A new divide? Investigating the effect of hybrid teleworking on socio-spatial job accessibility inequalities among groups in the Dutch workforce

MSc Thesis

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Abstract

In the context of society's growing digitalisation, the widespread use of Information and Communication Technologies (ICTs) in everyday life, and the increased ability to engage in activities without physical movement, job accessibility modelling requires the consideration of an additional dimension: digital connectivity to work opportunities. Recent shifts in society, such as the COVID-19 pandemic, have accelerated ICTs usage due to the adoption of hybrid teleworking. However, not all individuals have equal access to hybrid teleworking opportunities due to personal and work-related constraints. The emergence of hybrid teleworking is therefore concomitant with social consequences and has the potential to amplify disparities in job accessibility. This highlights the uncertainties around the distributive pattern of job accessibility in hybrid space. The aim of this research is therefore threefold. Firstly, this research aims to complement academic literature with the introduction of a novel agent-based and disaggregated job accessibility modelling framework that integrates occupational and educational job matching, cross-modal competition effects and hybrid teleworking. Secondly, this research aims to demonstrate its practical use by application of the model on the national scale in the Netherlands. Thirdly, this study aims to assess the effects of hybrid teleworking on socio-spatial job accessibility inequalities among groups in the Dutch workforce from an egalitarian perspective. The main research question driving this research is: *"How can a job accessibility measure that incorporates hybrid teleworking be constructed, and how does hybrid teleworking influence job accessibility inequalities among groups within the Dutch work force?"* A gravity-based physical accessibility measure is refined to create a Hansen- and Shen-based weighted hybrid job accessibility model. This model incorporates decay functions for commutes by car, public transport, and bike, that exhibit varying sensitivities to commuting times according to the number of days (0 to 4) teleworking during a full-time workweek. Results of the Hansen-based model indicate a rise in job accessibility levels by car (30%), public transport (14614%), bike (41%) and in general (40%) where hybrid teleworking primarily enhances job accessibility in economic vibrant areas as the Randstad, emphasizing an increase in spatial disparities. However, accounting for competition effects, Shen-based job accessibility increases for public transport (16366%) but decreases for commutes by car (-5%), bike (-8,5%) and all modes combined (-12%). The influx of interregional cross-modal demand for hybrid job opportunities leads to intensified competition in the urbanized zones, counterworks the accessibility increases found in the Hansen-based model and uniformly distributes the accessibility decreases throughout the entire country. As result, spatial inequalities are neither increasing nor decreasing. In the social analysis, similar trend of the Hansen-and Shen based models are found, albeit the precise impact varies per occupational class. A multiple linear regression analysis shows that high-educated males in teleworkable occupations, like education and healthcare, experience greatest inherent accessibility benefits in the Hansen-based model. However, it is within these specific occupational classes that the Shen-based model reveals the most significant increases in job competition; the initially advantaged hybrid teleworker faces largest decreases in job accessibility when competing individuals are included in the model. Application of the Gini-index shows that hybrid teleworking leads to greater social inequalities without competition (physical: $G_i = 0.44$, hybrid: $G_i = 0.45$), whereas the disproportional increase in job competition effects equalizes job accessibility scores among the population, thereby reducing social inequalities by 8,8% (physical: $G_i = 0.34$, hybrid: $G_i = 0.31$). Lastly, a comparative analysis using a conventional aggregate measure shows both quantitative and qualitative shifts in the detection of social inequalities. It is evident that the digitalisation within the employment landscape reshapes the inequalities within the Dutch workforce. This study therefore improves the understanding of hybrid teleworking on job accessibility inequalities, while also issuing the importance of using disaggregated data and further consideration of digital access to opportunities in the appraisal of accessibility.

Keywords: accessibility modelling, hybrid teleworking, agent-based modelling, inequalities, equity

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1. Introduction

The proliferation of digital technologies and digital infrastructure in society over the last decades offers new opportunities for individuals to engage in activities in virtual space (Ebner, Schmidthaler, & Brandstätter, 2021). Using Information and Communication Technologies (ICTs), activities and services can be reached regardless of geographical location as ICTs facilitate communication without physical movement (Caballini, Agostino, & Chiara, 2021; Versanen-Nikitin & Akermarck, 2017). Digital connectivity through the telecommunication system can facilitate access to activities such as telecommuting, teleshopping, tele-leisure, and e-learning (Muhammad, 2007a; Thulin & Vilhelmson, 2004) and is seen to interact with physical transport as it reduces the friction of distance, time, and effort to overcome spatial separation of activities (Muhammad, de Jong, & Ottens, 2008). The concept of accessibility, referred to as "the extent to which land-use and transport systems enable (groups of) individuals to reach activities or destinations by means of a (combination of) transport mode(s)," (Geurs & Van Wee, 2004, p. 128), is therefore faced with a reconceptualization in the light of the digitalized world (Audirac, 2002).

How society evolves around digital technologies is illustrated by the COVID-19 pandemic. The intelligent lockdown imposed by the Dutch government, transformed mobility patterns of individuals significantly: car and public transport usage decreased by 50% and 90% respectively compared to pre-pandemic times (Van der Drift, Wismans, & Olde Kalter, 2021). The need for social distancing required rapid integration of virtual communication in everyday lives, such as digitized work and leisure activities (Caballini, Agostino, & Chiara, 2021). As the pandemic steered investments towards tele-working facilities and provided experience for employers and employees with working from home, digital accessibility has become more common for large parts of society and is expected to play a prominent role in the post-pandemic world (Rli, 2021; Jongen, Verstraten, & Zimpelmann, 2021; Sostero, Milasi, Hurley, Fernandez-Marcias, & Bisello, 2020; Olde Kalter, Geurs, & Wismans, 2021).

With the increasing prevalence of teleworking, largely favoured in white-collar, high-education job positions, raises concerns about the emergence of a divide between individuals who have the ability to telework and those who do not (Sostero, Milasi, Hurley, Fernandez-Marcias, & Bisello, 2020). As teleworking is predominantly observed in white-collar high-educated job positions (Sostero, Milasi, Hurley, Fernandez-Marcias, & Bisello, 2020), this particularly risks marginalization of lower socio-economic classes, which are often excluded from affordable but well-accessible neighbourhoods (Slovic, Tomasiello, Giannotti, Andrade, & Nardocci, 2019; Hu, Fan, & Sun, 2017; Shen, 1998). Additionally, the reduced ability to engage in job opportunities digitally may further exacerbate the already disadvantaged position of these individuals concerning job accessibility. Although digital accessibility may improve the net accessibility of people, social inequalities should be limited as much as possible from an egalitarian perspective (Lucas, Van Wee, & Maat, 2016). Particularly, with the Dutch' governments focus on improving *broad-based prosperity,* the potential of accessibility to provide economic, environmental, and social benefits, large social relevance exists to discover the social and spatial impacts of teleworking.

Literature addressing socio-spatial inequalities in job accessibility show signs of a dichotomy. On the one hand, in a large part of the available literature is focussed on transport related socio-spatial inequalities such as lack of transport options, car dependency and transport poverty (Pyrialakou, Gkritza, & Fricker, 2016; Hernandez , 2018), exclusively through physical space. On the other hand, another well studied perspective within academic literature is focused on inequalities in accessibility to jobs or opportunities in virtual space using ICTs (Salemink & Strijker, 2015; Velaga, Beecroft, Nelson, Corsar, & Edwards, 2012). Yet, inequalities are determined by a lack of digital connectivity due to the so-called 'Digital Divide,' where accessibility to job opportunities is limited through deficiencies in access to digital infrastructure (First-level Digital Divide) or not possessing skills or capabilities to use digital technologies (Second-level Digital Divide). However, a combined understanding of implications of physical accessibility and teleworking on socio-spatial inequalities is lacking. Furthermore, the diverse capabilities of individuals to telework can create varied patterns in job accessibility for distinct demographic groups in the population. To explore inequalities among socio-economic worker groups and move beyond conventional aggregate job accessibility measures, it is crucial to employ detailed commuter data and adopt agent-based accessibility measures that simulate job accessibility at the individual level (Sang, O'Kelly, & Kwan, 2010; Tomasiello, Giannotti, & Feitosa, 2020). However, few studies have considered the use of some level of disaggregation in job accessibility measures (Sang, O'Kelly, & Kwan, 2010). Academic literature that investigate job accessibility inequalities often considers disaggregation for socio-economic backgrounds, such as gender and occupation (Sang, O'Kelly, & Kwan, 2010; Giannotti, Tomasiello, & Bittencourt, 2022), education levels (Merlin & Hu, 2017), income levels (Hu, 2016; Guzman, Oviedo, & Rivera, 2017; Cui, Boisjoly, El-Geneidy, & Levinson, 2019) and socio-economic status groups (Tomasiello, Giannotti, & Feitosa, 2020; Slovic, Tomasiello, Giannotti, Andrade, & Nardocci, 2019). Yet, studies that seem to apply some level of disaggregation in the job accessibility measures only appear on small scale regions (e.g. cities), but not on the national level using high resolution spatial zoning and for various modes of transport.

From both the societal and scientific needs to address the gaps in literature, the aims of this research are threefold. Firstly, while building further on a plethora of previous research on job accessibility modelling, the present study pioneers in current job accessibility modelling approaches with the introduction of a novel weighted hybrid job accessibility modelling framework to measure accessibility to physical and hybrid job opportunities. According to present knowledge, the modelling framework presents a first-of-its-kind agent-based job accessibility model to integrate job matching, newly defined cross-model job competition effects and hybrid teleworking tailored for different socio-economic population groups. This study thereby contributes to existing academic literature on disaggregated job accessibility modelling techniques and the joint consideration of physical and hybrid job opportunities. Secondly, this work not only presents a theoretical modelling framework, but also aims to demonstrate its practical applicability by implementation of the newly developed model on a national scale within in the Netherlands, effectively deriving physical and hybrid job accessibility for the entire Dutch work force on the individual-level. Lastly, this study aims to assess how hybrid teleworking influences accessibility to employment opportunities among Dutch individuals from varied socio-economic backgrounds. The analysis reveals the spatial and social ramifications of hybrid teleworking on job accessibility inequalities from an egalitarian perspective. The following main research question is central within this research: *"How can a job accessibility measure that incorporates hybrid teleworking be constructed, and how does hybrid teleworking influence job accessibility inequalities among groups within the Dutch workforce?"*

To obtain an answer to the main research question, the study is guided by the following sub-questions:

Q1. What is the definition of hybrid teleworking and what factors are of influence on the degree of teleworking?
Q2. How can a hybrid job accessibility measure with competition effects be constructed for different socio-demographic groups?
Q3. To what extent does teleworking lead to socio-spatial discrepancies in access to job opportunities compared to a physical accessibility measure?
Q4. What is the impact of an aggregate job accessibility measure on the distribution of physical and hybrid job accessibility?

The paper is structured as follows. An academic literature review on the definition of teleworking and the drivers and barriers to its uptake is provided in section 2. Section 3 presents the development of the weighted hybrid job accessibility model and discusses the methods of data synthesis and analysis on socio-spatial job accessibility inequalities. In section 4, the results of the spatial and social analyses are shown. Section 5 summarises the results and discusses the implications of hybrid teleworking emerging inequalities and lists the methodological limitations of this research. Lastly, the main conclusions are formulated in section 6.

2. Theoretical framework

2.1. Definition of hybrid teleworking

To understand how hybrid teleworking is affecting the socio-spatial distribution of job accessibility, a clear operationalization of the term needs to be made. The term (hybrid) teleworking remains unambiguously defined in literature, primarily due to the diversity among teleworkers in their work situation (Sullivan, 2003) and its use across research disciplines as transport and psychology (Allen, Golden, & Shockley, 2015). Consequently, multiple terms like teleworking, telecommuting, remote work, virtual work, and working from home are often used interchangeably (Sullivan, 2003; Nicklin, Cerasoli, & Dydyn, 2016), while each holds nuanced distinctions in the characterization of work (Nicklin, Cerasoli, & Dydyn, 2016). The extended literature review is provided in appendix A. This study defines hybrid teleworking based on four dimensions: *work location*, *the importance of ICT's*, *locational time distribution* and *contractual relationships* between employer and employee (Garret & Danziger, 2007).

Within this research, the following operationalization of hybrid teleworking is used (table 1). Firstly, the work location of teleworkers is set fixed to the home location. Incorporating mobile teleworking significantly inhibits the feasibility of this research due to larger data demands as the location of the mobile work should also be available. Secondly, it is generally determined that, to be categorized as (hybrid) telework, an individual must use ICT's (Garret & Danziger, 2007). Therefore, the use of ICTs in work-related activities is crucial in the operationalization of hybrid teleworking. With regards to the locational time distribution, hybrid teleworking within this research denotes an arrangement where employees divide their time between in-office and teleworking. This contrasts with teleworking, which involves solely full-time remote work. Narrowing the focus to hybrid teleworking primarily targets individuals in the study area who work from home. This is distinct from full-time teleworkers who might be located worldwide. Besides, it can be argued to what extent a job is still considered 'teleworking' when the nature of the job is continuously and full-timely performed online. Only employees with formal contracts will be considered in terms of contractual relationships, as categorizing work opportunities for self-employed individuals is challenging. Yet, important to note is that self-employed hybrid teleworkers may be overrepresented in the population of hybrid teleworkers (Sullivan, 2003).

Table 1: Hybrid teleworking operationalization according to four dimensions

	1: Work location		2: Use of ICT's		3: Locational time distribution		4: Contractual relationship	
	Fixed	*Mobile*	*Yes*	*No*	*Full-time*	*Partial*	*Contract*	*Self-employed*
Hybrid teleworking	X		X			X	X	

2.2. Drivers and barriers to hybrid teleworking

Teleworking, including hybrid teleworking, is not equally suitable for everyone and all occupations (Smite, Moe, Klotins, & Gonzalez-Huerta, 2021). While (hybrid) teleworking has become relatively popular in the Netherlands (appendix B), the adoption of teleworking or hybrid teleworking among individuals in the workforce is dependent on several driving and inhibiting macro-, meso- and micro-scale factors, which may explain why individuals engage in hybrid telework, why some do not and how differences in job accessibility levels between can sectors occur. Factors on the macro- and meso-level describe the relevant trends and developments on the national level (appendix C), whereas micro level factors describe the determinants for the uptake of full-tie teleworking and hybrid teleworking on the individual level. The micro-level factors are therefore directly related to individual-level job accessibility levels as teleworking is seen to affect job accessibility in two ways: "[ICTs] will increase accessibility only for those people who actually use the new technology. It will not directly affect the rest of the population," (Shen, 1998, p. 449). Increased hybrid teleworking rates thereby enhance job accessibility levels (Muhammad, de Jong, & Ottens, 2008). A description and conceptual framework that visualises the relationships between the factors and individual-level job accessibility is supplemented in appendix D.

2.2.1. Micro level factors

While the macro- and meso-scale factors describe the trends that may instigate the adoption of teleworking in the Netherlands, the degree to which an individual has the ability to telework is dependent on various micro-scale factors. This ability is also referred to as the *teleworkability,* which describes the "technical possibility of providing labour input remotely into a given economic process," (Sostero, Milasi, Hurley, Fernandez-Marcias, & Bisello, 2020, p. 29), which indicates the potential of working remotely in combination with the use of ICT's (Sostero, Milasi, Hurley, Fernandez-Marcias, & Bisello, 2020). First and foremost, the most important factor in academic literature that determines the teleworking behaviours of employees is the work situation of the individual (Olde Kalter, Geurs, & Wismans, 2021).

Individual work situation

The extent to which teleworking is available as working arrangement for the employee, is dependent on several factors that are related to the nature of the job (Asgari & Jin, 2015; Sostero, Milasi, Hurley, Fernandez-Marcias, & Bisello, 2020). These includes physical tasks, the need for face-to-face social interactions and information and processing tasks, where information loss via digital transmission is determinant for the teleworkability of the job (Sostero, Milasi, Hurley, Fernandez-Marcias, & Bisello, 2020). Besides the nature of the work, the teleworking environment, such as having access to teleworking equipment (Mihalca, Irimias, & Brendea, 2021) and facilities for technological support (Gschwind & Vargas, 2019), the commuting distance from and to work, the accessibility to the job location (Olde Kalter, Geurs, & Wismans, 2021) and the level of road congestion (PBL, 2021) are similarly determinants for the uptake of telework. Moreover, organizational support as monetary compensation of teleworking is another factor (Bélanger, Watson-Manheim, & Swan, 2013), which can include costs reimbursements for heating, electricity and coffee (Houtsma, Fennema, Warnaar, & Weijers, 2021), travel allowance, public transport subscriptions, parking fees (Van der Loop, 2018) and the willingness of the organization to facilitate teleworking for its employees, depending on trust in their employees, self-efficacy and knowledge to telework of the employee, the availability of office space and teleworking equipment and overall positive experiences with employees teleworking (Messenger, et al., 2017; Ministerie van Sociale Zaken en Werkgelegenheid, 2021; Bélanger, Watson-Manheim, & Swan, 2013; Van der

Loop, 2018). Lastly, if all preceding determinants of the individual work situation do not pose limits to teleworking, whether or not teleworking is adopted may finally depend on individual attitudes and experiences with teleworking (Olde Kalter, Geurs, & Wismans, 2021).

Socio-demographic characteristics

The second distinguished micro-level factor affecting the individual uptake and frequency of teleworking is determined by the socio-demographic characteristics of the individual, such as the home situation and individual characteristics (Olde Kalter, Geurs, & Wismans, 2021). Qin et al. (2021) showed that the intention to telework from home of Dutch workers decreases as the number of household members increases. Yet, households with small children are more likely to telework as this allows to combine work with care tasks (Qin, Zhen, & Zhang, 2021; Olde Kalter, Geurs, & Wismans, 2021). Contrastingly, Hamersma et al. (2020) report a negative association between having children and the degree of teleworking. With regards to age, Whereas Shabanpour et al. (2018) have seen that the prevalence of teleworking is highest for individuals between 35 and 55 years old, other studies report a high share of teleworking among Dutch employees between 35 and 45 years old (Hamersma, De Haas, & Faber, 2020). Besides, middle-aged employees are more able to telework, however rather work at the office location compared to younger employees (Singh, Paleti, Jenkins, & Bhat, 2013). Younger employees may not have jobs that are suitable for teleworking whereas the oldest age category might have difficulty using digital technologies and while working in senior positions, the accompanying tasks and responsibilities may require more in-office work, such as management roles (Tahlyan, et al., 2022; Singh, Paleti, Jenkins, & Bhat, 2013). The impact of an individual's education level is seen to highly correlate with teleworking propensity, where lower educated employees are less frequently teleworking than higher educated colleagues (Shabanpour, Golshani, Tayarani, Auld, & Mohammadian, 2018; Hamersma, De Haas, & Faber, 2020; Olde Kalter, Geurs, & Wismans, 2021; Sostero, Milasi, Hurley, Fernandez-Marcias, & Bisello, 2020). Thereafter, a positive relationship between income levels and the teleworking propensity is observed, where individuals with higher incomes (>€60.000) are more likely to telework (PBL, 2021; Sostero, Milasi, Hurley, Fernandez-Marcias, & Bisello, 2020). Lastly, male workers are more likely to telework (Shabanpour, Golshani, Tayarani, Auld, & Mohammadian, 2018), yet whether gender is a predicting factor for the degree of teleworking is uncertain given its potential relationship between job function and education level (Hamersma, De Haas, & Faber, 2020) and the occurring gender differences for these variables (Sostero, Milasi, Hurley, Fernandez-Marcias, & Bisello, 2020).

Initial travel behaviour

The third and last micro-level factor affecting the uptake of teleworking is related to the employees travelling behaviour to work (Olde Kalter, Geurs, & Wismans, 2021). Research has shown that the mode of transport is a determinant for switching towards teleworking. Hamersma et al. (2020) indicate how individuals travelling by public transport are likely to spend more hours teleworking compared to employees using private motorized vehicles like the car. Additionally, the distance and travel times and congestion to the work locations are positively associated with the probability of teleworking (Shabanpour, Golshani, Tayarani, Auld, & Mohammadian, 2018; Van der Loop, 2018), where teleworking is used to overcome the costs of commutes and to have access to affordable housing (Silva & Melo, 2018; Nicklin, Cerasoli, & Dydyn, 2016). Hence, the teleworker is seen to have preferences to locate in suburban areas (Silva & Melo, 2018), which is also reflected by the hours teleworked per level of urbanity in the Netherlands: the higher the urbanity, the less hours are being teleworked by the employee (Hamersma, De Haas, & Faber, 2020).

3. Methodology

In land-use and transportation studies, accessibility modelling is a commonly employed technique to analyse and communicate social and economic effects of land-use policies and developments (Geurs & Van Wee, 2004). Job accessibility modelling thereby provides valuable insights in the accessibility experience of individuals and can therefore be used for various equity related analyses (Grengs, 2012). For modelling accessibility to job opportunities, four general components can be defined as the distribution of worker and job locations over space (*land-use component*), the resulting travel patterns of individuals *(transport component*), the needs and abilities of individuals to access job opportunities (*individual component*) and variations in available job opportunities over time (*temporal component*) (Geurs & Van Wee, 2004). An individual is intrinsically constraint to a limited set of job opportunities respective to their socio-economic status as education level, occupational background (Dixon & Johnson, 2019; Geurs & Ritsema van Eck, 2003; Cheng & Bertolini, 2013), skills, gender and incomes (Huang, 2020) and individual travel behaviour and temporal budgets (Geurs & Van Wee, 2004; Huang, 2020) and, in the light of digital accessibility to job opportunities, the ability to telework. Particularly, with regards to socio-economic egalitarian appraisal of job accessibility, the inclusion of the individual component, by considering factors that account for personal restrictions on (hybrid) job prospects, is fundamental (Geurs & Van Wee, 2004; Geurs, 2018). The complexity of the factors that affect job accessibility requires the integration of multiple components in the modelling process that can both exert influence on, or be influenced by, accessibility (Geurs, Van Wee, & Rietveld, 2006; Geurs & Van Wee, 2004).

Since previous research on job accessibility analysis is not seen to fully encompass these elements (appendix E), Hansen's (1959) gravity-based job accessibility measure, a common and well performing approach in modelling access to job opportunities (Cavallaro & Dianin, 2022) (Appendix F), is employed. The measure, shown in figure 1, integrates accessibility across three modes of transport (car, public transportation, and bike), job matching based on socio-economic background, and a novel cross-modal demand-oriented competition component, and varying decay functions which are sensitive to the teleworking rates of the socio-economic subgroups is constructed. To discern the impact of competition effects on the job accessibility levels, both the Hansen-based variant, without competition effects, and Shen-based variant, with competition effects, are defined.

This study uses the Dutch Occupational Classification system (BRC2014) to define socio-economic groups in the job matching approach, considering 12 occupational classes and three education levels (low, middle, and high) as surrogate for socio-economic groups. For simplicity, a direct one-to-one relationship between occupational classes and education levels is assumed, preventing higher or middle-educated individuals from accessing lower education-required jobs. The classification results in the identification of 36 occupational and educational class groups, denoted as c. More information about job matching, occupational classes, and an overview of occupations per education level can be found in appendix G and H.

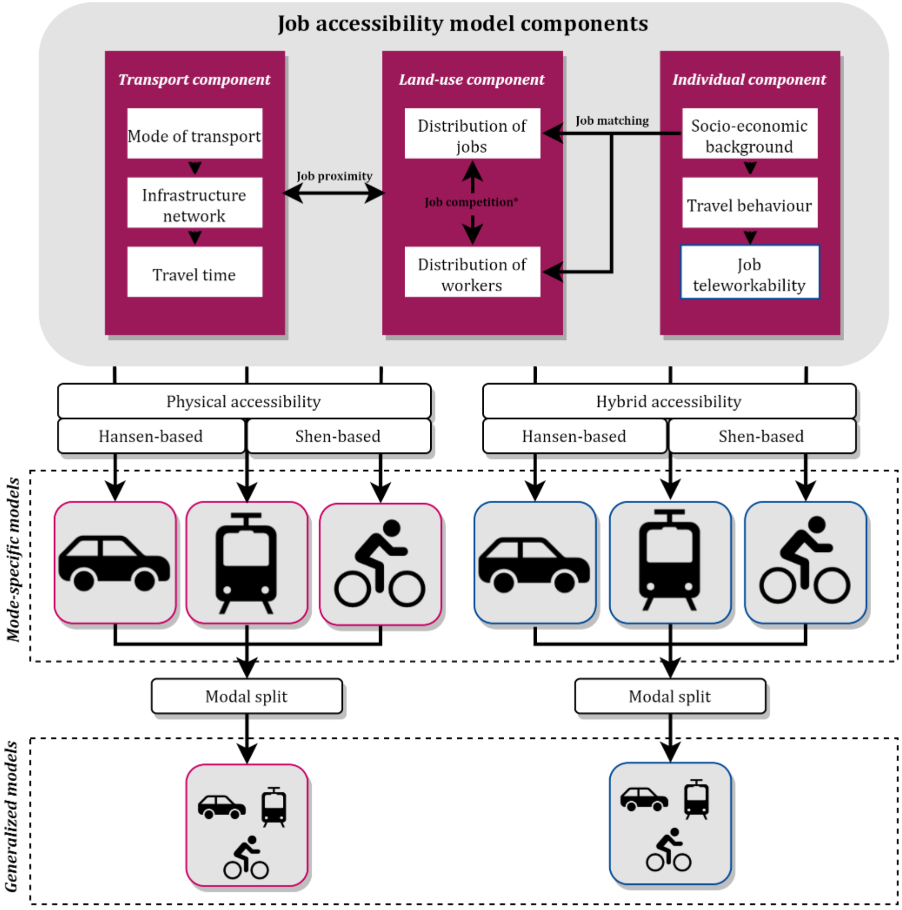


*Figure 1: Components of the Hansen- and Shen-based physical and hybrid job accessibility models, * = only for Shen-based models*

The methodological flowchart (figure 2) describes the overall step-by-step of this study's processes and the associated research questions. Firstly, the novel modelling framework for measuring job accessibility through physical and hybrid space is formulated in section 3.1. For the implementation of the modelling framework, three disaggregated data components are required as model input for which the synthesis approach and description of the data is presented in section 3.2. In Section 4, the results of the job accessibility models are analysed both spatially and socially, including a comparison between aggregated and disaggregated job accessibility measures.

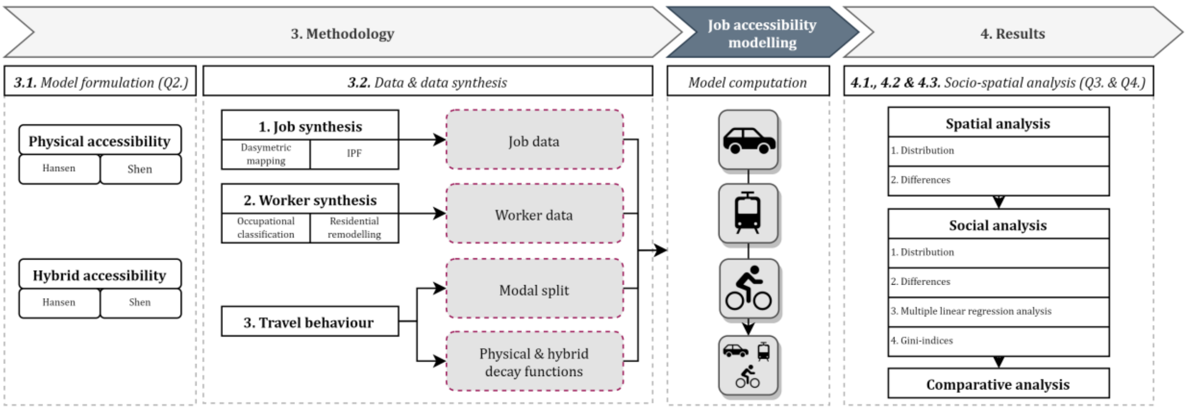


Figure 2: Methodological flowchart describing the step-by-step actions employed within this study

3.1. Gravity-based weighted hybrid job accessibility measure

Developing accessibility measures requires theoretical soundness, as capturing the multidimensionality of accessibility with the inclusion of multiple components, and practical applicability (Geurs, 2018). The effectiveness of the accessibility measure relies on its clarity, ease of application and accuracy, yet finding an equilibrium between these three requirements is difficult (Cheng & Bertolini, 2013). Similarly, in the construction of a hybrid job accessibility model, integration of job matching, spatial proximity and job competition effects is required to maintain the theoretical rigor. However, the challenge is to incorporate teleworking into the model in a way that is both intuitive and accurate without imposing more complexities. Considering teleworking using ICT's in job accessibility modelling requires extension of the Hansen- and Shen-based physical accessibility measures with access to new types of job opportunities: (1) opportunities in digital space, accessed through the telecommunication system, (2) opportunities in hybrid space, accessible via the transportation system and telecommunication system, (3) opportunities in physical space, solely accessible through the transport system (Muhammad, de Jong, & Ottens, 2008; Shen, 2000).

Various studies have proposed accessibility measure for these opportunity types. Shen (2000) developed an analytical framework of a location-based accessibility measure that incorporates accessibility to the three opportunity types, where an individual's ability to use ICT's is inherently connected job accessibility levels. Travel impedances are based on physical movement over the transportation network to both physical and hybrid opportunities and complementary physical movements made for fully digital opportunities (Shen, 2000; Muhammad, 2007a). Muhammad et al. (2008) build further upon Shen's modelling framework and analysed physical and hybrid job accessibility on a case study within the Netherlands. Cavallaro and Dianin (2022) advanced this methodology with a novel location-based hybrid job accessibility model. In their framework, job accessibility is determined based on the composite result of physical and hybrid accessibility to job opportunities. Impedances for hybrid job opportunities are based on physical travel costs and the generalized costs of teleworking, such as costs for internet subscription, energy costs and extra material costs (Cavallaro & Dianin, 2022).

The differences in model formulations in previous studies highlight the complexity and disagreements in operationalization of hybrid working in job accessibility modelling. The definition of impedances for digital and hybrid opportunities is varying among the models and pose theoretical difficulties for operationalization. In Shen's (1998) and Muhammad et al.'s (2008) models, ICT proficiency is represented as a binary variable, oversimplifying the diverse spectrum of technical skills. Moreover, given the diminishing concerns in the Netherlands regarding both access to ICTs (First-level digital divide) and the ability to use ICTs (Second-level digital divide) (Van Deursen & Van Dijk, 2019), using the latter as a determinant for the level of access to virtual and hybrid opportunities is incongruent with contemporary circumstances. Secondly, the adopted decay function for virtual access based on complementary trips increases the need for additional travel data of workers, which may be difficult to acquire and increases the data requirements. Both issues make the employed measure of Shen (2000) and Muhammad et al. (2008) unnecessarily complex for both theoretical and practical usage. While Cavallaro and Dianin (2022) introduce generalized cost impedances for hybrid teleworking, it can be questioned to what degree the generalized costs impedance holistically portrays the '(dis)utility' of teleworking. Particularly, while for physical accessibility travel times are used, generalized costs for physical travel are not included but could also be present (e.g. travel allowances). As consequence, the joint use of different costs representations of the impedances seems unfair.

The hybrid job accessibility model used within this study advances from previous models on two grounds. Firstly, instead of adopting individual-specific constraints to teleworking, e.g. whether an individual is able to use ICT's, hybrid job accessibility is determined by the type of job, i.e. the job type determines the extent to which teleworking is possible. This approach avoids the issue of the underlying determinants of being physically and intrinsically able or willing to telework or not and keeps this assumption dependent on the nature of the job for simplicity. Secondly, the choice of the impedance function is solely focussed on physical travel to job opportunities. Although teleworking eliminates the impact of friction of physical distance using ICTs, it does not grant access to all job opportunities irrespective of the spatial separation to those opportunities. Therefore, distance to the physical work location still plays an important role in the number of job opportunities and individual may reach for hybrid job opportunities. Firstly, employers may prefer to choose employees that are not geographically dispersed to limit social distances, i.e. demographic differences among team members, resulting in isolation of team members which affects the performance and communication of teams (O'Leary & Cummings, 2007; Bergum, 2014). Secondly, the employee still is still required to cover distances with their commutes on non-teleworking days. Consequently, this individual may still prefer to live in proximity to the work locations yet are seen to have greater tolerances with regards to the distances they are willing to travel on non-teleworking days (Ravalet & Rérat, 2020). The latter creates the assumption of an inversely proportional relationship between the number of days teleworking and the distance travelled to work opportunities (Muhammad, de Jong, & Ottens, 2008), i.e. individuals are willing to traverse greater distances the more they are allowed to work from home.

In the light of these findings, this study proposes a weighted hybrid job accessibility model that, similarly to Muhammad et al.'s (2008) and Cavallaro and Dianin's (2022) measure, focuses on second and third opportunity types, considering physical and hybrid job opportunities. Besides job matching and job competition, the model incorporates decay functions that exhibit varying levels of sensitivity to travel times, determined by the number of (t) days teleworking $(0 \leq t \leq 4)$ during a regular workweek.

3.1.1. Model formulation

The disaggregated weighted hybrid job accessibility measure (HA_{ic}^{v}) calculates accessibility on the individual-level to job opportunities per t-day teleworking for every socio-economic group (c) and three modes of transport (v): car, public transport, and bike. The measure builds further upon a physical job accessibility measure by subdividing the total set of job opportunities per t-day teleworking (O_{jc}^{t}), depending on the teleworkability of the job opportunity determined per occupational class and education level. In addition, for every t-day teleworking and mode of transport, a travel time decay function $(f_c^t(c_{ij}^v))$ is defined that takes into account the varying sensitivities to travel time in minutes (c_{ij}) to job opportunities and is expressed as a power function $f(c_{ij}) = -\alpha * c_{ij}^{\beta}$ according to the AIC (Akaike Information Criterion) (Appendix K). The travel time decay function for 0-days teleworking is equal to the physical decay function of the corresponding occupational class and mode of transport. However, for t-days teleworking, where $t \geq 1$, specification per occupational class is omitted due to data limitations and population average decay functions are used. With the specification of decay functions, it is assumed that an individual is willing to overcome larger travel times, the more the individual teleworks. Hence, an extra day teleworking relaxes the decay function and increases an individual's search space for potential job opportunities (figure 3).

To account for job competition, Shen (1998) has further refined Hansen's gravity-based function by adding an additional demand component (D). Since competition for jobs occurs more commonly between workers (demand-oriented) (Cheng & Bertolini, 2013), single-constrained demand-oriented competition effects are included. To account for job competition over different modalities, both intra-modal and multi-modal variations of the demand component exists as applied in the research of Pritchard et al. (2019a) and Pan et al. (2020), where in the former competition is considered over the same mode, and in the latter competition travels by the fastest mode. In this study, an alternative formulation to Shen's demand component is introduced that advances further upon the components observed in Pritchard et al. (2019a). In the newly defined cross-modal demand component (D_{jct}^{x}), a weighted average of the potential competing population for the same occupational class and education level group is taken by application of the modal split of the population group (where $w_c^r + w_c^p + w_c^b = 1$, for car r, public transport p and bike b). Additionally, competition is also measured per t-day teleworking. This approach considers that individuals face competition from other individuals who may choose a different mode of transportation to reach job opportunities. This yields a single competition component where an aggregate and most representative situation of the competition effects for an individual travelling by mode v is drawn. The formulation of the mode-specific Shen-based physical job accessibility model (PA_{ic}^{v}) and the newly developed weighted hybrid job accessibility measure (HA_{ic}^{v}) are shown in equation 1 and 3 respectively. By removing the cross-modal demand component ($D_{jc(t)}^{x}$), (equation 2 and 4) from both equations, the Hansen-based model variants are derived.

Physical job accessibility measure (mode-specific)

$$PA_{ic}^{v} = \sum_{j=1}^{n} \frac{O_{jc} * f_c\left(c_{ij}^{v}\right)}{D_{jc}^{x}} \tag{1}$$

$$D_{jc}^{x} = \sum_{k=1}^{m} (w_c^r * P_{kc} * f_c\left(c_{ij}^{r}\right) + w_c^p * P_{kc} * f_c\left(c_{ij}^{p}\right) + w_c^b * P_{kc} * f_c(c_{ij}^{b})) \tag{2}$$

Weighted hybrid job accessibility measure (mode-specific)

$$HA_{ic}^{v} = \sum_{t=0}^{d} \sum_{j=1}^{n} \frac{O_{jc}^{t} * f_c^t\left(c_{ij}^{v}\right)}{D_{jct}^{x}} \tag{3}$$

$$D_{jct}^{x} = \sum_{k=1}^{m} (w_c^r * P_{kc} * f_c^t\left(c_{ij}^{r}\right) + w_c^p * P_{kc} * f_c^t\left(c_{ij}^{p}\right) + w_c^b * P_{kc} * f_c^t(c_{ij}^{b})) \tag{4}$$

Where:

- PA_{ic}^{v} and HA_{ic}^{v} describe the accessibility of an individual living in zone i and working in occupational and educational class c, using mode v for physical and hybrid scenarios, respectively
- O_{jc} and O_{jc}^{t} refer to the number of (hybrid) job opportunities in zone j of occupational and educational class c, that facilitate t-days teleworking in the hybrid scenario
- $f_c(c_{ij}^{v})$ and $f_c^t\left(c_{ij}^{v}\right)$ represent the physical and hybrid power decay functions that simulates the travel time sensitivity for occupational and educational class c between zone i and j by mode v, per t-day teleworking when applicable
- w_c^r, w_c^p and w_c^b are the weights assigned to travel by car, public transport, and bike respectively per occupational and educational class group
- P_{kc} is the total number of workers of occupational and educational class group c that compete for the same job opportunity living in zone k
- D_{jc}^{x} and D_{jct}^{x} is the cross-modal demand for physical or hybrid job opportunities of occupational and educational class group c in zone j, determined per t-days teleworking in the hybrid model

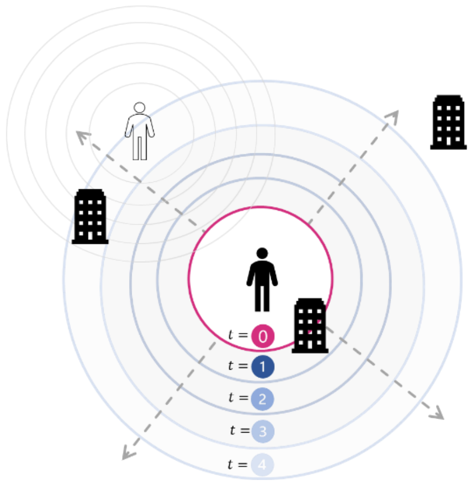


Figure 3: Weighted hybrid job accessibility measure with various sensitivities in travel time decay per t-days hybrid teleworking

Generalized job accessibility models

To arrive at the generalized physical and hybrid job accessibility models (PA_i and HA_i), the job accessibility scores at the individual-level for the mode-specific models (PA_i^v and HA_i^v) are aggregated based on the modal split of the corresponding occupational class of the individual. Subsequently, further aggregation from individual-level accessibility to geographical zonal job accessibility per zone I (PA_i and HA_i) is obtained through averaging the job accessibility score per occupational and educational class group c per zone and taking the weighted average of these scores depending on the underlying population distribution of the occupational and educational class group in the zone. This approach is described for generalised hybrid accessibility (HA_i) in equation 5.

$$HA_i = \sum_{c=1}^{q} \left(HA_{ic}^{r} * w_c^{r} + HA_{ic}^{p} * w_c^{p} + HA_{ic}^{b} * w_c^{b} \right) * \frac{P_{ic}}{P_i} \tag{5}$$

Where:

- HA_i is the generalised hybrid accessibility observed within zone i across all modes of transport
- HA_{ic}^r, HA_{ic}^p and HA_{ic}^b is the individual-level job accessibility score per occupational and educational class group c by car, public transport, and bike within zone i
- w_c^r, w_c^p and w_c^b are defined above
- P_{ic} is the number of individuals belonging to occupational and educational class group c living in zone i
- P_i is the total number of individuals living in zone i

3.2. Scope and study area

This study focusses on the Netherlands that is composed of 13809 zones according to the configuration adopted by OmniTRANS Spectrum dataset developed by Goudappel and Dat.mobility, shown in figure 4. Each zone contains information about the number of inhabitants, jobs, and other socio-spatial variables. A job is defined as an explicit or implicit employment contract between an individual and an economic entity that stipulates that work will be performed in exchange for (financial) compensation (CBS, 2021a). Accessibility calculations are carried out for every individual in the Dutch workforce, in each respective zone. This includes all workers between the ages of 15 and 75, apart from self-employed individuals and those who work entirely virtually. It is assumed that each person is employed full-time. Thereby, hybrid teleworking refers to working from home for a minimum of one day to a maximum of four days a week in the context of this research. Both physical and hybrid job accessibility is calculated for an average workday, considering mean travel times during the morning and every peak hour, as well as during off-peak periods, for each mode of transport. Finally, job accessibility will be modelled for the year 2021 and datasets have been selected according to this temporal scope.

Figure 4: The Netherlands (left) and zonal configuration of Amsterdam (right)

3.3. Data

The physical and hybrid job accessibility models require three main data components: job, worker, and travel behaviour data. The main limitation of the disaggregated job accessibility models is the lack of publicly available data that contains the same social and spatial resolution, e.g. occupational classification and appropriate spatial disaggregation. Therefore, data synthesis on secondary datasets (table 2) is required to obtain the necessary data components and consists of three general steps: job synthesis, worker synthesis, and deriving travel behaviour patterns. Most datasets are based on Dutch national statistics collected by the CBS (Dutch: Centraal Bureau voor de Statestiek). Other major data components are either internally generated by Goudappel (OmniTRANS Spectrum and Population Synthesizer) or sourced from empirical findings of academic research on Dutch travel behaviour (Landelijk Reizigers Onderzoek). The data synthesis builds further upon these datasets by (dis)aggregating or enriching the data using dasymetric mapping and Iterative Proportional Fitting (IPF) procedures, depending on their use within this research. A detailed description of the data and its use in the job and worker synthesis and travel behaviour analysis is presented in appendix I, appendix J and appendix K, respectively.

Table 2: Required data components as input for the job accessibility model and datasets used in the data synthesis

Source	Variables	Spatial scale	Temporal scale	Use
1. Job data				
1.1. Spectrum dataset (Goudappel - internal)	Delineation of study area Spatial/geographical coverage of jobs (BAG classification)	Spectrum neighbourhood level	2021	Dasymetric mapping: spatial coverage job locations
1.2. CBS (CBS, 2021a)	Number of jobs per sector (SBI2008)	Municipal level	2021	Translation BAG classification -> SBI2008
1.3. EBB (Enquête BeroepsBevolking) (CBS, 2021b)	Occupations (BRC2014) and education level of jobs within every sector (SBI2008)	National level	2019-2020	Translation SBI2008 -> BRC2014 + education levels
2. Worker data				
2.1. Population Synthesizer (Goudappel & Dat.mobility - internal)	Synthesized population Netherlands	Spectrum neighbourhood level	2021	Individual-level worker characteristics
2.2. CBS (CBS, 2022a)	Individual characteristics per occupational class (BRC2014)	National level	2021	Assigning occupations to workers
3. Travel behaviour				
3.1. Landelijk Reizigers Onderzoek (LRO) (Taale, Olde Kalter, Haaijer, & Damen, 2022; MuConsult, 2022)	Commuting behaviour Teleworking patterns	PC4 level	2021	Determination of teleworkability of jobs Modal split: car, public transport & bike Construction of physical and hybrid decay functions

3.3.1. Jobs and workers

Job and worker data have been extracted and synthesized by combining the OmniTRANS Spectrum dataset (internal dataset), CBS (CBS, 2021a; CBS, 2022a), CBS-EBB (CBS, 2021b) and the Population Synthesizer (internal dataset). Population synthesis is a method that generates a synthetic population for regions by combining various demographic and spatial data sources, such as census data, through statistical techniques such as Iterative Proportional Fitting (IPF) and Iterative Non-Negative Least Squares (INNLS). The Population Synthesiser represents the entire population of individuals and households within the Netherlands and has been internally developed by Goudappel and Dat.mobility. It provides insights on the spatial variation and demographic characteristics on the individual level, including characteristics as number of children and adults within the household, number of cars, migration background, gender, age, education level and social participation in society. In land use and transportation studies that utilize agent-based micro-simulation models, a synthesized population plays a fundamental role in assessing the effects of policies and various development scenarios on the individual-level (Sun & Erath, 2015). Hence, within this study, the Population Synthesizer is crucial for individual-level analyses and the determination of job accessibility inequalities among groups within the Dutch workforce.

The number of workers and jobs per occupational class and education level have been harmonized to conform with Dutch national statistics from 2021. Job teleworkability is determined by empirical observations from the LRO survey (Taale, Olde Kalter, Haaijer, & Damen, 2022; MuConsult, 2022) on teleworking behaviour that have been reclassified per occupational class. In general, around 8 million employed individuals and more than 8,5 million job opportunities have been derived. From those job opportunities, 71% has been identified as non-teleworkable, whereas the resultant 29% of job opportunities requires 1 or more days teleworking. Detailed description of jobs and worker characteristics and the spatial distribution of jobs and workers is supplemented in appendix L and appendix M respectively. Finally, appendix N shows the characteristics of the Dutch working population and jobs per t-day teleworking within the entire study area in 2021.

3.3.2. Travel behaviour

Modal split

The modal split and decay functions of the Dutch workforce are derived from LRO dataset (Taale, Olde Kalter, Haaijer, & Damen, 2022; MuConsult, 2022), which contains over 9 thousand (n=9761) survey responses on commuting behaviour of individuals, obtained in 2021. The modal splits are used to derive the occupational weight parameters for car (w_c^r), public transport (w_c^p) and bike (w_c^b), used for two purposes: 1) for deriving the physical and hybrid cross-modal demand component per occupational class ($D_{jc(t)}^x$), and 2) for the aggregation of job accessibility by car, public transport and bike into an overview of the generalised job accessibility, per occupational class and in general. The modal split of the Dutch workforce per occupational class and in general is presented in figure 5. Commutes by public transport include rail, motorized vehicles, and multi-modal trips.

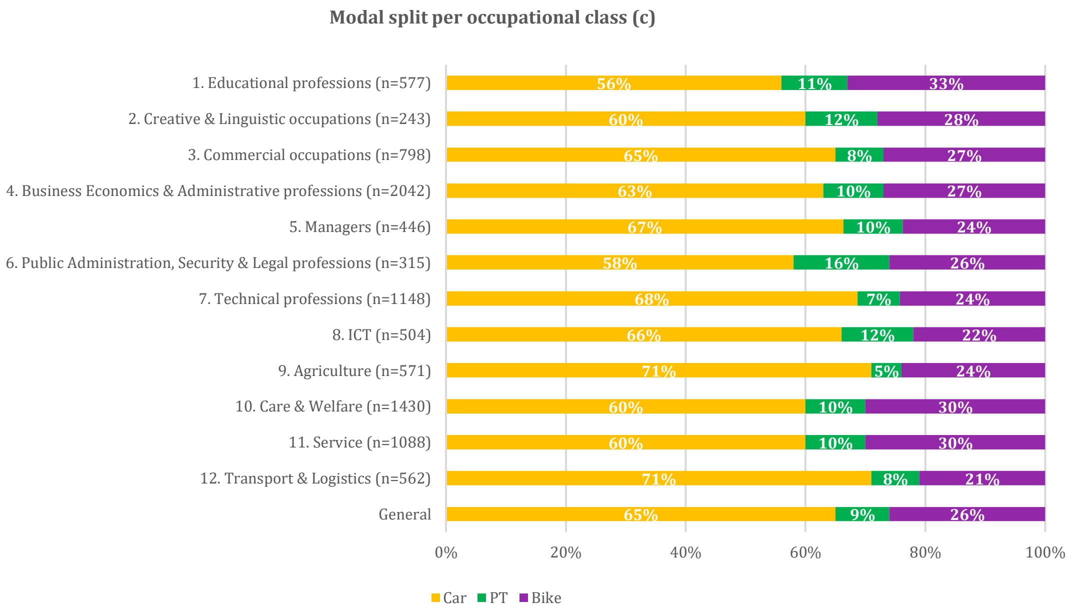


Figure 5: Modal split per occupational class c (Taale, Olde Kalter, Haaijer, & Damen, 2022; MuConsult, 2022)

Physical and hybrid decay functions

Parameters of the physical and hybrid decay functions in power-form $f(c_{ij}) = -a * c_{ij}^{\beta}$ have been calibrated on empirical commuting flows from home to work locations as observed in LRO data (appendix K). The decay functions $f_c^{(t)}(c_{ij}^v)$ describe the overall willingness of individuals per occupational class c to commute to physical and hybrid job opportunities by mode v. The physical and hybrid decay functions are displayed in figure 6 and figure 7, respectively. Separate decay functions for each occupational class, as well as a combined overview of physical and hybrid decays per mode of transport, can be found in Appendix O.

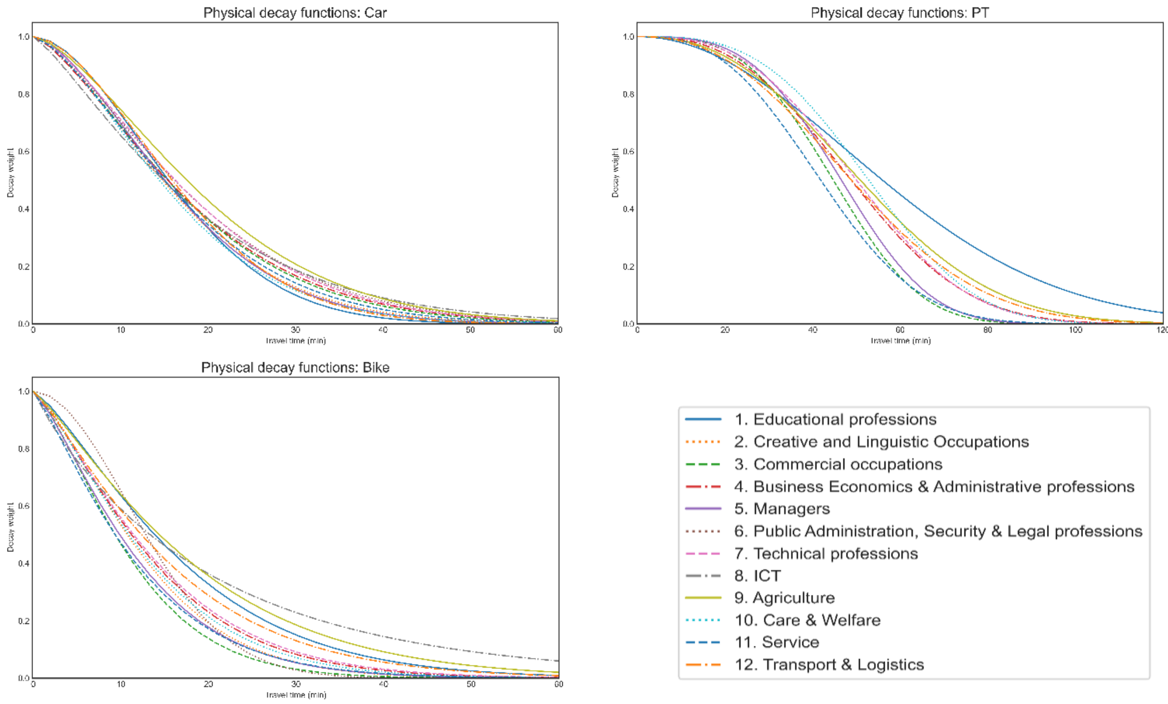


Figure 6: Decay functions per occupational class and mode of the physical job accessibility model

The decay functions of the weighted hybrid job accessibility model $f_c^t(c_{ij}^v)$ are further refined by incorporating decay rates associated per t-day teleworking ($t \geq 1$) (figure 7). Thereby, the decays for 0-days teleworking ($t = 0$) are replaced by the physical decay function per occupational class. For each mode, overlapping decay functions for t-days teleworking have been amalgamated into an average function, as indicated in the legend. The number of days hybrid teleworking results in gentler gradients of the decay functions. This implies that, regardless of the mode of transport, individuals are more inclined to accept longer commute to access job opportunities when they have the option to work from home for at least one day per week.

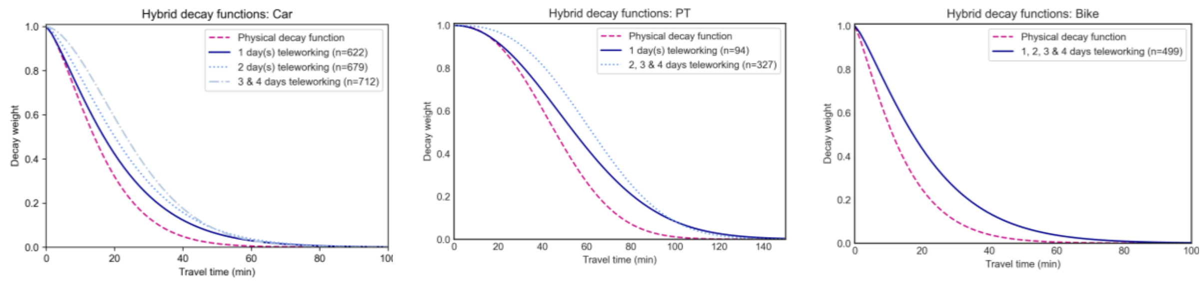


Figure 7: Decay functions per t-day hybrid teleworking and mode of the weighted hybrid job accessibility model

The difference between the physical and hybrid decay specifications raises concerns about the accuracy of hybrid decays in representing travel patterns for all occupational classes. The hybrid decay function reflects general decay of all workers combined and thereby lacks the nuances of travel patterns in the physical decay among different worker groups. Workers with heightened travel resistance in the physical scenario, e.g. education professions, or occupations with relatively limited job teleworkability, such as agriculture, service of transport and logistics, may face similar or larger travel resistances when hybrid teleworking. Such individuals might be less inclined to travel longer when hybrid teleworking and actual occupation-specific decay functions may be steeper than those depicted in Figure 7. Moreover, the decay functions not only determine the interaction potential to job opportunities which decreases with travel time, it also largely shapes strength of the competition effects. As result, for occupations with the steepest physical decay functions or general limited job teleworkability are overestimated in their willingness to travel and consequently see unrealistic strong impacts of hybrid teleworking on job accessibility, job competition or both. It is therefore important to acknowledge this caveat when interpreting the results as choice of decay function heavily influences job accessibility outcomes. To observe the discrepancies between the physical and hybrid decays for every occupational class and mode of transport, all decay functions have been plotted in the same figure in appendix O.

3.4. Analysis

From an egalitarian perspective, every individual should have equal access to job opportunities, regardless of their geographical location or underlying socio-demographic characteristics (Van Wee & Geurs, 2011). Since job accessibility is manifested over space, but also determined by the inherent individual-level characteristics and abilities, (vertical) equity can be achieved by addressing accessibility inequalities both spatially, in terms of how accessibility is distributed over space and different locations, and socially, how accessibility is distributed among individuals from diverse socio-economic backgrounds (Geurs & Van Eck, 2001b). Therefore, job accessibility inequalities and teleworking's socio-spatial effects will be assessed through spatial and social analyses, comparing the physical and hybrid accessibility models. Lastly, a comparative analysis is included to derive the effects of using a disaggregated measure on job accessibility measurements.

3.4.1. Spatial analysis

Spatial analysis considers the distribution of access to job opportunities across the entire working population over space. Spatial inequalities are addressed looking at the overall change in distributive pattern and height of the physical and hybrid job accessibility metrics, and across different modes of transport (car, public transport and bike) and the three modes combined (generalised). Inspired by the research of Shen (Shen, 1998), the spatial analysis involves three types of analyses, (1 the distribution of physical and hybrid job accessibility, (2 the spatial clustering and (3 the spatial differences of job accessibility.

In the distribution analysis, physical and hybrid job accessibility is presented spatially using maps and are supplemented with non-spatial information that present at the shape of the accessibility distribution of the working population (Liao, 2019), described by measures of central tendency and dispersion, and visualized by histograms (Garcia, Macário, Menesez, & Loureiro, 2018). A non-parametric Mann-Whitney U test is employed to compare whether the shape of the accessibility distribution is different between physical and hybrid scenario (H_0 = the distribution of job accessibility for both physical and hybrid job accessibility are equal) and is deemed suitable since normality of the data is not assumed (Burt, Barber, & Rigby, 2009). Secondly, spatial clustering of physical and hybrid job accessibility is captured with global spatial statistics (Garcia, Macário, Menesez, & Loureiro, 2018), for which a Global Moran's I is employed. Global Moran's I is a statistical measure that evaluates the overall spatial degree of similarity or dissimilarity of a one variable as job accessibility across all zones within the study area (Yin, He, Liu, Chen, & Gao, 2018). Global Moran's is calculated in using the Pysal ESDA (Exploratory Spatial Data Analysis) package in Python and are transferred to Arcgis Pro for visualization using the Arcpy package. Lastly, spatial differences between physical and hybrid job accessibility ($HA_i^v - PA_i^v$) are presented using maps supplemented with non-spatial data to discover the distribution of the differences across the working population.

3.4.2. Social analysis

Job accessibility inequalities are investigated by segmentation of the workforce by the twelve occupational classes in the social analysis. Thereby, the social analysis considers firstly descriptive statistics that provide insights in the height, variability, and differences in job accessibility across the different socio-economic backgrounds (Hidayati, Tan, & Yamu, 2021). To measure how physical and hybrid job accessibility is evenly distributed across the Dutch workforce, the Gini-index (G_i) and Lorenz curve are used. The Gini-index is one of the most widely used indicators of inequalities in transport and accessibility equity studies to assess the equality of accessibility across the population and the subgroups of the population (Lucas, Van Wee, & Maat, 2016; Van Wee & De Jong, 2023) and considered as most appropriate to be used in studies that approach equity in accessibility from an egalitarian perspective (Lucas, Van Wee, & Maat, 2016; Pritchard, Stepniak, & Geurs, 2019b). The Lorenz curve provides a visual representation of inequalities in the distribution of accessibility, where the cumulative distribution of job accessibility (y-axis) is plotted against the cumulative share of (groups of) individuals (x-axis). In addition, to assess the relationship between various socio-demographic characteristics of individuals and the impact of teleworking on job accessibility scores, an OLS multiple linear is performed. Variables that are included in the model are presented in table 3 and a correlation matrix to check for multicollinearity is provided in appendix P. The choice of socio-demographic characteristics as predictor variables is based on the identified individual-level factors that are affecting the individual uptake of teleworking. As linear regression models require numeric predictors, categorical and ordinal variables in the linear regression analysis are recoded into binary dummy variables. The dependent variable includes the generalised job accessibility differences. A K-fold cross-validation technique with 8075 folds is used as resampling method to avoid overfitting of the OLS model (Berrar, 2019), given the size of the dataset (n=8075000). The resultant beta coefficients (β_k) of every fold (n=1000) are subsequently averaged and presented in the model output. An additional regression analysis is run using standardized variables to obtain standardized regression coefficients. The latter are used to discern differences in impact of hybrid teleworking on all variables. The multiple linear regression model for estimating the impact of socio-demographic characteristics on absolute job accessibility differences is formulated as follows:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_j x_j + \cdots + \beta_k x_k + \epsilon$$

Where:

- y is the continuous dependent variable (change in job accessibility)
- β_0 is the coefficient of the intercept when all other variables are considered zero
- x_j is the independent variable
- β_j is the coefficient associated with independent variable x_j
- ϵ is the error term or residual of y

Table 3: Description of regression variables

	Level of measurement	Variable specification
Dependent variable		
Accessibility differences	Ratio	Displays the absolute differences (positive or negative) between individual-level hybrid job accessibility and physical job accessibility ($HA_i^v - PA_i^v$)
Independent variables		
Gender	Nominal	Female*, male
Age	Ordinal	15-24, 25-34, 35-44, 45-54, 55-64, 65-75
Education level	Ordinal	High educated, middle educated, low educated
Occupational class	Nominal	1. Educational professions, 2. Creative and Linguistic occupations, 3. Commercial occupations, 4. Business Economics & Administrative professions, 5. Managers, 6. Public Administration, Security & Legal professions, 7. Technical professions, 8. ICT, 9. Agriculture, 10. Care & Welfare, 11. Service, 12. Transport & Logistics
Household composition	Nominal	With children, single, without children
Household size	Ratio	Number of individuals within the household
Migration background	Nominal	Dutch, Western, not Western
Urbanity	Ordinal	Highly urbanized, strongly urbanized, moderately urbanized, slightly urbanized, non-urbanized
Physical accessibility	Ratio	Individual-level accessibility score in physical scenario (PA_i^v)

** = reference category*

3.4.3. Disaggregated versus aggregated comparative analysis

To discern the influence of the disaggregated nature of the job accessibility measure on the outcomes, a comparative analysis is performed. In the comparative analysis, the results of the previously defined disaggregated job accessibility measure (baseline) are compared to a newly constructed conventional aggregate job accessibility measure, that ignores occupational classes and education levels distinctions. The aggregate measure is similarly developed for every mode of transport and integrated into a generalised model using the average modal split of the population and a corresponding average decay function for the physical and hybrid model. Using median physical accessibility score (PA_i^v) of the disaggregated measure as baseline index (indexed at 100), the comparative analysis gives insights in the development of job accessibility scores. Moreover, the Gini-index is employed on generalised job accessibility scores to gauge how the aggregate measure impacts the identification of job accessibility inequalities.

4. Results

4.1. Spatial analysis

4.1.1. Spatial distribution of job accessibility

The spatial distribution of physical and hybrid job accessibility is additionally portrayed over the three transport modes, car, public transport (PT) and bike, and the generalised variant for the Hansen- and Shen-based models in figure 8 and figure 9, respectively. Descriptive statistics per model variant are supplemented in table 4 and 5. Mean normalisation is applied per model (car, public transport, bike and generalised) based on the values of the corresponding physical job accessibility model. The applied symbology of the figures uses a standard deviation-based method which highlights the areas that have higher (blue) and lower (red) values relative to the mean physical accessibility score (yellow). The histograms portray the distribution of job accessibility among the working population within the study area, where the dashed horizontal line in the histogram represents the median accessibility score. Spatial distribution of generalised job accessibility per urbanization level, occupational class and spatial clustering of job accessibility scores is analysed in Appendix Q, appendix R and appendix S.

Without competition effects (Hansen-based model), large urban agglomerations within the Randstad area in the west of the Netherlands experience overall higher job accessibility levels than the outer peripheries of the Netherlands (figure 8), visible for every mode of transport and in the generalised model. Travel by car yields highest job accessibility scores, followed by public transport, while cyclists experience lowest accessibility levels. Hybrid teleworking increases median job accessibility levels of the population significantly across all modes of transport according to the Mann-Whitney U test (table 4). Most significant accessibility improvements for car users are observed in the Randstad area, though job accessibility becomes slightly less clustered throughout the country as hybrid teleworking benefits many individuals commuting by car irrespective of their spatial location. Where high physical accessibility levels by public transport are mostly observed within the large urban cores of Amsterdam and Utrecht, hybrid teleworking improves job accessibility in areas well-connected to the public transport network. High scores are mostly bound to nodes in the underlying public transportation network, such as train stations and bus stops. This results in a spatially dispersed yet notably locally clustered pattern of job accessibility. Accessibility by bike exhibits a localized distribution, highlighting only certain Dutch cities. However, the spatial distribution of accessibility by bike sees only marginal spatial increases with hybrid teleworking. Lastly, the generalised job accessibility distribution presents a composite picture of all modes, where car-based job accessibility significantly dominates the spatial distribution due to its prominent role in mode choice of Dutch workers. Overall, the colour changes in the western part of the country indicate a large increase in job accessibility for individuals living in the dense urban areas, while job accessibility levels remain almost visibly unchanged in the non-urbanized zones. With the inclusion of hybrid teleworking, the contrast between the Randstad area and the outer regions becomes more evident in most scenarios (figure 8) and the spatial clustering of job accessibility increases.

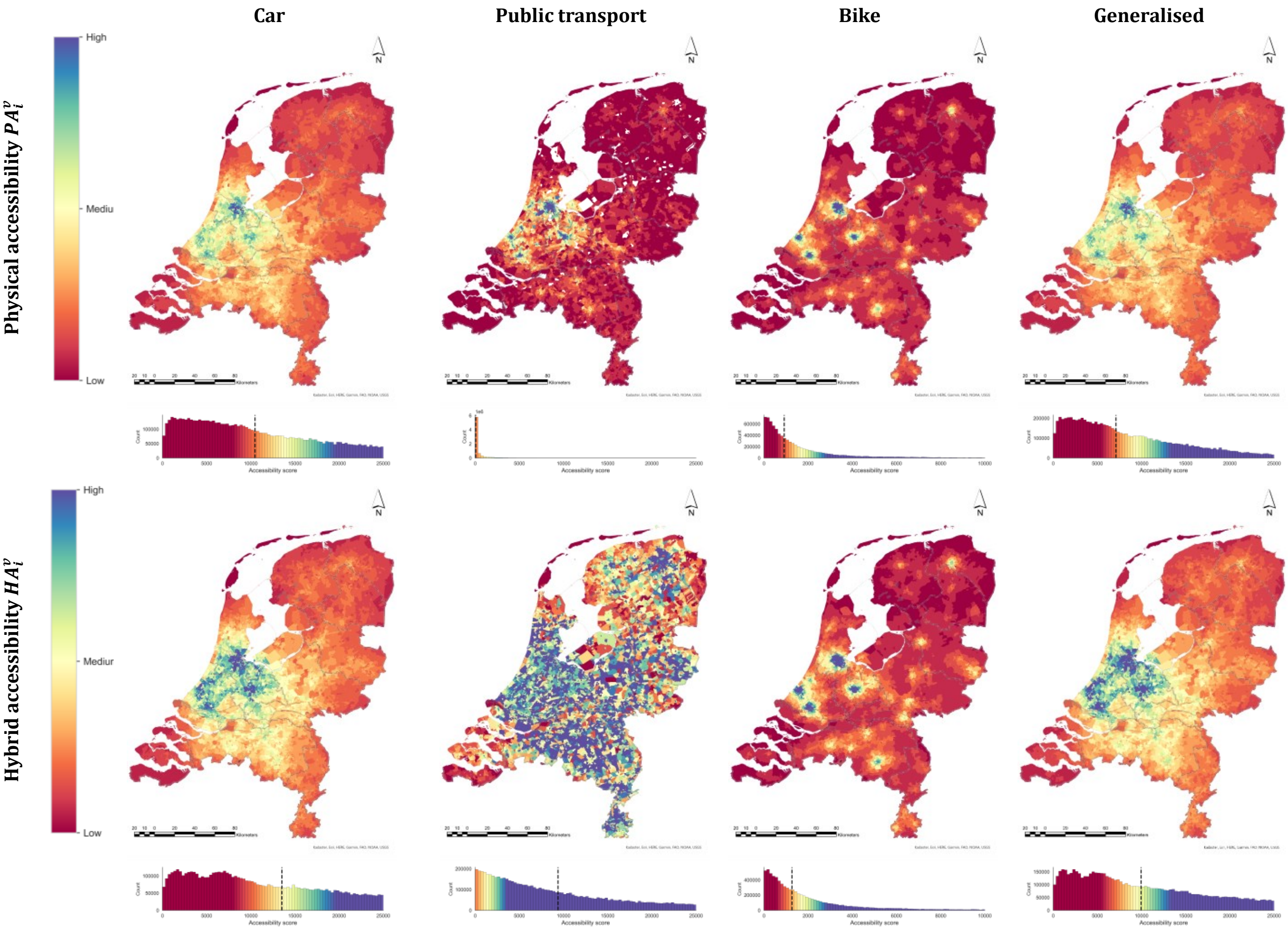


Figure 8: Spatial distribution of physical (PA_i^v) and hybrid (HA_i^v) job accessibility, without job competition (Hansen-based)

Table 4: Descriptive statistics of physical (PA_i^v) and hybrid (HA_i^v) job accessibility, without competition (Hansen-based)

Model											*Global Moran's I*		*Mann-Whitney U*	
	Mode		**Median**	**S.D.**	**Min**	**25%**	**75%**	**Max**	**SK.**	**KU.**	**I**	**p-value**	**U**	**p-value**
Hansen	Car	*Physical*	10672	11786	0	5103	19883	80218	1.438	2.465	0.972	<0.001	217055	<0.001
		Hybrid	13850	15350	0	6447	25456	101072	1.538	2.944	0.971	<0.001		
	PT	*Physical*	66	4567	0	6	447	73055	5.953	42.69	0.822	<0.001	9369436	<0.001
		Hybrid	9688	15832	0	4006	21276	140983	1.843	4.031	0.919	<0.001		
	Bike	*Physical*	940	2332	0	385	2071	20085	3.163	13.43	0.979	<0.001	229638	<0.001
		Hybrid	1323	3047	0	555	2819	26771	3.224	14.68	0.980	<0.001		
	Generalised	*Physical*	7225	8050	0	3465	13423	55819	1.477	2.669	0.980	<0.001	399204	<0.001
		Hybrid	10160	11775	0	4727	18938	81014	1.651	3.541	0.986	<0.001		

When competition effects are included (Shen-based model), an overall more homogeneous distribution of job accessibility is found (figure 9). The inclusion of hybrid teleworking alters the distribution of job accessibility within the population for every mode significantly according to the Mann-Whitney U test (table 5). Where job accessibility decreases by car and bike, hybrid teleworking only increases job accessibility for commuters by public transport. Physical accessibility by car is characterized by relatively high accessibility scores that follow the trajectories of the larger Dutch motorways. Although median job accessibility score decreases, higher values are still observed in these regions in the hybrid scenario. While job accessibility via public transport is less varied than by car, its spatial distribution is only marginally altered from the Hansen-based model. Despite job competition, high accessibility scores persist in the densely urbanized cores of the Netherlands, as the development and ability to distribute over space of (hybrid) job accessibility is largely governed by the existing public transport network. However, the histograms show the increased homogeneity of job accessibility due to job competition effects at the individual level. Job accessibility by bike slightly decreases due to hybrid teleworking, but these effects are almost negligible on the spatial level. Generally, the Shen-based model shows that job accessibility is less clustered in space and disperses more when hybrid teleworking is included. Hybrid teleworking thus results in a more dispersed pattern of job accessibility over space when competition effects are included, leading to lesser differences between regions within the Netherlands as compared to the Hansen-based model.

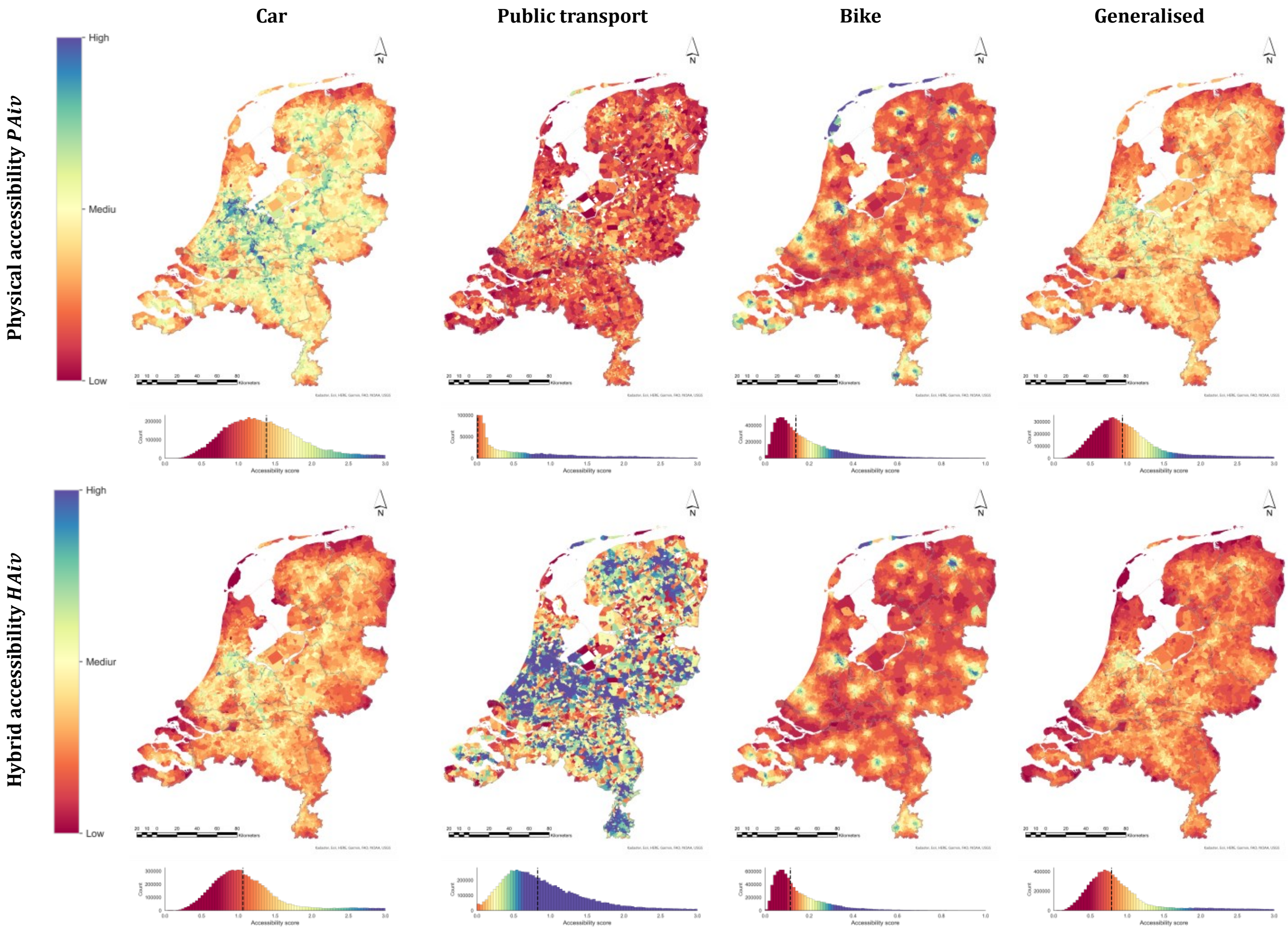


Figure 9: Spatial distribution of physical (PA_i^v) and hybrid (HA_i^v) job accessibility, with job competition (Shen-based)

Table 5: Descriptive statistics of physical (PA_i^v) and hybrid (HA_i^v) job accessibility, with job competition (Shen-based)

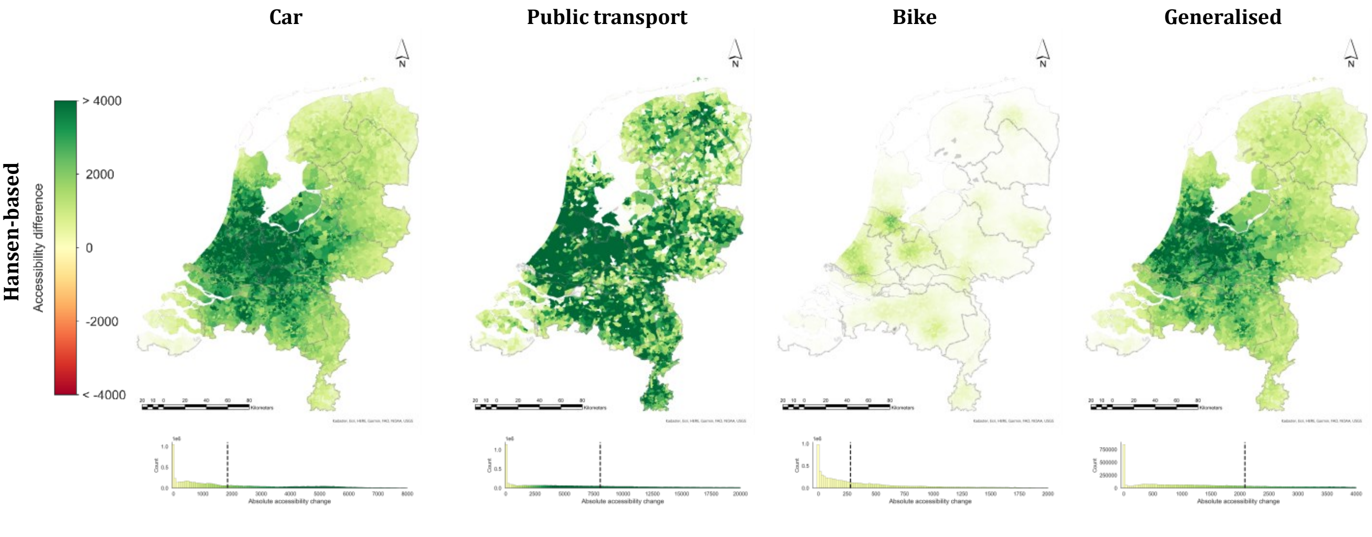
Model											***Global Moran's I***		***Mann-Whitney U***	
	Mode		**Median**	**S.D.**	**Min**	**25%**	**75%**	**Max**	**SK.**	**KU.**	**I**	**p-value**	**U**	**p-value**
Shen	Car	*Physical*	1.046	0.898	0	0.796	1.401	11.021	2.423	7.114	0.358	<0.001	4895	<0.001
		Hybrid	1.064	0.893	0	0.813	1.403	10.855	2.412	6.972	0.355	<0.001		
	PT	*Physical*	0.012	0.914	0	0.001	0.090	32.449	7.364	88.082	0.485	<0.001	94327	<0.001
		Hybrid	0.976	1.057	0	0.621	1.482	19.525	3.260	16.200	0.479	<0.001		
	Bike	*Physical*	0.117	0.166	0	0.078	0.214	9.722	4.347	57.719	0.449	<0.001	3874	<0.001
		Hybrid	0.115	0.161	0	0.077	0.207	9.601	4.418	60.421	0.470	<0.001		
	Generalised	*Physical*	0.897	0.752	0	0.731	1.199	9.279	2.452	7.556	0.797	<0.001	1050969	<0.001
		Hybrid	0.788	0.686	0	0.598	1.061	9.913	2.468	7.623	0.612	<0.001		

4.1.2. Spatial job accessibility differences

Figure 10 presents the spatial differences in job accessibility ($HA_i^v - PA_i^v$) for the Hansen-based and Shen-based models, where for every zone, the weighted average difference in job accessibility of all inhabitants is shown. The descriptive statistics of the job accessibility differences are presented in table 6. Spatial differences per occupational class for the Hansen- and Shen-based models can be found in appendix T.

The results of the Hansen-based model suggests that hybrid teleworking grants better access to more job opportunities compared to a scenario where solely physical travel is considered. On the spatial level, increases in job accessibility levels are mostly observed for individuals living in economic dense regions as the Randstad region. Job accessibility by car visibly increases throughout the entire country, where a median increase of 30% is observed compared to the physical scenario. For public transportation, the increase in job accessibility is far starker (14614%) and is more rigorously dispersed throughout the country. Smaller improvements in job accessibility levels are visible for the bike, where individuals living in urbanized regions mostly experience an increase in job accessibility (41%). Overall, hybrid teleworking, without competition effects considered, improves the job accessibility levels of most individuals throughout the entire country (+40%). Zones where hybrid teleworking has the least impact on job accessibility levels are located in the most disconnected and peripheral regions in the Netherlands, such as the Wadden Islands and the southern part of Zeeland. The improvements can be primarily attributed to the variations in shape of the employed physical and hybrid decay functions. The enhanced job accessibility levels for every mode of transport are influenced by the differences in slope between the physical and hybrid decay functions, where the hybrid teleworker generally accepts longer commutes for every mode per -day teleworking. The difference between the physical and hybrid decays are particularly visible for public transportation, explaining the sudden surge in job accessibility levels for this mode (appendix O). The extended willingness to commute of a hybrid teleworker expands the number of potential job opportunities, provided that these jobs are within reach and well-connected to the infrastructure network of the corresponding mode of transport.

The Shen-based job accessibility models presents a contrasting and less optimistic picture of the Dutch employment landscape when competing individuals are considered and shows the influence of competition on the spatial distribution of job accessibility. Whereas some increases in accessibility are seen among the population, on the spatial aggregate, a general decrease can be observed in the hybrid scenario. Commuters by car experience largest decreases in accessibility (-5%), mostly visible along the motorways and in the most peripheral regions of the Netherlands. On the other hand, commuters by public transport face a similar soaring of job accessibility in the hybrid scenario compared to the Hansen-based models (16366%). The job accessibility pattern via public transport shows stark increases and decreases across the country. This is due to cross-modal competition effects; individuals living within zones that are disconnected from the public transport network are heavily penalized on job accessibility levels due to competition for jobs over car and bike. Accessibility by bike decreases on average by 8,5%, where most heavy declines are seen on the Wadden Islands in the north of the country. All modes combined, both spatially and in quantitatively, job accessibility generally decreases in the hybrid scenario (-12%). The overall decline in the Shen-based model can be ascribed to the inclusion of the competition component; individuals are penalized on their job accessibility levels by the disproportionate enhancement of competition effects, where the number of competitors outnumbers the quantity of jobs that can be reached through hybrid teleworking. Considering cross-modal demand, job competition is mostly dominated by competitors commuting by car based on the general modal split (figure 5). From a spatial perspective, the more peripheral areas that appeared to be unaffected by hybrid teleworking in the Hansen-based scenario, face stark decreases in job accessibility due to the influx of hybrid teleworking competitors from large, urbanized zones within the country, such as the Randstad area, as shown in appendix U. Besides, while the effects of job competition are observed throughout the entire country, zones with high economic densities similarly experience greatest number of competing individuals in contrast to the more peripheral regions within the Netherlands. This suggests a near-equilibrium in the spatial distribution of supply of jobs and demand for jobs across all geographic locations. As a result, the job competition component in the Shen-based model alters the spatial distribution of job accessibility differences towards a more homogeneous distribution throughout the country, compared to the Hansen-based model.



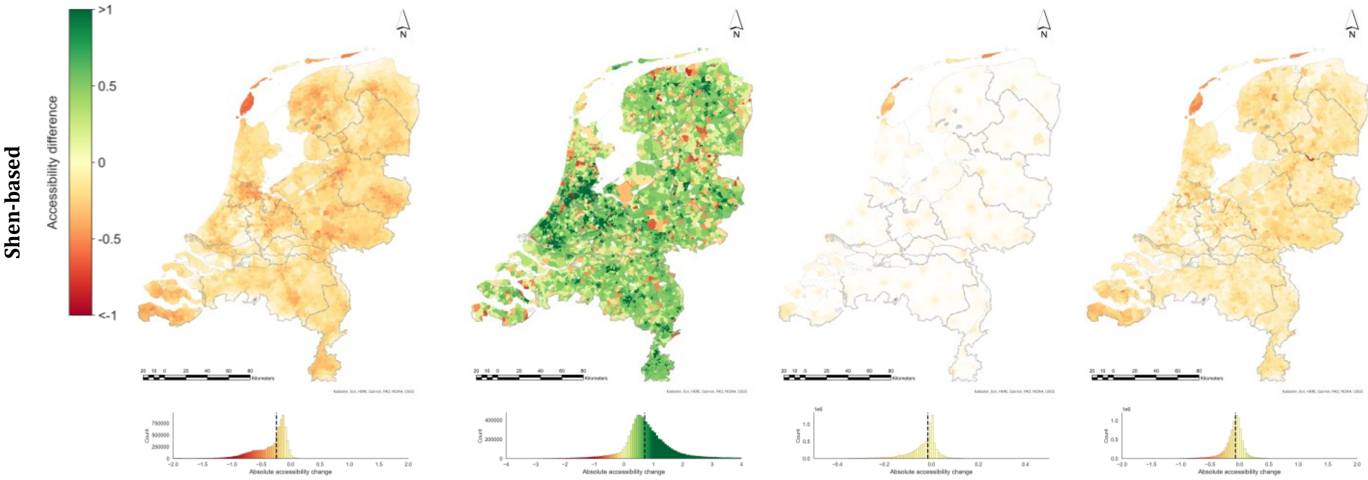


Figure 110: Spatial distribution of job accessibility differences ($HA_i^v - PA_i^v$) Hansen (upper) and Shen (lower)

Table 6: Descriptive statistics of job accessibility differences per mode ($HA_i^v - PA_i^v$)

Model											*Global Moran's I*	
	Mode	**Median**	**(%)**	**S.D.**	**Min**	**25%**	**75%**	**Max**	**SK.**	**KU.**	**I**	**p-value**
Hansen	***Car***	1917	30%	4880	0	487	5310	25847	1.694	2.285	0.835	<0.001
	PT	8283	14614%	16003	0	2436	19878	139065	1.853	3.954	0.888	<0.001
	Bike	287	41%	891	0	77	748	6909	3.227	14.093	0.940	<0.001
	Generalised	2141	40%	4544	0	751	5444	28061	1.823	3.293	0.876	<0.001
Shen	***Car***	-0.242	-6%	0.658	-16.442	-0.565	-0.143	0.699	-3.933	20.634	0.642	<0.001
	PT	0.830	16366%	1.386	-31.992	0.442	1.370	19.525	-0.612	21.411	0.659	<0.001
	Bike	-0.015	-9%	0.101	-16.146	-0.066	0.003	0.675	-16.275	17.053	0.877	<0.001
	Generalised	-0.096	-12%	0.416	-14.757	-0.398	0	2.677	-4.0123	26.062	0.566	<0.001

4.2. Social analysis

4.2.1. Social impact of hybrid teleworking

The distribution of generalised physical and hybrid accessibility levels (Hansen- and Shen-based) among occupational classes of the Dutch workforce is visualised in figure 11. Outliers have been removed for clarity in the visualisation. The corresponding descriptive statistics of the job accessibility scores per occupational class and socio-demographic characteristics of the population can be found in appendix V.

The visual comparison of the boxplots reveals how accessibility to job opportunities is variedly distributed across the working population in both the physical and hybrid working scenarios. The Hansen model on the left in the figure presents large within- and between-group variation of job accessibility scores per occupational class. Workers with higher job accessibility scores are more likely to secure jobs within their specified travel budgets than those with lower scores. Individuals working in occupations such as security personnel, police, politicians, and lawyers (4. Business economics & Administrative professions) experience the highest median job accessibility levels whereas workers in agriculture have the least accessibility to job opportunities. In the generalised Shen-based model, the inclusion of competition between workers reveals a more homogeneous distribution of potential job accessibility scores across the occupational classes. While the differences in the distribution between the occupational classes have become smaller, most within-group variation of potential job accessibility can be found within less teleworkable occupational classes as agriculture, service and transport and logistics.

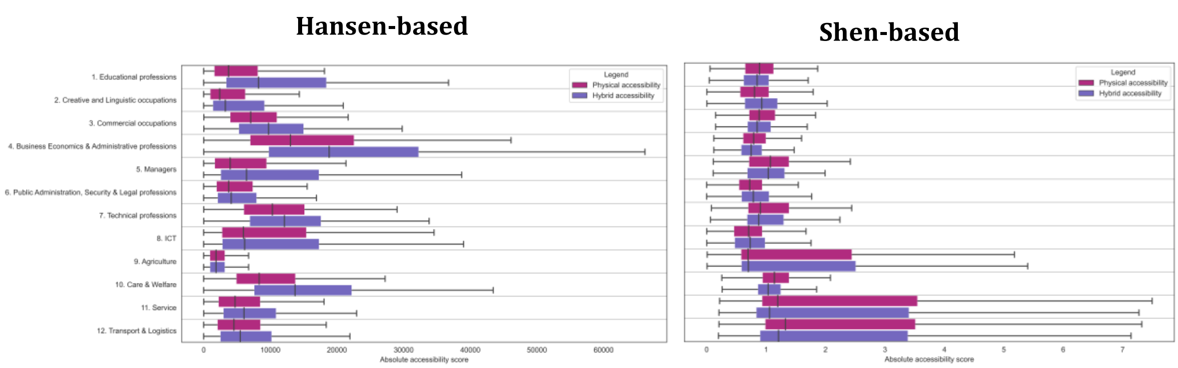


Figure 11: Distribution of generalised physical and hybrid job accessibility per occupational class

Differences between physical and hybrid job accessibility per occupational class are visualised in figure 12. The Mann-Whitney U test shows that most distributions of physical and hybrid job accessibility are significantly different (p<0.001) in both the Hansen- and Shen-based variants except for agriculture in the Hansen-based model. This suggests that while hybrid teleworking alters the distribution of accessibility for most population groups (appendix V), its impact varies by occupational class.

The Hansen-based results show the inherent job accessibility benefits of hybrid teleworking experienced by the individual that are determined by the spatial distribution of jobs and workers, job teleworkability, travel budgets and modes of transport. Whereas individuals working in 1. Educational occupations and in 10. Care and Welfare, such as teachers and hospital personnel, experience the greatest increases in access to potential job opportunities, 120% and 65% respectively, workers in agriculture (9. Agriculture) do not see increases in job accessibility. The ability to telework, combined with an assumed increased willingness to travel longer when hybrid teleworking, primarily explains the observed impacts per occupational class. Occupational classes, such as 1. Educational professions and 10. Care and Welfare, which are seen relatively more reluctant to endure long physical commutes and have steeper physical decay functions, experience significant increases in job accessibility when general travel behaviour of hybrid teleworkers is assumed, as portrayed by the hybrid decay functions. In contrast, occupational classes accustomed to longer physical commutes, such as 9. Agriculture, see only modest improvements in job accessibility scores. This is because their physical travel behaviour more closely resembles that of hybrid teleworkers.

The competition effects seen in the Shen-based model indicate more moderate and both positive and negative job accessibility changes. For instance, hospital personnel (10. Care and Welfare) is largely benefit from hybrid teleworking in the Hansen-based model, yet the potential accessibility to job opportunities has worsened when competition is included. Moreover, occupational classes that do experience median job accessibility increases are 2. Creative and Linguistic occupations (15%), 6. Public Administration, Security and Legal professions (8%), 8. ICT (3%) and 9. Agriculture (1%). These results can mostly be explained by strong influence of competition for job demand on a relatively scarce number of jobs, penalising job accessibility for occupational classes with intensive competition but also heightening job accessibility for occupational classes with weaker competition effects. Most pronounced increases in job competition occur among teachers (1. Education professions), hospital personnel (10. Care and Welfare), service personnel (11. Service) and professional drivers and loaders (12. Transport and Logistics), all of whom work in occupational classes where hybrid teleworking leads to lower job accessibility levels. Least increases in job competition are found across workers in 8. ICT and 9. Agriculture, who simultaneously experience a positive net improvement of job accessibility levels through hybrid teleworking (appendix V). As the decay functions not only model the travel behaviour of the working individual, but also that of the competing individuals, it partially influences the intensity of the competition effects per occupational class. Specifically, occupational classes with a relatively gentler slope of the hybrid decay function compared to physical decay are similarly attracting more workers to job opportunities in the hybrid scenario. This is less prominent in occupational classes where distinctions in physical and hybrid decay shapes are less apparent. Consequently, these occupational classes are more likely to experience intensified competition effects and substantial declines in job accessibility, especially for the more teleworkable occupations.

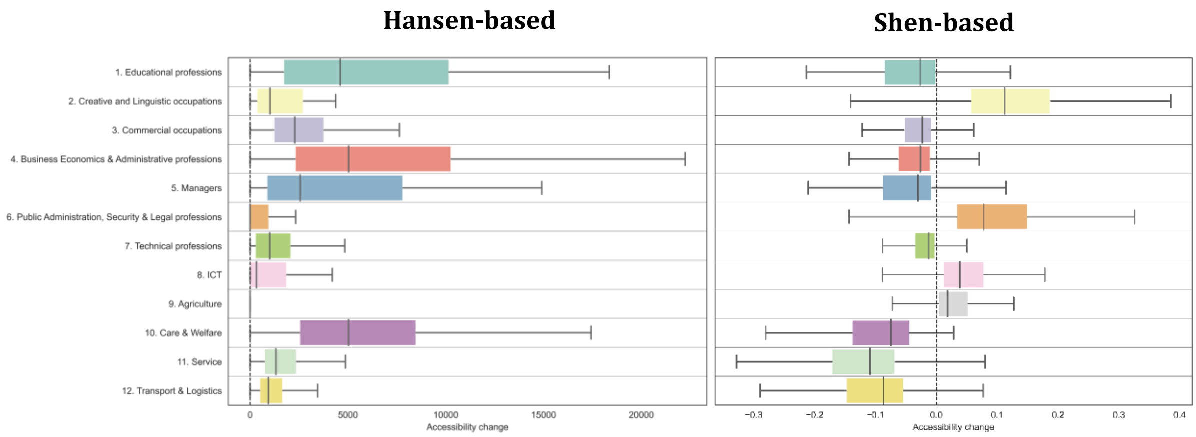


Figure 12: Distribution of accessibility change per occupational class

4.2.2. Influence of individual characteristics on job accessibility changes

Table 7 shows the output of the multiple linear regression on generalised job accessibility changes for every individual within the employed workforce (n=8075000), without competition effects (Hansen) and with competition effects (Shen). The presented model results are the average of all 8075-folds that have been performed to avoid overprediction when using large datasets. Independent variables have been checked on multicollinearity to assess their appropriateness for inclusion in the models (appendix P). Results of the correlation matrix show that no problematic correlation above 0,8 (Shrestha, 2020) is observed between the variables, hence no variables have been omitted from the analyses. Most variables have a significant ($\alpha = 0.05$) relationship with changes in job accessibility in the Hansen-based model, whereas some insignificant relationships are found in the Shen-based model (table 7). The complete regression output is presented in appendix W.

A positive correlation between being male and job accessibility differences is found, which implies that being male individuals can reach more job opportunities by than women. Men may work in jobs with higher teleworking potential, whereas women may predominantly work in occupational classes with lower teleworking rates (appendix M), however opposite situations are also reported (Sostero, Milasi, Hurley, Fernandez-Marcias, & Bisello, 2020). Nevertheless, an insignificant relationship is found when competition effects are included, indicating that there is no meaningful association with gender and impact of hybrid teleworking on potential job accessibility.

Table 7: Multiple linear regression on changes in job accessibility

	Hansen (0.830)		Shen (0.797)	
	β	P-value	β	P-value
Intercept	-263	<0.001	-0.168	<0.001
Gender (ref = Female)				
Male	121	<0.001	<0.001	0.992
Age category				
15-24 years	-66	<0.001	-0.031	0.116
25-34 years	21	<0.001	-0.031	0.005
35-44 years	4	<0.001	-0.035	0.005
45-54 years	-36	<0.001	-0.027	0.011
55-64 years	-53	<0.001	-0.044	<0.001
65-75 years	-132	<0.001	0.009	0.780
Education level				
Low educated	-1992	<0.001	0.027	0.087
Middle educated	-612	<0.001	-0.091	<0.001
High educated	2341	<0.001	-0.105	<0.001
Occupational class				
1. Educational professions	2985	<0.001	0.399	<0.001
2. Creative and Linguistic occupations	-701	<0.001	0.661	<0.001
3. Commercial occupations	173	<0.001	0.428	<0.001
4. Business Economics & Administrative professions	1447	<0.001	0.433	<0.001
5. Managers	1393	<0.001	0.465	<0.001
6. Public Administration, Security & Legal professions	-1517	<0.001	0.530	<0.001
7. Technical professions	-1903	<0.001	0.434	<0.001
8. ICT	-3167	<0.001	0.478	<0.001
9. Agriculture	180	<0.001	0.431	<0.001
10. Care & Welfare	2240	<0.001	0.405	<0.001
11. Service	614	<0.001	0.430	<0.001
12. Transport & Logistics	161	<0.001	0.427	<0.001
Household composition				
Single	-22	<0.001	-0.062	<0.001
With children	-128	<0.001	-0.069	<0.001
No children	-112	<0.001	-0.036	0.001
Household size	-16	<0.001	0.011	0.134
Migration background				
Dutch	-21	<0.001	-0.043	<0.001
Western	-110	<0.001	-0.077	<0.001
Not Western	-130	<0.001	-0.048	<0.001
Urbanity				
Highly urbanized	-167	<0.001	0.012	0.279
Strongly urbanized	33	<0.001	-0.034	0.004
Moderately urbanized	-13	<0.001	-0.020	0.093
Slightly urbanized	-26	<0.001	-0.054	<0.001
Non-urbanized	-89	<0.001	-0.072	<0.001
Accessibility				
Physical accessibility	0.369	<0.001	-0.081	<0.001

Thereupon, age categories are variedly correlated with job accessibility changes, yet no clear trend can be observed. For the Hansen-based results, individuals belonging to the youngest and oldest age categories experience job accessibility changes in a negative direction, whereas individuals aged from 25 up to 44 see a positive change in job accessibility levels. Both younger and older individuals experience a less advantageous position in the job market due to hybrid teleworking. With competition effects, age does explain changes in accessibility to some extent, but mostly results in a decrease in job accessibility levels considering the influence of hybrid teleworking.

The height of the attained level of education largely increases the job accessibility levels when hybrid teleworking is included in the Hansen-based model; those who possess a diploma in higher education see a larger increase in potential job opportunities compared to the lower educated individual. This is not surprising, as systematically higher teleworkability levels are seen for jobs that require high education levels (Appendix L). However, a remarkable effect of job competition is visible; lower educated individuals experience larger increases in job accessibility, whereas higher education levels see the opposite effect, opposing the impacts observed in the Hansen-based model.

The correlation between job accessibility changes and occupational class in the Hansen-based regression model follows a similar pattern as is presented in figure 12. The large deviations between the classes illustrate how discrepancies in the impacts of hybrid teleworking exist, related to the nature of the jobs and the existent employment landscape per occupational class, such as the supply of (teleworkable) job opportunities. In the Shen-based model, occupational class is positively correlated to changes in job accessibility.

With regards to household composition, single person household experience relatively larger job accessibility increases than couples with and without children. In addition, the larger the household size, the smaller the number of potential job opportunities reached via hybrid teleworking. As Dutch individuals with children are less likely to live in inner cities (Muhammad, Ottens, Ettema, & De Jong, 2007b), the job accessibility benefits through hybrid teleworking diminishes, since larger households need family homes located in areas that are further away from potential job opportunities. Job competition presents similar findings on the impact on household type and job accessibility changes due to hybrid teleworking. Yet, contrarily, household size does positively correlate with changes in job accessibility in the Shen-based model but is seen to have an insignificant effect on the dependent variable.

Overall, individuals with a non-Dutch migration background experience lesser increases in job accessibility compared to individuals born in the Netherlands. Similarly, the Shen-based models present comparable negative correlations with every migration background and the change in job accessibility levels due to hybrid teleworking. The smallest impacts on differences are observed for Dutch individuals. Such discrepancies can be attributed to potential ethnic and residential segregation of immigrants within the Netherlands, residing in less affluent neighbourhoods with lower levels of access to job opportunities (Van Tubergen & Volker, 2015).

The urbanity of the residence location also significantly influences the job accessibility levels of the Dutch workforce. Thereby, the largest increases in job accessibility are found for individuals living in strongly urbanised regions, such as suburbs. Contrarily, the lowest increases are observed for individuals living in highly urbanised areas, such as inner cities. Potentially, as already high job accessibility values are observed for those individuals, hybrid teleworking does not improve their position relatively as much as it does for other individuals in less urbanized zones. When including competition effects, highly urbanized and moderately urbanised areas have no longer a significant effect on job accessibility changes, yet the overall impact on job accessibility differences is still negative, implying lesser deviations between job accessibility scores for every urbanity level of the residential location.

Lastly, the extent to which individuals have access to potential job opportunities in physical space is positively correlated to an increase in job accessibility due to teleworking, indicating that individuals with an already high job accessibility level see a larger increase in job accessibility compared to those with lower job accessibility levels. On the other hand, an opposite negative relationship is found when competition effects are considered: individuals with higher physical job accessibility levels experience larger negative impacts of job accessibility changes due to hybrid teleworking.

Further analysis on the strength and direction of the association of the variables with the changes in job accessibility is visualized in figure 13. The unstandardized mode-specific regression outputs are supplemented in appendix W. The data reveals that the Hansen- and Shen-based models exhibit non-identical relationships to the socio-demographic variables. In both models, most significant associations on job accessibility differences are occupational classes, education levels and initial physical accessibility levels of individuals, surpassing other socio-demographic variables. Results of the Shen model shows strongest effects on occupational classes, suggesting that competition largely influences the size of the changes in job accessibility, especially depending on job type. Moreover, job competition changes the distribution of job accessibility to such extent that remarkable opposing relationships between the Hansen-based and Shen-based models are found for education level, level of urbanization and physical accessibility levels. Job competition thus not only changes the job accessibility levels of individuals on a more superficial level, but also alters the underlying relationships of individual-level characteristics on job accessibility changes.

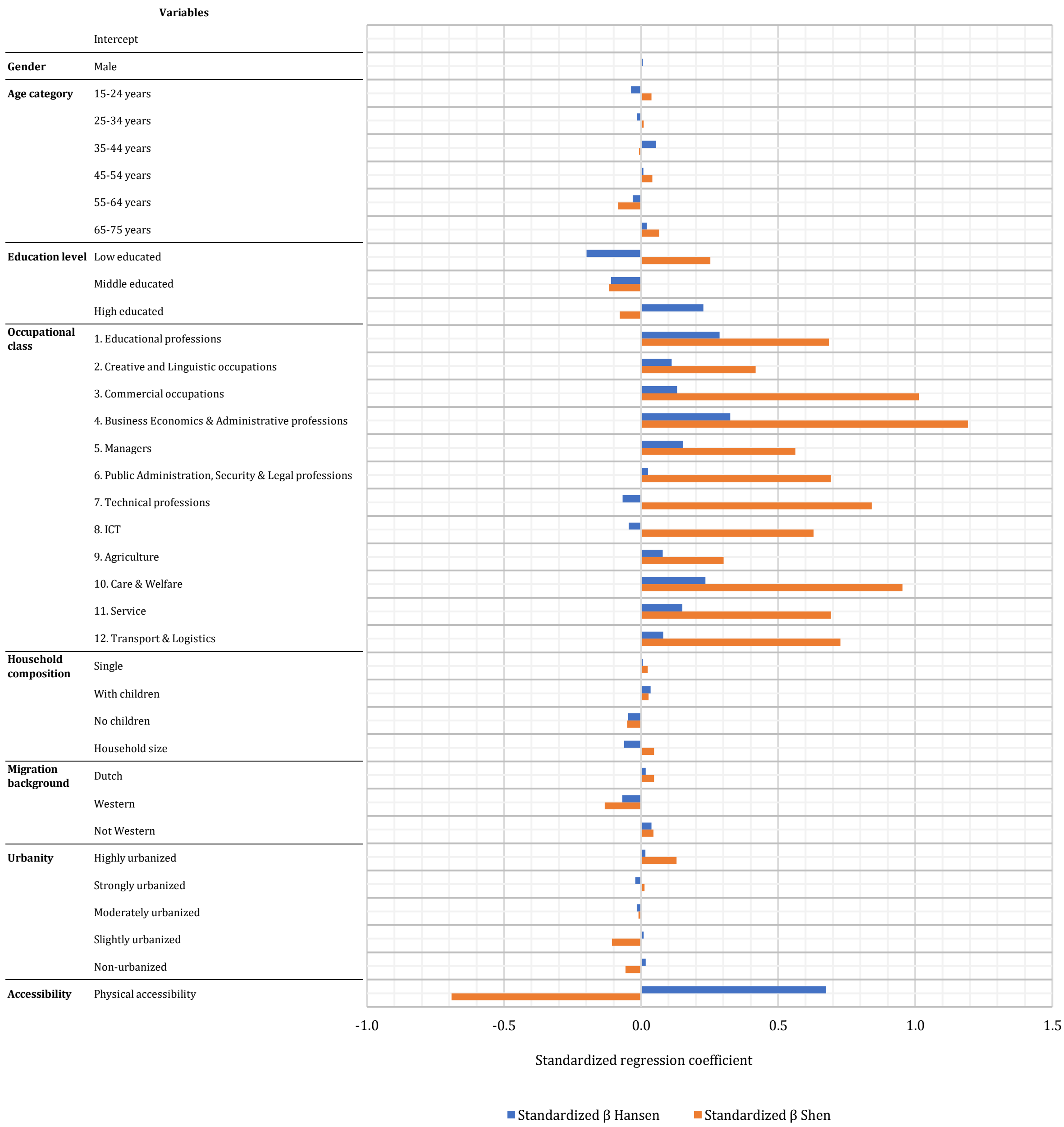


Figure 13: Comparison of standardized β-coefficients of Hansen- and Shen-based generalized job accessibility differences

4.2.3. Social inequalities in job accessibility

The extent to which the change in job accessibility due to hybrid teleworking leads to a more or less equitable distribution of accessibility among the population is explored using Gini-indices. Figure 14 presents the Lorenz curve and Gini-coefficient (G_i) of the Hansen- and Shen-based generalised physical and hybrid accessibility scores of every individual in the entire Dutch workforce.

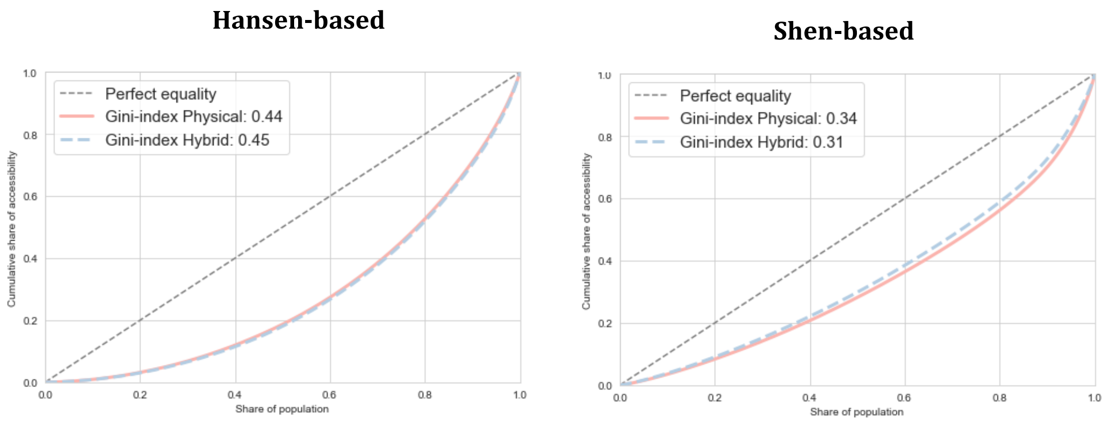


Figure 14: Social inequalities in the distribution of generalised physical and hybrid job accessibility, visualized by Lorenz-curves

As can be observed, in the Hansen-based model, hybrid teleworking is seen to lead to a more unequal distribution of accessibility within the working population, but only to a marginal extent (2,2%). Although job accessibility levels are increasing without considering competition effects, hybrid teleworking is seen to increase job accessibility more for certain individuals within the population than others. Especially, regression analysis has shown that certain individual level characteristics, such as high education, can lead to discrepancies in job accessibility levels among individuals, particularly compared to lower educated individuals. On the other hand, generalised job accessibility in the Shen-based model reveals that, compared to already existing physical accessibility inequalities within the total workforce (G_i = 0,34), hybrid teleworking results in a more equitable distribution of accessibility (G_i = 0,31, -8,8%).

Further decomposition of the Gini-index calculations on accessibility for every occupational class is made and provided in table 8. Without competition for jobs, hybrid teleworking has a varying impact on the emergence of social inequalities. Interestingly, high educated, white-collar occupational classes see an exacerbation of existing job accessibility inequalities, such as economists, policy advisors, and accountants (4. Business Economics and Administrative professions) and government leaders and lawyers (6. Public administration, security & legal professions). Occupations with limited teleworkability, such as agriculture, service and transport and logistics all see a remarkable decrease in job accessibility inequalities. The inclusion of competition effects does alter the impact of hybrid teleworking on inequalities. Not only is job accessibility more equally distributed across almost all occupational classes compared to the Hansen model, but the observed improvements in job accessibility distributions due to hybrid teleworking are more considerable (e.g. workers in 1. Educational professions).

Table 8: Gini-coefficients for generalised physical and hybrid job accessibility

	Hansen			Shen		
Occupational class	**G_i Physical**	**G_i Hybrid**	**%**	**G_i Physical**	**G_i Hybrid**	**%**
1. Educational professions	0,48	0,45	-6,2%	0,29	0,26	-10,3%
2. Creative and Linguistic occupations	0,52	0,51	-1,9%	0,23	0,23	0,0%
3. Commercial occupations	0,34	0,33	-2,9%	0,37	0,34	-8,1%
4. Business Economics & Administrative professions	0,37	0,39	5,4%	0,34	0,31	-8,8%
5. Managers	0,49	0,49	0,0%	0,25	0,23	-8,0%
6. Public Administration, Security & Legal professions	0,41	0,44	7,3%	0,31	0,32	3,2%
7. Technical professions	0,31	0,3	-3,2%	0,31	0,29	-6,5%
8. ICT	0,5	0,52	4,0%	0,25	0,27	8,0%
9. Agriculture	0,45	0,43	-4,4%	0,43	0,44	2,3%
10. Care & Welfare	0,35	0,35	0,0%	0,2	0,19	-5,0%
11. Service	0,48	0,46	-4,2%	0,46	0,45	-2,2%
12. Transport & Logistics	0,48	0,47	-2,1%	0,42	0,39	-7,1%

4.3. Disaggregated versus aggregated comparative analysis

The development of physical and hybrid job accessibility using a basic aggregate measure is presented in table 9. The table shows the median job accessibility values per model, the size of the difference between physical and hybrid accessibility in percentages, the development of the Gini-index and the development of these scores compared to the disaggregated physical job accessibility levels (baseline index = 100) between brackets. The spatial distribution of job accessibility, per mode of transport and generalised, is presented in appendix X.

The aggregate measure leads to overall higher job accessibility scores and stronger impacts of hybrid teleworking on accessibility levels. Remarkable differences are visible in the Shen-based results, where the aggregate hybrid measure leads to an increase in job accessibility for every mode of transport, as opposed to the decreases in the disaggregated baseline models. Moreover, accessibility inequalities are seen to decrease in the aggregate Hansen-based model (-34%), contrasting the findings for the disaggregated model (+2%). A similar, albeit stronger, decrease in inequalities is observed in the aggregate Shen-based model (-24%).

The results of the analysis show reduced sensitivity to the impact of hybrid teleworking on job accessibility levels and social inequalities using conventional indicators that ignore subgroup-specific variations in travel budgets, job supply, and job demand. The occupational and educational job matching approach in the disaggregated measure yields smaller and more nuanced results, and job competition effects among the population are stronger. At the same time, aggregate job accessibility measures may consequently overestimate job accessibility for every individual within the population. Similarly, conventional accessibility measures present a rather optimistic picture regarding social inequalities, where overall more equitable distributions of job accessibility are observed. Consequently, the actual impacts of job accessibility on social inequalities may be worse that what is captured through the measure.

Table 9: Development of median job accessibility per mode of transport and accessibility measure, including the Gini-index (G_i) for generalised job accessibility

			Generalised				Car		PT		Bike	
	Measure	Model	**Median**		G_i		**Median**		**Median**		**Median**	
Hansen	***Baseline (disaggregated)***	PA_i	7225	*(100)*	*0.44*	*(100)*	10672	*(100)*	66	*(100)*	940	*(100)*
		HA_i	10160	*(141)*	*0.45*	*(102)*	13850	*(130)*	9688	*(14679)*	1323	*(141)*
		Difference $(HA_i - PA_i)$	2141	*40%*	0.01	*2%*	1917	*30%*	8283	*14579%*	287	*41%*
	Aggregated measure	PA_i	205542	*(2845)*	0.35	*(80)*	283523	*(2657)*	142878	*(216483)*	26980	*(2870)*
		HA_i	1244054	*(17219)*	0.23	*(52)*	1810241	*(16963)*	286310	*(433803)*	159022	*(16917)*
		Difference $(HA_i - PA_i)$	1031981	*505%*	-0.12	*-34%*	1507585	*538%*	141799	*100%*	128451	*489%*
Shen	***Baseline (disaggregated)***	PA_i	0.897	*(100)*	0.34	*(100)*	1.127	*(100)*	0.826	*(100)*	0.115	*(100)*
		HA_i	0.788	*(88)*	0.31	*(91)*	1.063	*(94)*	1.195	*(145)*	0.106	*(92)*
		Difference $(HA_i - PA_i)$	-0.096	*-12%*	-0.03	*-9%*	-0.242	*-6%*	0.711	*45%*	-0.015	*-8%*
	Aggregated measure	PA_i	1.153	*(129)*	0.17	*(50)*	1.579	*(140)*	0.830	*(100)*	0.159	*(138)*
		HA_i	4.467	*(498)*	0.13	*(38)*	6.451	*(572)*	0.896	*(108)*	0.615	*(535)*
		Difference $(HA_i - PA_i)$	3.233	*287%*	-0.04	*-24%*	4.759	*309%*	0.055	*8%*	0.447	*287%*

5. Discussion

5.1. Interpretation of results

The integration of hybrid teleworking in both the Hansen and Shen accessibility models results in a notable shift in the distribution of job accessibility among the population and over space. When job competition is not accounted for, hybrid teleworking leads to an increase in job accessibility (41%); however, this effect reverses when competition is considered (-12%). This research emphasizes prevailing uncertainties in academic literature surrounding the impact of hybrid teleworking on job accessibility. The findings contrast the work of Cavallaro and Dianin (2022) and Shen (1998), who found both increases and decreases in spatial accessibility. The results also directly oppose Muhammad et al.'s (2008) observations, where hybrid teleworking enhanced job accessibility, irrespective of competition effects.

The discrepancies in results can initially be traced back to Shen's (1998) and Cavallaro and Dianin's (2022) assumptions about the teleworkability of occupations. Respectively, only 12% and 6% of job opportunities were considered suitable for telework, compared to 29% found in this study (appendix N), potentially yielding subtler and more spatially varied impacts of hybrid teleworking within their research. However, the primary effect of these differences between the studies can be attributed to their use of more aggregate job accessibility measures and spatial scales, which introduces the Modifiable Areal Unit Problem (MAUP). The use of higher resolution data can provide more accurate accessibility insights and reduces susceptibility to ecological fallacies (Neutens, 2015). The comparative analysis on (dis)aggregate measures, showing quantitative and qualitative shifts in the impact of hybrid teleworking and the detection of inequalities based on the measure employed, demonstrates the MAUP. This indicates that hybrid teleworking is seen to enhance job accessibility with aggregate measures, aligning with Muhammad et al.'s (2008) observations and substantiating the contrasting findings. Nonetheless, the Hansen- and Shen-based results do conform with the findings that larger urban agglomerations maintain prominent position with hybrid teleworking included (Muhammad, de Jong, & Ottens, 2008; Shen, 1998; Cavallaro & Dianin, 2022), indicating that hybrid teleworking does not change the spatial distribution drastically.

Although ICTs have been theorized to balance out spatial disparities in job accessibility, a concept known as locational equalization (Shen, 1998), no evident impact of this is observed at the national level within the Netherlands. In line with Shen's (Shen, 2000) findings, the spatial distribution of hybrid accessibility remains similar to its physical pattern. Yet, the homogenization of the spatial pattern of job accessibility between regions may manifest at a local scale, albeit potentially in a subtle manner that may be overlooked from a national viewpoint. The findings of this study further contradict the emergence of an opposing effect observed by Shen (Shen, 1998), spatial polarization, at least when competition effects are considered. In the context of the Hansen-based model, the inherent regional differences in economic densities, i.e. job supply, amplifies spatial disparities in job accessibility within the Netherland and thereby increases spatial polarization between these regions. However, when job competition is taken into account, the integration of hybrid teleworking results in a more uniform decline in job accessibility levels across the country. Consequently, already present spatial disparities between the highly urbanized and non-urbanized regions within the Netherlands persist, which suggests that hybrid teleworking does not intensify the current spatial divides. The absence of observed spatial homogenization or polarization in the distribution of job accessibility, does not provide evidence that hybrid teleworking in job accessibility measurements leads to exacerbation or alleviation of existing spatial inequalities.

Yet, the most significant impacts of hybrid teleworking arise from changes in job competition, which become particularly evident when examining the social distribution. Intrinsically, individuals with characteristics that inhibit their ability to telework (e.g. lower education levels or blue-collar occupations) experience less accessibility benefits from hybrid teleworking in the Hansen-based model compared to other individuals, and vice versa. However, when competition effects are considered, this pattern changes and the emergence of job accessibility inequalities is no longer directly related to the individual's (in)ability to telework but are shaped by the occupational and educational mismatch between supply and demand for hybrid job opportunities. Competition for jobs thereby largely dictates whether hybrid teleworking will lead to actual improvements or worsening of individual-level job accessibility. Particularly those who firstly experienced high job accessibility (high educated individuals in teleworkable jobs) are more negatively impacted by hybrid teleworking by enhanced competition effects which penalizes their initial advantageous position on the job market. As many high-skilled job opportunities are predominantly clustered in economic dense urban areas, competition may be relatively stronger among these individuals (Geurs & Ritsema van Eck, 2003). Moreover, the reduction of the Gini-coefficients for almost every occupational class and the population as a whole in the Shen-based model reveals that hybrid teleworking leads to a more equitable distribution of job accessibility. Surprisingly, socio-economically disadvantaged groups see relative job accessibility gains compared to white-collar individuals, leading to social convergence, countering the findings of Shen (1998). Thus, from an egalitarian perspective, job competition results in an unchanged effect of hybrid teleworking on spatial inequalities, however, more equitable distribution of job accessibility is found looking at the social dimension.

5.2. Limitations and further research

This research contains some methodological limitations that may affect the validity of the results. Firstly, the integrity of the data is potentially compromised by the data synthesis approach. Residential modelling of workers, influenced by individual-level factors such as work location and teleworking ability (Muhammad, Ottens, Ettema, & De Jong, 2007b), is considered a study on itself, often tackled by economic geographers through the use of (macro)economic models (Deitz, 1998). Therefore, the simplistic worker synthesis method, which randomly allocates occupations based on socio-demographic variables without considering environmental factors, may introduce bias with regards to the residential locations of workers per occupational class. Consequently, the presented results might not fully represent actual potential job accessibility patterns of groups within the workforce.

The difference in the specification of the occupation-specific physical decays and general hybrid decays due to data limitations, may not be most suitable for every occupational class and therefore imposes a second limitation within this research. For occupational classes predominantly composed of blue-collar workers, who may be less inclined to make lengthy commutes, there may be an overestimation of their spatial search range for potential job opportunities in the hybrid scenario. Application of general hybrid decays may therefore have resulted in unrealistic increases in job accessibility for those individuals, but also incur biases for occupational classes that actually have a more subtle decline of the decay function. In case of repetition of this research, efforts should be made to include occupation-specific hybrid decay functions.

Furthermore, the proposed weighed hybrid job accessibility model assumes that the degree of teleworking is solely determined by the individual work situation, such as nature of the work, work environment and organisational support of the employer. Yet, personal attitudes and circumstances towards teleworking are similarly influential factors (Olde Kalter, Geurs, & Wismans, 2021). Overlooking these factors may result in an overestimation of the demand-oriented competition effects for hybrid job opportunities and job accessibility for a substantial proportion of the population. Further refinement of the model that accounts for individual-level teleworking potential is recommended.

The fourth limitation in this study is related to the accuracy and applicability of the Shen-based competition component in the measurement of hybrid job accessibility. Muhammad et al. (2008) argue that the Shen-based model falls short in assessing hybrid job accessibility on a national scale, particularly in capturing interregional job competition accurately. Their claim largely arises from differing assumptions regarding the travel behaviours of (hybrid) teleworkers compared to this study. However, while this perspective may be valid for full teleworkers, this assumption is potentially less applicable for hybrid teleworker for whom physical proximity to job opportunities remains relevant. Nevertheless, Geurs and Ritsema van Eck (2003) present another critique on competition in the Shen-based model. They conclude that the Shen-based potential accessibility measure overestimates competition effects, particularly in areas with high supply of jobs. Not only is it seen that worker-side demand for opportunities becomes less pronounced when many alternative opportunities become available (Neutens, 2015), yet job competition also commonly occurs between employers for workers (Geurs & Ritsema van Eck, 2003). Single-sided competition effects captured by the gravity-based models are therefore not most suitable for measuring (hybrid) job accessibility. Further work should explore the use of doubly constrained spatial interaction model with inverse balancing factors at the residential and employment location to capture individual-level job accessibility levels more accurately.

Moreover, the generalised job accessibility models present the combined effect of job accessibility by car, public transport, and bike, weighted by the modal split of the corresponding occupational class. Yet, this method of aggregation may present unreliable aggregated results since modal choice may not only be determined by socio-economic backgrounds, but also the spatial location and availability of (public) transport options. Preferably, aggregation based on social- and location-dependent modal splits would improve the method of aggregation.

For more nuanced insights on the impact of teleworking on socio-spatial job accessibility inequalities, it is crucial to consider the heterogeneity of workers and temporal dynamism in the accessibility measure. Although outside of the scope of this research, the accessibility measures do not capture accessibility of part-time workers, self-employed workers, or full-time teleworkers. As part-time workers are observed to have lower teleworking rates, self-employed individuals significantly telework on a regular basis (Sostero, Milasi, Hurley, Fernandez-Marcias, & Bisello, 2020) but respectively account for 12% and 48% of the Dutch workforce (CBS, 2022b; CBS, 2023). Besides, around 14% of the employed Dutch workforce is considered a full-time teleworker (CBS, 2020). Thereupon, cross-border commuting and versatility in employment, such as the ability to find employment in other occupational classes or education levels, have not been considered in the job accessibility model. Similarly, as hybrid teleworking comes with more temporal flexibility compared to physical workers (Mustafa & Gold, 2013), it is important to consider temporal variability of job accessibility scores as seen in Pritchard et al. (2019c), especially when considering job accessibility inequalities. Further research can be dedicated to refining the job accessibility measure for these three worker types and including temporal dynamics to enhance the model's accuracy.

Lastly, the presented results on the spatial distribution of job accessibility may not be accurate for isolated zones or border regions within the Netherlands. Job accessibility scores on the Wadden Islands and less developed regions within the Netherlands may have been disproportionately disadvantaged due to falsely assumed influx of hybrid working competitors from the mainland or areas of higher economic significance. Agglomeration economies found within urban areas may attract more workers compared to more isolated regions, resulting in potential overestimation of demand for jobs. Yet such nuances in locational preferences for job opportunities could not be captured by the gravity-based job accessibility models.

6. Conclusion

The integration of ICTs in everyday lives over the last decades has sparked a paradigm shift in job accessibility modelling. Given the increasing prevalence of teleworking, concerns arise about potential job accessibility disparities that may arise between those who can and those who cannot telework. This paper aims to advance further on current accessibility modelling practises through the development of a novel disaggregated agent-based job accessibility framework. This framework integrates hybrid teleworking, job matching, and competition effects. In addition, this study aims to investigate the spatial and social distribution of job accessibility at the individual-level and emerging job accessibility inequalities among population groups. This research provides an answer to the following research question: *"How can a job accessibility measure that incorporates hybrid teleworking be constructed, and how does hybrid teleworking influence job accessibility inequalities among groups within the Dutch workforce?"* Thereby, four sub-questions have been formulated.

The first sub-question concerns *"What is the definition of hybrid teleworking and what factors are of influence on the degree of teleworking?"* The academic literature review has shown that (hybrid) teleworking is defined in various ways across multiple disciplines and often is confused with related terms such as telecommuting, remote work and virtual work. In this study, hybrid teleworking is operationalized as partial home-based work using ICTs by employees under a formal contractual agreement with an employer. Identified drivers and barriers directly influencing the uptake of telework are related to factors in the individual work situation, socio-demographic characteristics of the individual and initial travel behaviour. These factors are further influenced by broader macro- and meso-level trends, such as globalisation and national policies related to telework. Thereby, an increased ability to telework positively influences individual-level job accessibility.

The second sub-question on *"How can a hybrid job accessibility measure with competition effects be constructed for different socio-demographic groups?"* delves into the methodological rationale and formulation of a job accessibility that jointly considers physical travel to work and hybrid teleworking. By extending a gravity-based accessibility measure with occupational and educational job matching, demand-oriented cross-modal competition effects and a decay function sensitive to t-days teleworking per full-time work week, a weighted hybrid job accessibility measure has been constructed. The measure captures individual-level job accessibility, refined for every occupational class and education level in the population by car, public transport, bike and generalised through aggregation over the three modes.

To answer the third sub-question, *"To what extent does teleworking lead to socio-spatial discrepancies in access to job opportunities compared to a physical accessibility measure?"*, the distribution of physical and hybrid job accessibility is explored both spatially and socially, generalised and per mode of transport. Spatially, hybrid teleworking leads to a 40% median increase and 12% decrease in job accessibility levels for the Hansen- and Shen-based models respectively, with overall similar trends visible per mode of transport. Yet, as hybrid teleworking does not alter the underlying spatial pattern of job accessibility, no improvement or worsening of already existing spatial inequalities is found, at least when competition effects are considered. However, without competition effects, individuals in the most economically dense urban regions experience stronger accessibility benefits than those in the peripheral regions, indicating an increase in spatial inequalities. From a social perspective, analysis of the Gini-indices reveals that hybrid teleworking leads to a worsening of social inequalities by 2,2% without competition effects but is seen to improve by 8,8% when job competition is considered and leads to an overall more equitable distribution of job accessibility.

The comparative analysis for the last sub-question, *"What is the impact of an aggregate job accessibility measure on the distribution of physical and hybrid job accessibility?"*, shows that the employment of a conventional aggregate job accessibility measure yields higher job accessibility levels, both with and without competition effects, and stronger impacts of hybrid teleworking on social inequalities, where in both scenarios, hybrid teleworking results in a strong improvement of social job accessibility inequalities (34% and 24% respectively) compared to the disaggregated job accessibility measures.

With the development and application of the novel weighted hybrid job accessibility measure, this research has shown how hybrid teleworking impacts both spatial and social inequalities in the Dutch context. While hybrid teleworking inherently enhances access to job opportunities for most individuals in the population, the accessibility benefits are mostly experienced by those that are well able to telework and live in regions of already high economic significance. In a job market without competition, hybrid teleworking would therefore enlarge existing both spatial and social inequalities. Yet, its impact on job accessibility inequalities is not predominantly determined by spatial location or the teleworkability of the individual's occupation. Instead, intensified competition on the job market between workers is seen to play a most significant role. The spatially uniform impacts of job competition indicate that hybrid teleworking does not exacerbate existing spatial inequalities within the Netherlands nor bridge the accessibility divide between urban accessibility-rich and rural accessibility-poor regions. On the social side, the initially advantaged hybrid teleworker finds itself in a highly competitive world where digital access to job opportunities offers more diversity of jobs but does not necessarily lead to better prospects for employment. The additional reduced effect of job competition on hybrid workers with limited teleworkability results in a relative improvement of their positions on the job market and reduces the social disparities in job accessibility levels among the general workforce and various socio-economic population groups.

This research has shown the application of the pioneering agent-based weighed hybrid modelling framework in a Dutch context and presents it as an innovative instrument for researchers, planners, and policymakers for the appraisal of physical and hybrid accessibility and inequalities. The model enhances understanding of hybrid teleworking on job accessibility levels and highlights the importance of using disaggregated data over generalised measures. It also extents current discourse on the influence of ICTs on accessibility and opens opportunities for its consideration in the appraisal of transportation and land use developments and policy making, such as its linkage to broad-based prosperity and chances for individuals to thrive in society and its adoption in urban planning as "the 15-minute city" concept. In the light of future trends, the potential further adoption of hybrid teleworking, the increasing digitalization of society and activities and external influences such as tele-migration in the globalised job market, it is crucial for decision-makers to consider digital connectivity to (job) opportunities in the assessment of accessibility and develop protectionist policies to avoid potential deterioration of accessibility inequalities.

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