to different domains (e.g., housing policies, school enrolment polices, etc.) are closely related to the sorting processes and contextual effects.

Finally, the sorting into activity sites and consequent segregation patterns in different life domains are further structured by time and space (cf. Hägerstrand, 1970; Silm & Ahas, 2014; Tammaru et al., 2021). Longitudinal approach (time) and activity space approach (space) provide new empirical avenues for undertaking multi-domain or multi-contextual studies.

5.1. Longitudinal approach in segregation research

Segregation evolves over the life course and is partly inter-

generational (Hedman & van Ham, 2021; Sharkey, 2008; van Gent et al., 2023). A child is born in a neighbourhood in which that child's parents moved into at some point. As time passes, the child will likely go to a local school and this way the patterns of residential segregation of the parents affects the sorting of children into schools (Bernelius & Vaattovaara, 2016). Educational inequality generated in schools affects the sorting of people into workplaces and the incomes that people earn later in life (Lam et al., 2015). Income earned, in turn, determines in which neighbourhoods individuals can afford to live (Hulchanski, 2010). There may also be significant time-lags between changes in underlying factors such as growth of income inequality and residential segregation (Tammaru et al., 2021). The transmission of segregation from one domain to another over the life course and generations is complex as families form and dissolve, jobs are created and lost and so on. Also, preferences change over the life course. Singles often prefer to live in the city centre with many leisure time activities, but as people enter the family stage, school quality often becomes an important factor in the housing search process (Owens, 2017). Likewise, joint decisions in sorting into different activity sites may take place. For example, parents may choose a neighbourhood of residence based on the quality of schools in different residential neighbourhoods (Bernelius et al., 2021).

New directions of conceptual thinking have been supported by advances in the data availability for studying the mechanisms of segregation. One way of shedding more light on the complexities that underlie segregation is the use of longitudinal population data. For this purpose, data from several censuses (or from registers) is linked to follow people over a longer period of time. Register-based research has been ground-breaking in this regard, allowing not only to link individuals over time, but also to link individuals with family members, neighbours, co-workers and schoolmates (e.g., Rahnu et al., 2020). Despite the richness of register data, it misses key pieces of information on preferences, desires, leisure time activities and mobility patterns. To overcome these limitations, large-scale surveys focussing on these missing pieces of information may be linked to register data. The gains from getting more complete information come with the cost of working with samples instead of full populations. Working with such complex data comes along with heightened needs for paying attention to research ethics.

5.2. Activity-space based studies

In addition to longitudinal studies, more in-depth research on space and geographies of segregation is needed as well. For example, a recent study on global segregation revealed that the underlying geographies of segregation are much more extensive compared to what we learn from the computing of indices of segregation (van Ham et al., 2021). As different ethnic and socioeconomic groups sort and resort into residential neighbourhoods, schools and workplaces, diverse patterns of segregation and desegregation may emerge in different life domains. Studying segregation in the full activity space of people and families would help to better understand these spatial complexities of segregation (Silm & Ahas, 2014). Home is the key anchor point from where daily activities usually start and end. All individual visits to activity sites (schools, workplaces leisure time activity sites) form the activity space for the given person (Golledge & Stimson, 1997). Families live linked lives as all family members have to have easy access from home to other important daily activity sites.

The sorting into activity sites is shaped by urban planning, for instance in how various types of housing, workplaces, schools, and leisure time activity sites are spatially distributed across the urban region (Tammaru et al., 2021). Proximity, connectivity and accessibility shape the daily trajectories of individuals in urban space, as undertaking activities closer to home or other central activity sites costs less time and money (Hägerstrand, 1970). This implies that an increase in residential segregation may trigger segregation in other life domains as well. For the elderly, ethnic minorities, and low-income people, the residential

neighbourhood is usually the most important arena for daily interaction (Van Kempen & Wissink, 2014). Using mobile phone-based tracking has been an important advancement in capturing the complexities of daily moves and spatially linked lives of family members (Silm et al., 2021). As smartphones went mainstream, running complex experiments with people who have given consent for the tracking of their daily moves is one of the promising routes for the better understanding of connected geographies of segregation. Ultimately, the digital transition and the shift of numerous activities from physical to digital spaces, including remote work, warrant careful attention from researchers studying segregation.

6. Conclusions

The 1969 and 1971 papers by Thomas C. Schelling on models of segregation are among the most influential and most cited papers in the social sciences. A closer inspection of the papers citing Schelling reveals that his models of segregation have mainly served as an inspiration for research, rather than the subject of rigorous empirical testing. Although Schelling's models are simple and straightforward, their explicit testing is complicated. Those studies that have tested the models have therefore focussed either on studying moving desires and preferences, or on actual moves. The full model of Schelling has never been tested empirically by using real population data. The existing literature that examines certain parts of the Schelling models generally validates the models. The majority of the papers confirm that individual preferences lead to actual moves and suggest that this leads to residential segregation on the aggregate level. Schelling's work also elaborated on the way of how to construct neighbourhoods by either using fixed spatial borders or by using ego-centric neighbourhoods. Studies using ego-centric bespoke neighbourhoods seldom cite Schelling, which implies that the influence of his segregation models goes beyond what we can actually measure with the bibliometric analysis as used in this paper. While the ideas initially triggered by Schelling remain relevant and undergo further development, not all studies acknowledge their originator, whether intentionally or non-intentionally. Finally, in discussing the fixed neighbourhoods, Schelling argues that in addition to neighbourhoods, other spatial units such as schools, workplaces or leisure time activity sites need to be considered. This has inspired theorizing on the connectedness of segregation in all these spatial units. The availability of new forms of population data such as longitudinal census and register data or mobile phone data also allow to widen the horizons of empirical work on how segregation is produced and reproduced in contemporary cities.

Although many contemporary studies on residential segregation no longer reference Schellings' models, his ideas have not lost their relevance and continue to be influential in shaping the direction of the segregation research. The field of research continues to evolve by moving away from pre-defined spatial and social categories in studying residential segregation. Instead, it is increasingly common to study how spatial segregation processes are connected as people move around in the city and interact with other people at workplaces, schools and leisure time activity sites. Bespoke neighbourhoods help us to understand how segregation process may evolve at different spatial scales given the nature of the activities and the extent of the activity spaces of people, shaped by institutional contexts and power relations between population groups. The discussion thus increasingly delves in methodological dilemmas, challenges in defining neighbourhoods and population groups, the intersectionality of segregation, and the recognition of segregation as a multi-domain phenomenon. This evolving landscape of research demonstrates both the enduring impact of Schelling's work as well as the progress in finding new directions for a deeper understanding of spatial segregation.

CRediT authorship contribution statement

Rūta Ubarevičienė: Writing – review & editing, Writing – original draft, Visualization, Methodology, Data curation. **Maarten van Ham:** Writing – review & editing, Conceptualization. **Tiit Tammaru:** Writing – review & editing, Conceptualization.

Declaration of competing interest

The authors declare that they have no conflict of interest.

Data availability

No data was used for the research described in the article.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cities.2024.104838.

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