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https://doi.org/10.1016/j.scs.2021.103039

BIM-enabled multi-level assessment of age-friendliness of urban housing based on multiscale spatial framework: enlightenments of housing support for "aging-in-place"

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Declaration of interests

None.

Acknowledgement

This study was funded by the Department of Building and Real Estate at The Hong Kong Polytechnic University. The authors are grateful to all experts who participated in the research survey, and researchers who offered valuable suggestions to this study.

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Abstract

The worldwide population of the elderly has increased rapidly. Housing issue is regarded as the main barrier to implementing "aging-in-place", which is a recommended strategy to encourage the elderly to age in their residences. Although many studies have contributed to age-friendly cities and communities, few studies have focused on measuring housing age-friendliness with consideration of urban spatial scales. This study proposes a multiscale spatial framework of housing and develops a multi-level assessment of housing age-friendliness based on literature review and fuzzy-analytic hierarchy process (AHP). The multi-level assessment of age-friendliness takes advantage of building information modeling (BIM) to simplify the computation process of the housing age-friendliness index (HAFI). The feasibility of BIM-enabled multi-level assessment is proved by comparative analysis of two housing examples. Results of HAFI and sub-HAFIs indicate housing may perform variously with spatial levels. This study contributes to developing the age-friendly performance assessment for housing by considering various significances of housing characteristics in multiple spatial levels. The BIM-enabled multi-level assessment is an effective tool to help the elderly choose more appropriate housing, assist the government in allocating suitable public housing for aged applicants, and provide property developers and local governments with additional guidelines for housing design and urban renewal.

Keyword: urban housing; age-friendliness; multiscale spatial framework; multi-level assessment; building information modeling; aging in place.

1. Introduction

Population aging has become a primary global concern. The *World Population Prospects 2019* stated that 9% of the global population is over 65 years old and forecasted that this would increase to 12% and 16% in 2030 and 2050, respectively (United Nations, 2019). The majority of the population in many countries is projected to be aged 65 years or above by 2050 (Fig. 1). Governments have to face many social problems, such as the shortage of pension, changes in population structure, and re-employment of the elderly (Steels, 2015), for achieving successful aging, which means low probability of disease, high cognitive and physical functional capacity, and active engagement with life (Rowe & Kahn, 1997).

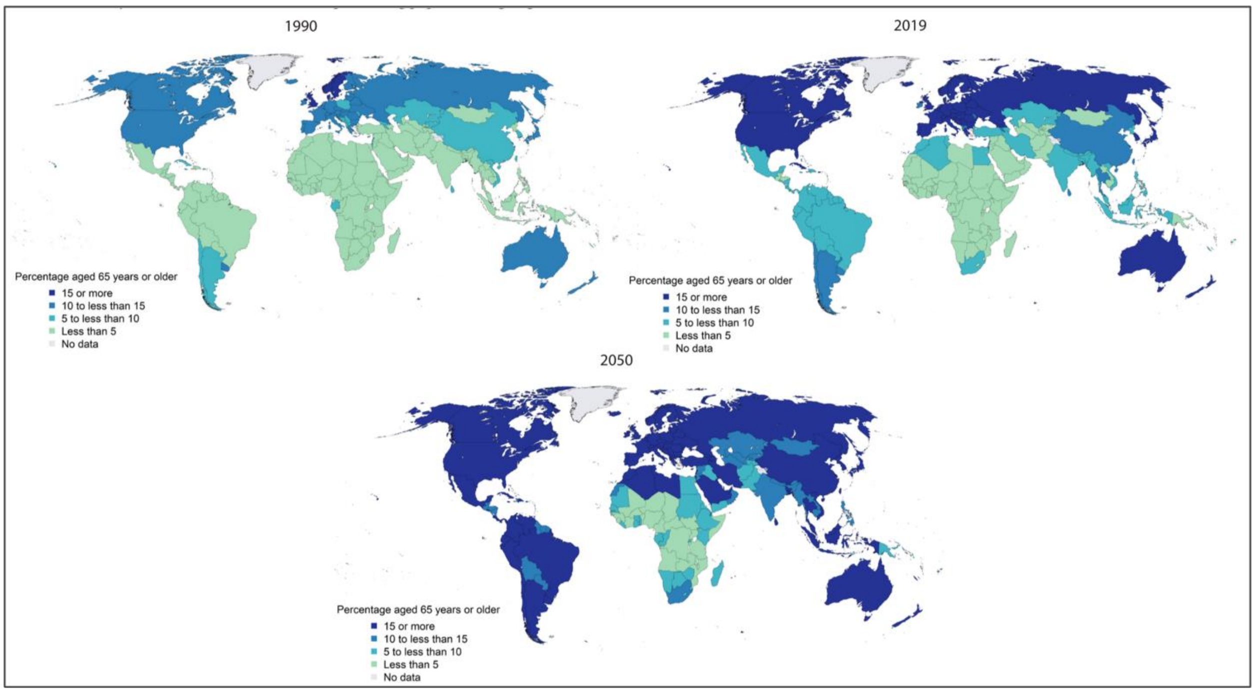

Fig. 1. Percentage of population aged 65 years or over in 1990, 2019, and 2050 (United Nations, 2019)

"Aging-in-place", the most popular mode of living of the elderly, has already been accepted by many individuals and governments in the world (Iecovich, 2014; Serrano-Jiménez, Lima, Molina-

Huelva, & Barrios-Padura, 2019). “Aging-in-place” encourages the elderly to live in their familiar environment with some level of dependence, rather than move to professional care facilities and institutions (Iecovich, 2014). “Aging-in-place” is regarded as the most humane and cost-effective way for the elderly to grow old (Stephen M Golant, 2015; Iecovich, 2014; Jayantha, Qian, & Yi, 2018), since it benefits individuals by saving expenses and improving the level of privacy and dignity, and also help local governments to release pressure to meet huge requirements on care institutions (Wiles, Leibing, Guberman, Reeve, & Allen, 2011). According to several years of practice in many cities, the biggest barrier to promoting “aging-in-place” is that many older adults’ housing conditions are not eligible to support later lives (Golant, 2015). On the one hand, some old housing was built following out-dated standards; on the other hand, the housing suitability for all ages is seldom considered by both developers and individuals. Once individuals notice they cannot continue living comfortably and independently in current housing in the following days, they have to move to another unfamiliar place; otherwise, they will live in inconvenience and danger. It means that housing must be adequate to accommodate the needs of the elderly for enabling aging-in-place (Luciano et al., 2020).

Therefore, it is essential to measure the housing age-friendliness for checking in advance if the housing is eligible for later lives. It would benefit stakeholders, whether the government, developers or the elderly. In the practice of public housing, the proportion of senior applicants has kept growing for the past years. As per the annual report of the Hong Kong Housing Authority[1], 33% of public housing applicants are over 60 years old. Experts have appealed to concern more

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[1] https://www.housingauthority.gov.hk/tc/common/pdf/about-us/housing-authority/ha-paper-library/SHC68-18TC.pdf

about public housing problem of low-income older people (Breysse, Dixon, Jacobs, Lopez, & Weber, 2015; Stephen M. Golant, 2003; Gu, Li, & Li, 2018). Age-friendliness of public housing can provide evidence for the government to allocate the most appropriate housing to senior applicants. Moreover, given that the proportion of older adults will keep increasing in the future, developers of housing projects should consider more older adults' living requirements during the process of development. To individuals, more people prefer aging-in-place, the age-friendliness of housing would be one of the main indexes to assist them in selecting appropriate housing to support later life.

However, it is hard to evaluate and improve the housing's age-friendliness systematically without a convenient assessment. For now, *Global age-friendly cities: A guide* (WHO, 2007) and *Measuring the age-friendliness of cities: A guide to using core indicators* (WHO, 2015) developed by the World Health Organization (WHO) are widely used to assess the age-friendliness of cities and instruct the development of age-friendly cities. Even though housing attributes are mentioned partly in city-scale measurement of age-friendliness, WHO guidelines are still not entirely applicable to assist in future housing development to cope with global aging problem, since focal objects of these guidelines are generally cities and communities, rather than housing. Housing is also a large and complicated system containing many components and elements under different spatial scales, such as the location in the city scale, supporting facilities in the block scale, and indoor design in the home scale. It is not easy to know which components and elements should have priority in the decision-making of housing planning, housing design, housing maintenance, and even housing allocation. There is still a lack of complete measurement or assessment for the age-friendliness of housing, considering the significance of multiple spatial scales (Mercader-Moyano, Flores-García, & Serrano-Jiménez, 2020).

Consequently, this study aims to develop a multi-level assessment to measure the housing age-friendliness, extending the traditional age-friendly assessment of housing from the perspective of spatial scales. Finally, the assessment result, namely the housing age-friendliness index (HAFI), can be adopted by stakeholders as evidence to facilitate the successful aging-in-place.

The multi-level assessment of age-friendliness requires considerable data on housing. The computation would be a heavy workload and time-wasting in a traditional manual way. With the rapid development of building information modeling (BIM) techniques, more dimensional life-cycle data of buildings are stored and more analysis functions are realized in BIM. Besides 3D data of architectural modeling, structural modeling, mechanical, electrical, and plumbing (MEP) modeling, and construction modeling, BIM can extent to 4D modeling by adding time-series data, 5D modeling by adding cost information, 6D modeling by adding operation data, etc. Therefore, owing to life cycle data of buildings and robust data analyses that BIM can offer, this study adopts BIM to optimize the computation of the multi-level assessment.

This paper is organized as follows. Section 2 conducts the literature review about age-friendliness and BIM applications in housing assessment; section 3 proposes the multiscale spatial framework for housing, develops the multi-level assessment of housing age-friendliness, and makes the computation process of HAFI. Section 4 presents the results of age-friendliness assessment of two housing examples. Section 5 discusses the comparison of age-friendliness of different housings and recommends the utilization of the multi-level assessment of housing age-friendliness to individuals, local governments, and property developers. Section 6 concludes the contents of this study, and points out its theoretical and practical implications, limitations and following research.

2. Literature Review

2.1 Age-friendly housing, community and city

In 2006, WHO proposed the concept of "age-friendly city (AFC)" (Menec, Newall, & Nowicki, 2016). WHO launched the "AFC Initiative" in 2005 (Wong, Chau, Cheung, Phillips, & Woo, 2015), then released an official guideline called "*Global age-friendly cities: A guide*" in 2007 (WHO, 2007). WHO gave the official definition of age-friendly city in this guide as

> *"policies, services, settings and structures support and enable people to age actively by: recognizing the wide range of capacities and resources among older people; anticipating and responding flexibly to ageing-related needs and preferences; respecting their decisions and lifestyle choices; protecting those who are most vulnerable; and promoting their inclusion in and contribution to all areas of community life" (WHO, 2007).*

This WHO guideline only provided checklists for age-friendly cities' development. Furthermore, WHO conducted a structured approach between 2012 and 2015, and then published "*Measuring the age-friendliness of cities: A guide to using core indicators*" (WHO, 2015), determining a framework and a series of indicators to monitor the development of age-friendliness for each city's practice (Kano, Rosenberg, & Dalton, 2018). Until now, the framework and indicators offered by WHO guidelines are regarded as the most authoritative basis to measure the age-friendliness of cities. The performance of an age-friendly city is evaluated in seven aspects: outdoor spaces and buildings, transportation, housing, social participation, respect and social inclusion, civic participation and employment, communication and information (WHO, 2007, 2015).

Based on WHO guidelines, many studies were conducted in different areas. For instance, the age-friendliness of various neighborhoods is measured, and then the demographic and socio-economic characteristics are introduced to explain differences in age-friendliness among neighborhoods (Wong et al., 2015). Qian et al. used WHO guidelines to quantify the age-friendliness of eight districts in Hong Kong for detecting the relation between age-friendliness and sustainability (Qian, Ho, Ochoa, & Chan, 2019).

Apart from WHO guidelines, there are several official tools from other institutions, like Visiting Nurse Service of New York (VNSNY) and American Association of Retired Persons (AARP). In the AdvantAge Initiative framework of VNSNY[2], essential elements of age-friendly communities are divided into four domains: elements addressing basic needs; elements improving physical and mental health and well-being; elements maximizing independence for the frail and persons with disabilities; elements promoting social and civic engagement (Evans, Oberlink, & Stafford, 2020). AARP evaluates the livable communities in eight aspects: transportation, walking, safety and security, shopping, housing, health services, recreation and culture, and caring and mutual support (Kihl, Brennan, Gabhawala, List, & Mittal, 2005).

Since the concept and measurement of age-friendliness and its quantitative measurements are the critical basis of further researches, researchers also contributed to re-understanding age-

[2] https://apps.vnsny.org/advantage/advantage.html

friendliness. The ecology theory explicitly emphasizes the relations between environment and individuals, just similar to age-friendliness. “Age-friendly communities” was conceptualized under the particular perspective of ecology, and interrelation among indicators was reconsidered (Menec, Means, Keating, Parkhurst, & Eales, 2011). Another age-friendly environment assessment tool (AFEAT) was developed to gauge the elderly’s perception of communities by using the WHO checklist as the foundation. Differently, the AFEAT focuses on individual-oriented age-friendliness with the consideration of individual environment interaction (Garner & Holland, 2020).

As mentioned above, most existing assessments of age-friendliness were implemented in a larger scale, like communities and cities. Such assessments for cities and communities are not quite suitable for assessing housing and prioritizing housing interventions (Luciano, Pascale, Polverino, & Pooley, 2020). In the microscopic view, studies about age-friendly housing usually focus on indoor components, such as age-friendly interior design, universal design, applications of smart techniques, and other indoor attributes of housing. Few studies explicitly outline a standard of housing to achieve, and interventions on buildings may be inconsistent without leading to the desired rise in living standards (Luciano et al., 2020). However, besides indoor housing attributes, housing also has outdoor attributes within communities, neighborhoods, regions, and even cities. Housings located in different floors, orientations, buildings, and even in different neighborhoods, districts, regions, may perform quite differently in age-friendliness, because the age-friendly performance is jointly determined by attributes from different spatial levels. Only one recent study considered different spatial scales of dwelling and neighborhood during assessing the built environment for the elderly (Mercader-Moyano et al., 2020). The summary of the main guidelines and literature about age-friendliness (Table 1) reveals a lack of a comprehensive approach to assessing housing age-friendliness considering its attributes in multiple spatial scales.

Table 1

The summary of main literature and guidelines about age-friendliness

Main literature/guideline	Source	Purpose	Outcome	Spatial scale
AdvantAge Initiative framework	https://apps.vnsny.org/advantage/advantage.html	To know older adults' perceptions and experiences in their communities, identify barriers to aging-in-place, and plan for action to make their communities better places to live for older adults and their families.	An original framework, a set of indicators to measure how well communities are supporting older residents' needs, a consumer survey questionnaire, and a process to engage community stakeholders.	Community
Livable communities: An evaluation guide	(Kihl et al., 2005)	To help community volunteers to look into their own communities for promoting livability for persons of all ages and abilities.	A Community Survey.	Community
Global age-friendly cities: A guide	(WHO, 2007)	To provide a universal standard for an age-friendly city.	A set of checklists of age-friendly city.	City
Measuring the age-friendliness of cities: A guide to using core indicators	(WHO, 2015)	To monitor and evaluate progress in improving the age-friendliness of urban environments.	A framework of age-friendliness of cities and a set of core and supplementary indicators.	City
Conceptualizing age-friendly communities	(Menec et al., 2011)	To make explicit key assumptions of the interplay between the person and the environment and conceptualize age-friendly community by applying ecological perspective.	Age-friendly community's conception and five ecologic principles.	Community
Age-friendly environment assessment tool	(Garner & Holland, 2020)	To assess individual function and frailty impact on perceptions of environmental age-friendliness.	Age-friendly environment assessment tool (AEFAT).	City
Multidimensional Assessment System of the Built Environment (MASBE)	(Mercader-Moyano et al., 2020)	To provide an integral diagnosis on the perceived suitability of urban and housing environments for the elderly.	35 multidisciplinary variables and their weights	Multiple scales

Measuring Age-Friendly Housing: A Framework	(Luciano et al., 2020)	To offer in-depth identification of housing features relevant for older adults and decision support system for stakeholders.	A tool to assess the age-friendliness of housing.	Housing

2.2 Applications of BIM in the housing assessments

Numerous data are required to assess the housing age-friendliness and offer enough tangible actions or recommendations for planners and policymakers (Ruza, Kim, Leung, Kam, & Ng, 2015). Digital techniques have been utilized to facilitate the data collection and accelerate the computation process of the assessment in actual projects. For instance, the research team of Stanford University adopted Web-based geographic information system (GIS) to enrich the rigidity of the evaluation of age-friendliness of cities (Ruza et al., 2015). Another Web-based GIS platform was designed to assess and monitor the citywide dynamic age-friendliness by seven criteria (Jelokhani-Niaraki, Hajiloo, & Samany, 2019).

The appearance of BIM significantly facilitates the information revolution in AEC/FM industry (Liu, Lu, & Peh, 2019; Santos, Costa, & Grilo, 2017). By making processes more efficient and results more precise (Hollberg, Genova, & Habert, 2020), BIM has been widely applied in housing assessments, such as life-cycle assessment (LCA), building sustainable assessment (Ilhan & Yaman, 2016; Jalaei, Jalaei, & Mohammadi, 2020; Sanhudo & Martins, 2018), green building assessment (Ansah, Chen, Yang, Lu, & Lam, 2019), energy performance assessment, indoor environment performance assessment, post-occupancy evaluation (POE). For example, at the early stage of design, the integration of BIM and authoritative criteria of green building helps check the sustainable performance of design schemes automatically, then provides evidence for decision-making (Jalaei, Jalaei, & Mohammadi, 2020).

Since the housing assessments usually involve interdisciplinary analyses, BIM is an effective platform to share, exchange and then integrate buildings' interdisciplinary information (Utkucu &

Sozer, 2020). The utilization of BIM is proved to significantly optimize the traditional assessment flow by integrating Multi-source data via plug-ins of Revit and independent software (Carvalho, Braganca, & Mateus, 2019). Templates or plug-ins for Revit and automated processes combining different data and software are frequently-used methods in the BIM-based LCA (Soust-Verdaguer, Llatas, & García-Martínez, 2017). A dynamic LCA model is developed based on the time-series data of buildings provided by BIM, for reducing the time and effort on collecting data (Su, Wang, Han, Hong, & Liu, 2020). The sensing data detected by environment sensors are imported to the BIM platform to analyze the indoor environment performance, such as thermal performance, ventilation performance (Natephra, Motamedi, Yabuki, & Fukuda, 2017). During the POE, complex procedures are included, and information of POE is isolated among different stakeholders. BIM helps store various data in the same standard so that stakeholders can benefit from new POE procedures and data exchange via BIM (Gonzalez-Caceres, Bobadilla, & Karlshøj, 2019).

BIM techniques have been widely applied in different types of housing assessments. As is well known, age-friendliness is a comprehensive aspect of housing performance as well. Even though the housing age-friendliness is complicated and time-wasting to be evaluated, BIM techniques are seldom applied in the assessment of age-friendliness. Therefore, this study initiates the computation of HAFI based on BIM utilization.

3. Research methodology

The research methodology consists of three main steps. Step 1 proposes the multiscale spatial framework of housing; step 2 develops the multi-level assessment of housing age-friendliness with determinations of indicators and weights; step 3 provides BIM-based computation method of

HAFI and sub-HAFI by integrating multi-source data. The logic of the research methodology is shown in Fig. 2. Each step in the methodology is elaborated in detail as follows.

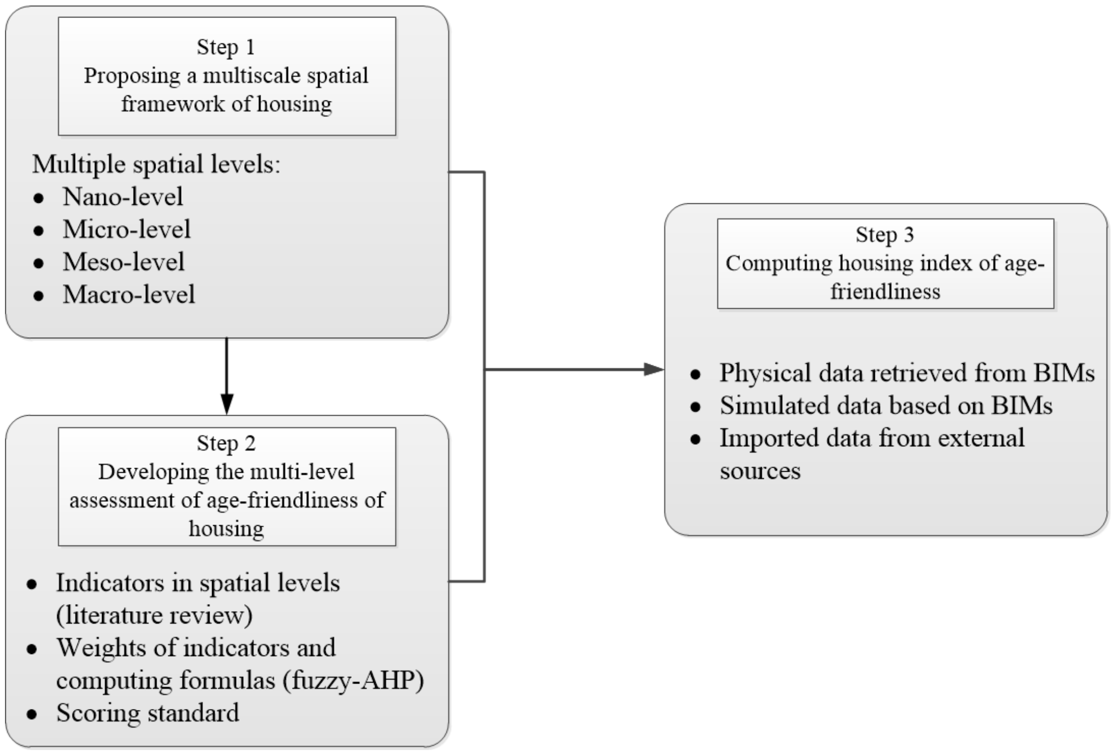

Fig. 2. The flowchart of the research methodology

3.1 The multiscale spatial framework of housing

Even though the individual lives in a particular place, he/she usually ranges around home and workplace daily. Owing to the retirement and decline of their mobility, daily activity areas of the elderly shrink significantly. Previous studies considered the elderly's living environment on multiple spatial scales, containing home scale, the neighborhood scale, and region/city and beyond scale (B. P. Loo, Lam, Mahendran, & Katagiri, 2017; Zhang, Li, Ahrentzen, & Feng, 2020). Thus, the attributes of housing belong to different spatial scales as well. Given that older adults are quite sensitive to spatial distance, transition areas connecting indoor areas of homes and outdoor public spaces should not be ignored. Finally, this study proposes a multiscale spatial framework of housing (as shown in Fig. 3). The four spatial levels are described in detail as follows.

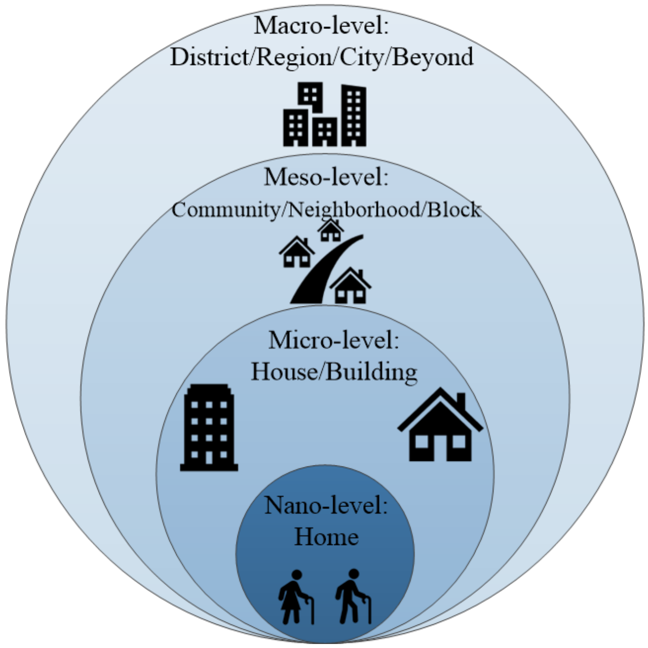

Fig. 3. The multiscale spatial framework of housing

- Nano-level

The nano-level of housing refers to the space inside the home or apartment, exactly where individual lives daily. Generally, the home is divided into several independent spaces, like living room, bedroom, dining room, kitchen, bathroom, balcony, and storeroom. Each separate area should be designed and equipped well for living.

- Micro-level

People cannot enter their living space from communities or neighborhoods directly. There is always a transition area between daily living space and outdoor social space. Usually, the micro-level of ordinary multi-story residential buildings refers to public areas outside the home, but inside the building, such as the entrance hall, lobby, elevator hall, staircase, and corridor. Regarding the single-family house or villa, the private area just around the house and villa is regarded as the micro-level range, such as private garden, lawn, private swimming pool, and private roads.

- Meso-level

The community, neighborhood or block near the housing is regarded in the meso-level. Older adults require to go outsides for a certain period, so their spheres of daily activities are normally within the familiar nearby areas of communities and neighborhoods, like community facilities, green spaces, street networks and pavements.

- Macro-level

At last, the macro-level refers to beneficial areas to the elderly within the district, region, city, or beyond. Older adults cannot obtain all essential resources within their neighborhoods. The utilization of municipal hospitals, municipal services, regional transportation hubs, and other civil infrastructure is also a part of the elderly's life.

3.2 Multi-level assessment of housing age-friendliness

(1) Determining indicators of multi-level assessment

First of all, indicators used to measure age-friendliness are retrieved from documents and literature. WHO guidelines of *Global age-friendly cities: A guide* (WHO, 2007) and *Measuring the age-friendliness of cities: A guide to using core indicators* (WHO, 2015) are adopted as main materials to provide eligible indicators. Since WHO guidelines lacks the consideration of housing in the micro-level and nano-level, indicators in the micro-level and nano-level are supplemented by literature, such as neighborhood walkability (Cerin, Saelens, Sallis, & Frank, 2006), and the indoor walkability within the building (Shin & Lee, 2019).

Furthermore, since ways to group and categorize indicators are dissimilar among different guidelines and literature, indicators selected from diverse sources should be re-categorized for a uniform classification. For instance, Evans et al. have categorized the indicators of age-friendliness in their own way, which is quite different from the way of WHO guidelines (Evans et al., 2020). All selected indicators are assigned to the right levels according to the multiscale spatial framework; meanwhile, overlapped indicators should be deleted. All re-categorized indicators and their sources are listed in Table 2 in detail.

The scoring standard of indicators is developed to carry out this assessment in practice. The full mark of each sub-indicator is set as 10. Since all buildings should be designed and built in compliance with the latest official standards of civil buildings released by national or local government, the requirements on the part of indicators (labeled * in Table 2) are stated explicitly in official standards. Generally, official standards are updated periodically to adapt to the development, and buildings built before the release of new standards are possible to fail to meet the requirements of new standards. Mandatory requirements of the latest official standards are adopted as the baseline in the multi-level assessment. The scoring standard presented in Table A1 is developed based on the Chinese national standards of buildings, which should be replaced by other local standards for carrying out in other countries or regions.

Table 2

The multi-level indicators of age-friendliness in detail

Spatial levels	Indicators	Sub-indicators	Description	Source
Nano-level **(NA)**: Home	**NA_1** Affordability	-	The housing price is affordable for the elderly with a certain income.	(Evans et al., 2020; Kano et al., 2018; Kihl et al., 2005; Luciano et al., 2020; WHO, 2007, 2015)
	NA_2 Interior design	Indoor floors	The housing is with multiple floors (like duplex apartments, skip floors, loft) or single floor (like flat floor).	(Luciano et al., 2020; WHO, 2007)
		Layout	The topology of floor plan is convenient and flexible to adopt specific needs of the elderly.	(Luciano et al., 2020; WHO, 2007)
		Space*	Housing size is moderate for the elderly, sufficient and convenient to move around, and passage and doorways are large enough to accommodate a wheelchair.	(Luciano et al., 2020; Verena H Menec et al., 2011; WHO, 2007)
		Barrier-free design*	The interior design considers barrier-free requirements.	(WHO, 2007)
	NA_3 Indoor environment quality (IEQ)	Lighting*	The daytime illuminance of home meets local standards.	(Luciano et al., 2020; WHO, 2007; Tao, Gou, Yu, Fu, & Chen, 2020)
		Sunlight*	The duration of direct sunlight meet local standards.	(Luciano et al., 2020)
		Thermal environment*	The thermal design should meet local standards, and the necessary heating/cooling system is provided.	(WHO, 2007; Tao et al., 2020)
		Ventilation*	The indoor ventilation design meets local standards.	(WHO, 2007; Tao et al., 2020)
		Noise*	The acoustic environment meets local standards.	(WHO, 2007; Tao et al., 2020)
	NA_4 Equipment	Basic equipment *	Basic equipment is equipped for the elderly's daily life.	(Luciano et al., 2020; WHO, 2007)
		Safety equipment	Fire equipment and emergency equipment are equipped for the elderly's safety.	(Hong Kong Housing Society, 2005)
		Smart equipment	Smart equipment adopting artificial intelligence, the internet, sensors and other techniques are equipped to prevent the elderly from danger and injuries.	(Wong, Leung, Skitmore, & Buys, 2017)

Micro-level **(MI)**: Building/ House	**MI_1** Functional zone	Rest area	The rest area is reserved for the elderly to take a rest on their way home (in the multi-story building) or to encourage outdoor life (in the villa and single-family house).	(WHO, 2007)
		Entrance area*	Entrance area should be accessible and convenient to older adults.	(WHO, 2015)
		Corridor*	The corridor should be wide and smooth enough to pass wheelchairs.	(WHO, 2007)
	MI_2 Walkability	Circulation pattern	The circulation pattern contains horizontal circulation and vertical circulation. Horizontal circulation refers to designed walking circulation on one floor, and vertical circulation refers to using elevators or stairs to move among floors.	(Lee, Shin, & Lee, 2020; WHO, 2007; Shin & Lee, 2019)
		Pedestrian-friendly design	The ramp, hand railing, non-slip flooring, and other design is set to help walking.	(WHO, 2007)
		Direction signage	Signage is placed to show directions and routes clearly.	(WHO, 2007; Qian et al., 2019; Hong Kong Housing Society, 2005)
	MI_3 Safety	Entrance guard	The entrance guard is set at every entrance of building/house.	(Evans et al., 2020; Luciano et al., 2020)
		Lighting at night	The electric lighting is sufficient at night.	(Luciano et al., 2020; Hong Kong Housing Society, 2005)
		Danger alarm and escape route	The visual and audible danger alarm is set for danger warnings.	(Orpana, Chawla, Gallagher, & Escaravage, 2016; Hong Kong Housing Society, 2005)
		Warning sign	The warning sign is placed for caution.	(Hong Kong Housing Society, 2005)
Meso-level **(ME)**: Community/ Neighbor-hood/Block	**ME_1** Walkability	Pedestrian amenities	The street is alone with pedestrian path, sidewalk, trail, and others for walking.	(Cerin et al., 2006; Jelokhani-Niaraki et al., 2019; Kano et al., 2018; Kihl et al., 2005; Mei, Hsu, & Ou, 2020; WHO, 2007, 2015; Orpana et al., 2016)
		Crosswalk	The crosswalk is equipped with traffic signal and other necessary facilities helping the elderly cross the road safely.	(Cerin et al., 2006; Kihl et al., 2005; Loo & Lam, 2012)
		Topography	The topography is suitable for the elderly's walking.	(Cerin et al., 2006)

	Outdoor seating	The public seating is set alone sideways.	(Kihl et al., 2005; Mei et al., 2020; WHO, 2007; Orpana et al., 2016)
	Street signage	The street has clear signs and lane marks, which are readable at night, and written by large letters to be seen at a distance.	(Kihl et al., 2005; Mei et al., 2020; Orpana et al., 2016)
ME$_2$ Accessibility to facilities	Entertainment and exercise facility	Numbers of parks, green spaces, exercise facilities, community centers, and other entertainment and exercise facilities with walking distance (500 meters).	(Cerin et al., 2006; Jelokhani-Niaraki et al., 2019; Kano et al., 2018; Luciano et al., 2020; Verena H Menec et al., 2011; WHO, 2015)
	Shopping facility	Numbers of groceries, markets, shopping centers, and other shopping facilities within walking distance (500 meters).	(Kihl et al., 2005; Luciano et al., 2020)
	Medical facility	Numbers of drugstores, pharmacies, community clinics, hospital outpatient and other medical facilities within walking distance (500 meters).	(Kihl et al., 2005; Luciano et al., 2020)
	Transportation stops	Numbers of public transportation stop within walking distance (500 meters), like bus stops, subway stations, and ferry terminal.	(Jelokhani-Niaraki et al., 2019; Kano et al., 2018; Kihl et al., 2005; Luciano et al., 2020; Verena H Menec et al., 2011; WHO, 2015; Orpana et al., 2016)
	General facilities	Numbers of bank, laundry store, bookstore, library and other facilities providing general services within walking distance (500 meters).	(Luciano et al., 2020)
ME$_3$ Community services	Food programs	Community food programs provide available meals to older adults, like meals on wheels, wheels to meals, food bank.	(Evans et al., 2020; Jelokhani-Niaraki et al., 2019; Kano et al., 2018; Verena H Menec et al., 2011; WHO, 2007; Orpana et al., 2016)
	Community-based care services	Community services help older adults cope with instrumental activities of daily living (IADLs), like yard work, home delivery of shopping, snow removal, garbage collection, home cleaning, housekeeping, personal care, etc.	(Evans et al., 2020; Kano et al., 2018; Kihl et al., 2005; Verena H Menec et al., 2011; WHO, 2007; Orpana et al., 2016)
ME$_4$ Safety	Traffic safety	The nearby traffic condition is safe for the elderly.	(Cerin et al., 2006; Loo & Lam, 2012)
	Warning sign	The warning sign is set to caution danger places.	(Kihl et al., 2005; WHO, 2007)
	Lighting at night	The street is lighted at night adequately, and streetlamps are placed at regular intervals.	(Jelokhani-Niaraki et al., 2019; Kihl et al., 2005)

		Crime	How frequent criminal case occurs nearby.	(Cerin et al., 2006)
		Security and police service	Numbers of emergency call boxes, police patrol, policy station, and other policy services within walking distance (500 meters).	(Jelokhani-Niaraki et al., 2019)
Macro-level **(MA)**: District/ Region/ City	**MA_1** Citywide medical infrastructure	Availability	Numbers of citywide infrastructure (municipal hospitals, city hall, and other municipal services).	(Jelokhani-Niaraki et al., 2019; Kihl et al., 2005; WHO, 2007, 2015)
		Accessibility	Shortest distance to citywide infrastructure (municipal hospitals, city hall, and other municipal services).	
	MA_2 Intercity transportation infrastructure	Availability	Numbers of railway stations, airports and ferry stations of city.	(Wong et al., 2015)
		Accessibility	Shortest distance to railway stations, airports and ferry stations of city.	

Note: * - should comply with local official building standards.

(2) Determining weights by the fuzzy-AHP

Since older adults spend different time within different spatial levels, the importance of spatial levels must be various. Even indicators of the same spatial level play different roles in the elderly's daily life. In order to reflect these variances, fuzzy-AHP is applied to determine the weight of each spatial level. AHP is an effective decision-making tool by quantifying the weights of decision criteria by utilizing individual experts' experience, first developed by Saaty (Saaty, 1988; Ayhan, 2013). The fuzzy-AHP is an effective extension of AHP by using fuzzy numbers for calculation instead of real numbers (Ayhan, 2013). The steps of fuzzy-AHP are as follows.

a. Establishing a hierarchical structure model

The hierarchical structure model can be established quickly in terms of multiscale spatial framework and regrouped indicators of age-friendliness. The hierarchical structure model for fuzzy-AHP analysis is usually a multi-level hierarchy, containing decision goals, decision criteria, and alternatives of schemes or solutions (Darko et al., 2019). In this study, the fuzzy-AHP analysis's objective is only to determine weights of decision criteria, so alternatives are not shown in the hierarchical structure model. Therefore, the hierarchical structure model is established as Fig. 4: the decision goal, with the black border, is to assess the housing age-friendliness; the decision criteria, in the red border, are the four spatial levels in the conceptual framework, including nano-level, micro-level, meso-level, and macro-level; the elements of decision criteria, in the blue border, are the indicators of spatial levels listed in Table 2.

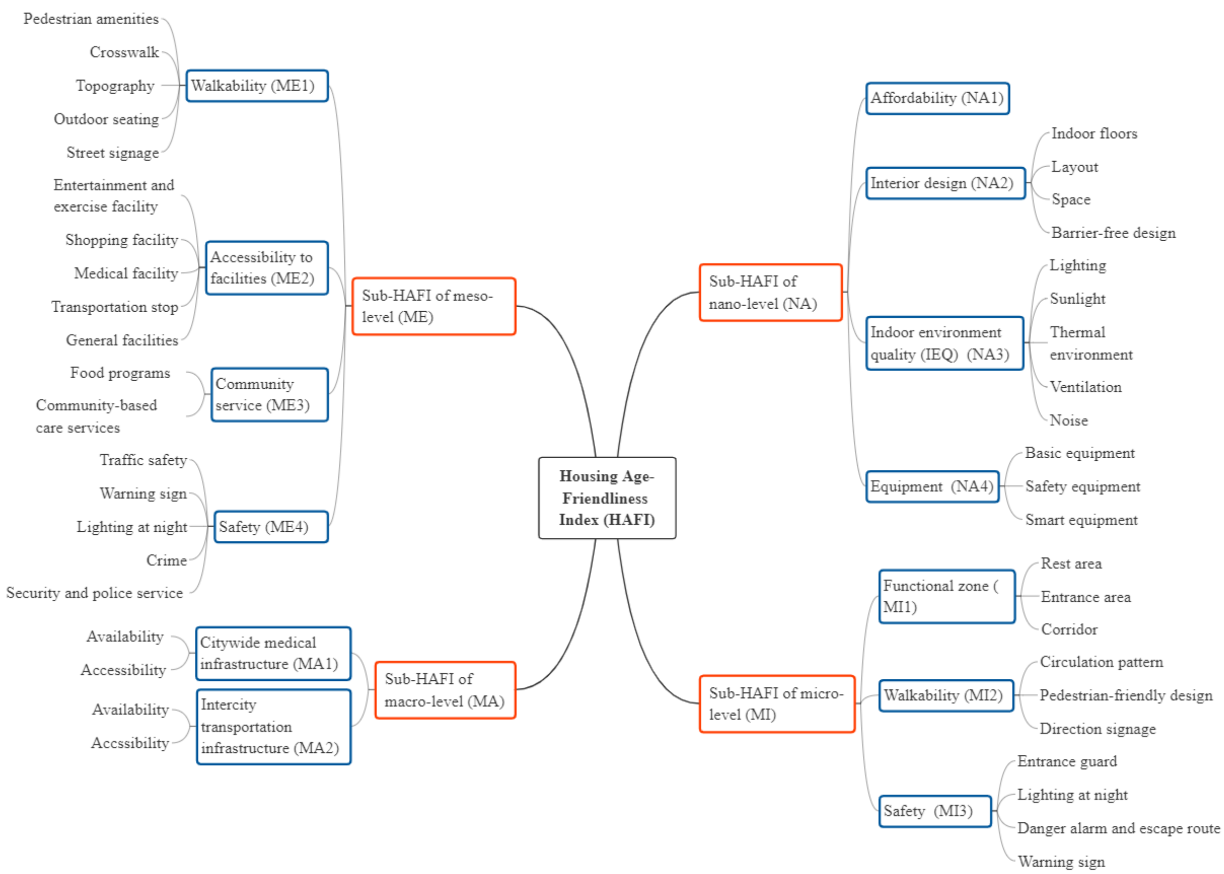

Fig. 4. The hierarchical structure model for fuzzy-AHP analysis

b. Designing questionnaires to build the fuzzy judgment matrix

Saaty, the founder of AHP method, has emphasized that one of rationalities of AHP is having enough knowledge and experience and access to knowledge and experience of others to assess the priority of importance among the relations (Saaty, 2000). In this study, the multi-level assessment not only assists individuals in housing selection, but also benefits other stakeholders, like governments and developers. The authority of fuzzy-AHP should be further ensured. Therefore, professional experts in age-friendly housing should be AHP process participants to share their opinions, rather than ordinary people generally lacking enough professional knowledge and various personal experience.

To transform experts' opinions into quantifiable data, the questionnaire is designed according to the hierarchical structure model, as shown in Table A2&A3. In the questionnaire survey, experts in the age-friendly field are asked to mark scores of pairwise comparison with the fuzzy scaling method (Table 3). The average values of fuzzy scaling from different experts are regarded as the final result of pairwise comparisons, which constitute the fuzzy judgment matrix (Table 4) of each hierarchy in the hierarchical structure model. At last, five fuzzy judgment matrixes should be generated, one belongs to the spatial levels, and the other four belong to different levels.

Table 3

Fuzzy scaling method (Ayhan, 2013; Saaty, 1988)

Description	Fuzzy triangular scale(V_{ij})	Fuzzy triangular scale(V_{ji})
I_i and I_j are equal importance (Eq. Imp.)	(1,1,1)	(1,1,1)
Moderate importance I_i over I_j (M. Imp.)	(2,3,4)	(1/4,1/3,1/2)
Essential or strong importance I_i over I_j (S. Imp.)	(4,5,6)	(1/6,1/5,1/4)
Very strong importance I_i over I_j (V. Imp.)	(6,7,8)	(1/8,1/7,1/6)
Extreme importance I_i over I_j (E. Imp.)	(9,9,9)	(1/9,1/9,1/9)
Intermediate values between the two adjacent judgments	(1,2,3)/(3,4,5)/(5,6,7)/(7,8,9)	(1/3,1/2,1)/(1/5,1/4,1/3)/(1/7,1/6,1/5)/(1/9,1/8,1/7)

Table 4

Example of Fuzzy judgment matrixes

	I_1	I_2	I_3	I_4
I_1	(1,1,1)	V_{12}	V_{13}	V_{14}
I_2	V_{21}	(1,1,1)	V_{23}	V_{24}
I_3	V_{31}	V_{32}	(1,1,1)	V_{34}
I_4	V_{41}	V_{42}	V_{43}	(1,1,1)

c. Determining the weights of indicators in each hierarchy

The fuzzy judgment matrixes are analyzed by the fuzzy-AHP approach proposed by Ayhan (Ayhan, 2013): step 1 is calculating the geometric means of fuzzy comparison values based on the fuzzy judgment matrixes, step 2 is figuring out relative fuzzy weights of each matrix, and step 3 is to obtain the averaged and normalized relative weights of each matrix.

(3) Formulas to calculate HAFI

The score of each indicator is set as the average score of its sub-indicators. The sub-HAFI of each spatial level is set as the weighted average score of its indicators, and the HAFI is set as the weighted average score of four sub-HAFIs. The weights are decided by the result of fuzzy-AHP. The computational formulas are designed as Equations 1-5.

$$NA_m = (\sum_n NA_{m,n}) \big/ n \qquad NA = \sum_m W_{NA_m} \bullet NA_m$$ *Equation 1*

$$MI_m = (\sum_n MI_{m,n}) \big/ n \qquad MI = \sum_m W_{MI_m} \bullet MI_m$$ *Equation 2*

$$ME_m = (\sum_n ME_{m,n}) \big/ n \qquad ME = \sum_m W_{ME_m} \bullet ME_m$$ *Equation 3*

$$MA_m = (\sum_n MA_{m,n}) \big/ n \qquad MA = \sum_m W_{MA_m} \bullet MA_m$$ *Equation 4*

$$I = W_{NA} \bullet NA + W_{MI} \bullet MI + W_{ME} \bullet ME + W_{MA} \bullet MA$$ *Equation 5*

Where, *NA* represents sub-HAFI of nano-level, *MI* represents sub-HAFI of micro-level, *ME* represents sub-HAFI of meso-level, *MA* represents sub-HAFI of macro-level, *m* represents the number of indicators, *n* represents the number of sub-indicators, *W* represents the weight of indicators or spatial levels, *I* represents the HAFI.

3.3 The computation process of HAFI

In terms of the multiscale spatial framework, the age-friendly assessment of housing is extended to contain indicators belonging to four spatial levels. Comparing with WHO guidelines and other evaluations, this multi-level assessment is definitely more challenging to collect essential data for calculating HAFI. In order to simplify procedures and save time of calculation, this study proposes a BIM-enabled rating approach by integrating multi-source data. Three main types of data are required, including life-cycle data of buildings stored in BIMs, building simulation data that are available in simulation analysis of BIMs, data from external sources. The flowchart of BIM-based computation is presented in Fig. 5.

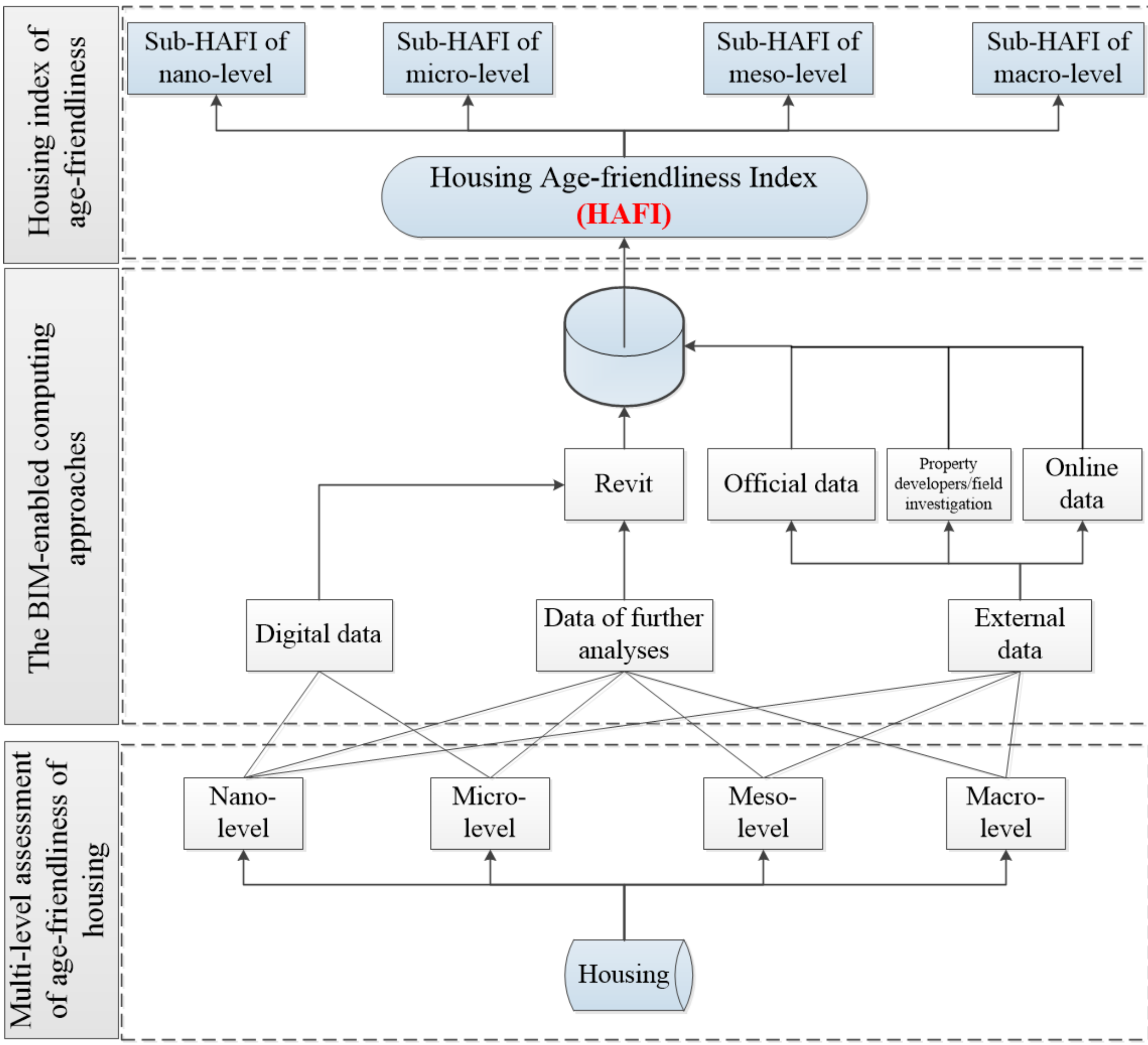

Fig. 5. The flowchart of computation of HAFI

(1) Querying digital data from BIM files

BIM files offer kinds of digital building information, and original data of some indicators can be retrieved conveniently from BIMs. Generally, data of nano-level, micro-level, as well as part of meso-level indicators are possible to be queried from BIMs. For example, architectural modeling provides the physical information of housing, like floorplan, layout, space, barrier-free design in home/apartment, and rest area, entrance area, corridor, walking circulation, pedestrian-friendly design in buildings; and MEP modeling provides the equipment information. In this study, the Autodesk Revit 2022 is used as the professional BIM software.

However, the quality of data query depends on the level of development (LOD) of BIMs, which represents the detailed degree of the components' specification, geometry, and attached information have been thought through[3]. There are six LODs according to how professionals can rely on the information of elements: LOD 100, LOD200, LOD300, LOD350, LOD400, LOD500 (BIM Forum, 2019). BIMs of low LOD cannot offer sufficient exact data, for example, information derived from LOD 100 models only be regarded as approximate. Further supplementary data from other sources would be essential, when LOD is lower than LOD 300.

(2) Conducting further analyses of BIMs

Besides the data that can be retrieved from BIMs directly, some data need to be obtained through the further analysis of BIM, like lighting analysis for housing lighting data and solar analysis for housing direct sunlight data. These analysis functions are provided by BIM software, add-ins of BIM software, and analysis software of BIM. For instance, solar studies in the Autodesk Revit simulates the shadows on buildings, Insight 360 add-in of the Autodesk Revit can analyze the lighting performance, and the Autodesk Ecotect Analysis can simulate a series of green building performance.

Since Autodesk company decided to no longer support the software of Ecotect, and transferred the analysis functions of Ecotect and Insight 360 to Revit, this study conducted further analysis in

[3] https://www.united-bim.com/bim-level-of-development-lod-100-200-300-350-400-500/

Revit 2022. The parameter setting of the further analyses should be in compliance with the analysis requirements of local official standards. For instance, the Chinese "*Standard for urban residential area planning and design*" (GB 50180-2018) requires the housing for the elderly should have at least 2 hours of direct sunlight in the winter solstice. Thus, the date of solar analysis should be set as the winter solstice. Based on the digital models, the IEQ performances of housing can be further analyzed in Revit 2022.

(3) Importing external data

The multiscale assessment requires lots of information, not only about the physical housing itself, but also about the surrounding environment, services, and support. BIM cannot offer all essential data for the multiscale assessment of housing age-friendliness, and the low LOD of BIMs leads to a further lack of essential building information. Therefore, the remaining data have to be supplemented by external data sources, like web data, official statistics, property developers, and field investigation.

a. Property developers/field investigation

Some missing data can be supplemented by property developers or investigated on site. In the design stage, this information is determined by property developers initially, or after the construction completion, it can be investigated on site.

b. Online data

Essential data of geographical information are generally available from online map platforms. For instance, online map platform offers plentiful geographical information for computing the HAFI, like facility location, elevation, road data, routes data, and traffic data. Most map platforms provide the application program interface (API) and user interface (UI) to request data.

c. Official data

The official data whose copyrights belong to the government are hard to request online or from property developers. Some data are regulated by governmental policies and planning, like traffic regulations; some data rely on governmental statistics, like residential income.

The above data from different external sources have diverse formats, making it hard to integrate them into the assessment process directly. Therefore, all retrieved data should be transformed into scores of sub-indicators based on the scoring standard (Table A1). And then, Office ACCESS database is used to store, compute and query the HAGIs and sub-HAFIs of alternative housing projects.

(4) Computing HAFI and sub-HAFI

Table 5 summarizes the data source of each sub-indicators. The full mark is set as 10 points, then the HAFI and sub-HAFIs of four spatial levels are computed with equations of the multi-level assessment (Equation 1-5).

Table 5

Summary of data sources of age-friendliness assessment of housing

Spatial levels	Indicators	Data sources		
		Data retrieved from BIMs	Simulated data based on BIMs	External data
Nano-level	Affordability			Online data, Official data
	Interior design	√		Property developer/field investigation*
	IEQ	√	√	Online data*
	Equipment	√		Property developer/field investigation*
Micro-level	Functional zone	√		Property developer/field investigation*
	Walkability	√		

	Safety	√	Property developer/field investigation*
Meso-level	Walkability	√	Property developer/field investigation, Online data*
	Accessibility to resources	√	Online data*
	Community services	√	Property developer/field investigation*
	Safety		Online data, Official data
Macro-level	Citywide medical infrastructure		Online data
	Intercity transportation infrastructure		Online data

Notes: * - Necessity depends on LOD of BIM.

4. Results

4.1 Information of housing examples

There are several housing types in urban areas, such as single-family housing, townhouse, multi-family housing, condo, apartment. Two typical examples, both of which are the most common housing types in urban areas, are selected to ensure the adaptability of the multi-level assessment to different types of housing projects. One is a three-story single-family house with 400 square meters' floor area, located in the provincial capital suburb in the southwestern Chinese region. The other example is the apartment in a high-rise building with around 150 square meters' floor area, located in a third-tier city's downtown area. The multi-level assessment of age-friendliness is applied to these two housing examples to identify clear differences of typical housing types at spatial scales.

4.2 Results of fuzzy-AHP

Five experts, who are sufficiently experienced in age-friendly researches, were invited to express their opinions about the importance of indicators in different spatial levels to the age-friendly performance. The basic information of experts is shown in Table 6. All experts were asked to mark symbols on questionnaires based on their knowledge and experience. Examples of the questionnaire are shown in Tables A2&3. These marked symbols are converted to the fuzzy judgment matrixes according to the rules in Tables 2&3. The final fuzzy judgment matrix for the following analysis is the average of five fuzzy judgment matrixes. Weights of indicators and spatial levels are calculated based on the final fuzzy judgment matrix.

The results of the fuzzy-AHP are summarized in Table 7. Experts' opinions reveal that the significances of spatial levels and indicators for the housing age-friendliness are definitely various. Since the elderly spend different lengths of time within different spatial levels of housing in their daily life. Older adults stay in their own homes most of time, so nano-level is the most important for housing age-friendliness; on the contrary, older adults do not require to access citywide infrastructure frequently, so the macro-level is the least important; and micro-level and meso-level have similar moderate importance for age-friendly performance. Similarly, even belonging to the same spatial level, different indicators play roles with different importance in the daily life of the elderly.

Table 6

Basic information of experts

Category	Type	Percentage (%)
Age	Under 30	40
	30-50	40

	Above 50	20
Occupation	Researcher	40
	Professor	40
	Official	20
Region	Asia	80
	Africa	20

Table 7

The results of the fuzzy-AHP analysis

Code	Spatial level	Code	Weight	Code	Indicator	Code	Weight
NA	Nano-level	W_{NA}	0.496	NA_1	Affordability	W_{NA1}	0.321
				NA_2	Interior design	W_{NA2}	0.326
				NA_3	IEQ	W_{NA3}	0.266
				NA_4	Equipment	W_{NA4}	0.087
MI	Micro-level	W_{MI}	0.203	MI_1	Functional zone	W_{MI1}	0.212
				MI_2	Walkability	W_{MI2}	0.341
				MI_3	Safety	W_{MI3}	0.447
ME	Meso-level	W_{ME}	0.255	ME_1	Walkability	W_{ME1}	0.199
				ME_2	Accessibility to resources	W_{ME2}	0.289
				ME_3	Community services	W_{ME3}	0.098
				ME_4	Safety	W_{ME4}	0.414
MA	Macro-level	W_{MA}	0.046	MA_1	Citywide infrastructure	W_{MA1}	0.703
				MA_2	Intercity transportation	W_{MA2}	0.297

4.3 Results of data retrieval of housing examples

According to the research methodology, necessary data can be obtained from its BIMs, simulation analysis based on BIMs, and external sources. In terms of Level of Development Specification (BIM Forum, 2019), the model of example 1 is LOD 200, and the model of example 2 is LOD 300. Besides the data of indicators that can be retrieved from BIMs directly, data of other indicators is more difficult to obtain from further analyses and external sources. As a result, the data acquisitions from further analyses and external sources are elaborated as follows.

(1) Data of further analyses of BIM.

Further analyses are conducted in Revit 2022 as well, including the lighting analysis, solar analysis, and thermal analysis.

Firstly, the Chinese "*Standard for urban residential area planning and design*" (GB 50180-2018) requires the housing for the elderly should have at least 2 hours' direct solar radiation in the winter solstice when the solar altitude is lowest. One window toward the south on the first floor is chosen in each housing example, and the solar study of Revit 2022 is used to simulate the direct sunlight on this window. The simulation date is set to 22 December, and the location is set as the actual locations of housing examples. Table 8 presents the durations of direct sunlight of examples 1&2 in the winter solstice. The duration of both examples 1&2 are over 2 hours, and housing example 1 can obtain a longer duration of direct sunlight.

Secondly, the lighting analysis is implemented in Revit 2022 to simulate the natural lighting performance indoors. As official requirements on natural lighting in the Chinese "*Standard for the daylighting design of buildings*" (GB50033-2013), the indoor illuminance of daylight of main functional spaces should be over 300 lux under local weather conditions. Therefore, the local weather files of two examples are imported for simulation, the analysis grid is set at the height of 30 inches above the floor, and the data is set at 12:00 PM of the winter solstice. The lighting analysis shows that the area with the illuminance over 300 lux accounts for 75% area of housing example 1, and 93% of housing example 2. Both examples 1&2 reach the lighting standards. The result of lighting analysis is listed in Table 8.

Furthermore, the indoor thermal environment is mainly determined by local climate and building envelope. For evaluating the thermal environment more conveniently, the climate zone and average heat transfer coefficient (U) of building envelope are used to evaluate the thermal environment. The Chinese "*Code for the thermal design of civil building*" (GB 50176-2016) divides the country into different climate zones, including severe cold zone, cold zone, hot-summer and cold-winter zone, hot-summer and warm-winter zone, and mild zone. Example 1 is located in the mild zone, and example 2 is located in cold zone. The results of average U are listed in Table 8, and the information of envelope of housing examples are shown in Table A4. That means the local climate of example 2 is worse than example 1, while the thermal insulation of the envelope of example 2 is better than example 1.

Table 8

The summary of the results of further analyses

Analysis	Item	Example 1	Example 2
Solar analysis	Begin time	11:11 AM	12:29 PM
	End time	15:56 PM	15:44 PM
	Duration	4 hour 45 minutes	3 hours 15 minutes
Lighting analysis	Illuminance over 300 lux	75% area	92% area
Thermal analysis	Local climate	Mild	Cold
	Average U	1.077	0.484

(2) The external data.

Firstly, the data of some indicators are queried from Baidu map platform, which is a widely used online map platform in China. For instance, a circle region retrieval is conducted on Baidu map platform to search entertainment and exercise facilities within 500 meters radius of housing location. The data show that only one green space and one fitness room is located around example 1, but parks, green spaces, fitness rooms, and community centers can be accessed within a distance of 500 meters from example 2.

Moreover, official data can be checked from the local government's official statistics, policies and regulations, such as the housing price-to-income ratio, limited speed, traffic conditions, community services, etc. Finally, the remaining data have to be supplemented by property developers or field investigations of examples 1&2.

All the detailed scores based on the external data are presented in Table A1.

4.4 Results of HAFI of housing examples

Figs. 6&7 conclude the results of HAFI and sub-HAFI two housing examples, and the detailed scores of sub-indicators are shown in Table A1. The HAFIs of examples 1&2 are 6.479 and 7.236, respectively. Example 2 performs better than example 1 in the assessment of age-friendliness, but the difference between HAFIs of two examples is not very huge, and both are less than the full mark (10 points). It means that both two housing examples are not entirely perfect for the elderly, and each has its own merits and demerits. To be more specific, according to Figs. 6&7, housing examples perform quite dissimilarly in different spatial levels. Therefore, it is quite crucial to assess the age-friendliness under the multiscale perspective, for exploring the housing merits and demerits to facilitate aging-in-place.

As one typical urban housing, example 2 is regarded as suitable housing for later life, with well age-friendly performances in nano-level and meso-level. By contrast, example 1 is not so suitable for the elderly. The only strength of this single-family housing is better city infrastructure in macro-level. The performances in other three spatial level, this single-family housing have no obvious strength.

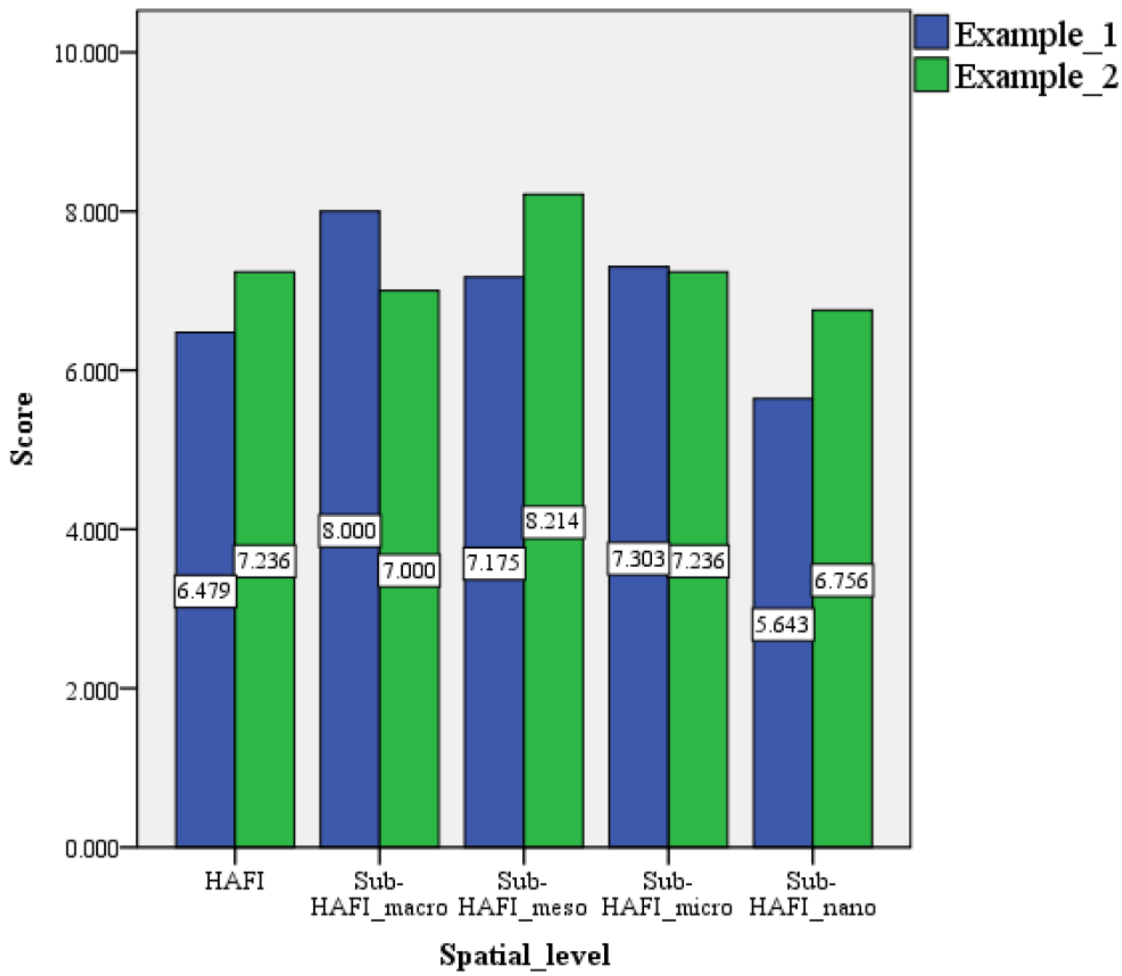

Fig. 6. The HAFIs of housing examples

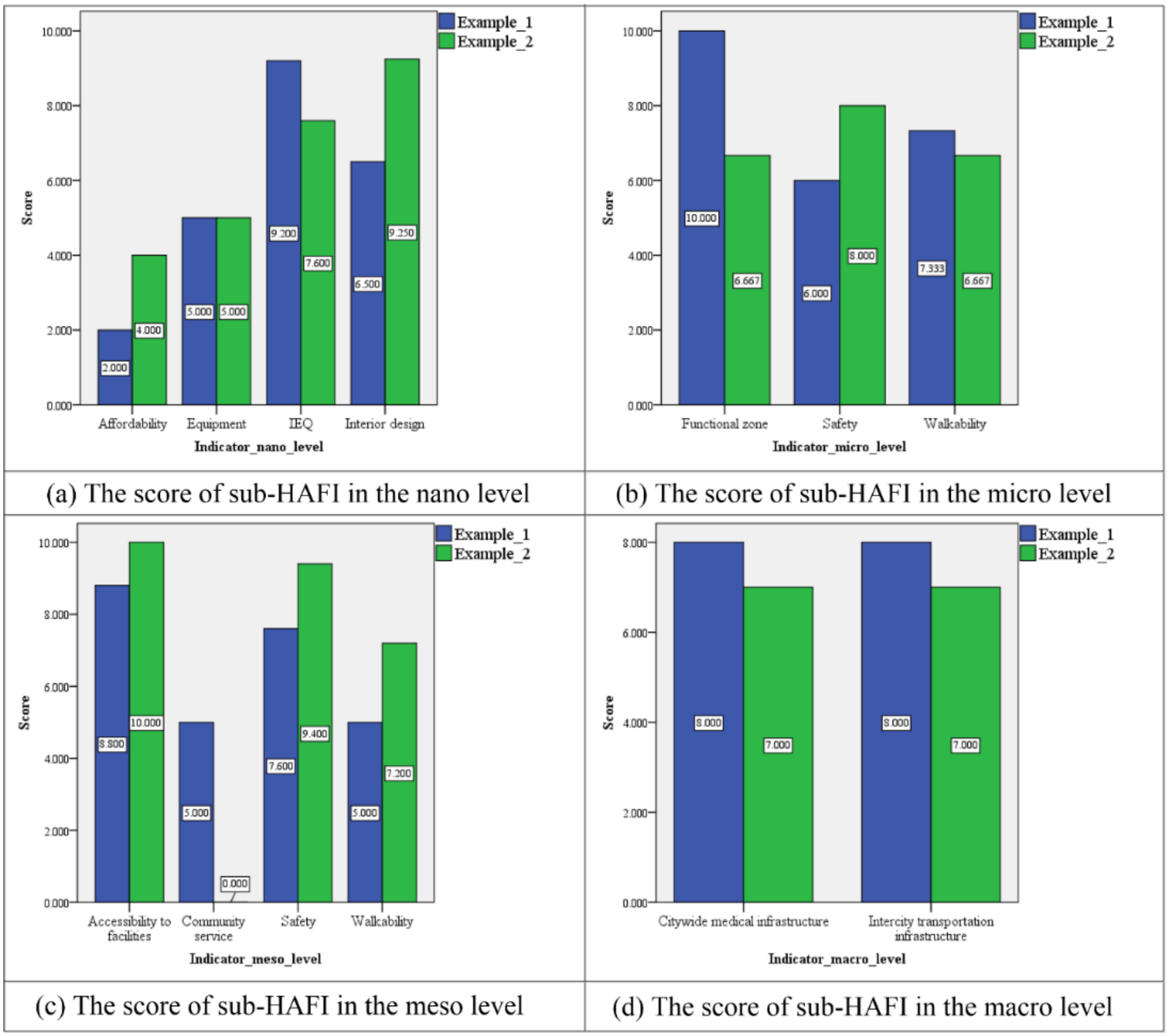

Fig. 7. The Sub-HAFIs of housing examples

5. Discussions

5.1 The comparative analysis of HAFIs

(1) The comparison in nano-level

In terms of weights of indicators in Table 7, housing affordability, interior design, IEQ and equipment contribute to age-friendly performance diversely in the nano-level of housing. Housing affordability and interior design are regarded as the most important indicators to develop age-friendly housing, while the home equipment seems not very influential. Since example 2 performs better than example 1 in both housing affordability and interior design, the sub-HAFI of the nano-level of example 2 is higher than example 1, as shown in Figs. 6&7.

Generally, the single-family house is more expensive than ordinary apartment, especially in the provincial capital or metropolises. But, only the housing price cannot represent affordability entirely, due to various economic statuses of different cities. The housing price-to-income ratio is usually used to reflect housing affordability (Sani & Rahim, 2015). The price-to-income ratio of example 1 is higher than example 2, indicating that the price of this apartment is easier to be afforded by local seniors than this single-family house, and puts less economic pressure on the elderly. Besides, the elderly's indoor daily life is under the impact of interior design all the time. Barrier-free access is important to the elderly due to the declining mobility capacity (Hong Kong Housing Society, 2005). Elevators are seldom equipped at home, so multiple floors cause inconvenience to access upstairs. Moreover, suitable indoor space and flexible layout can bring better living experience to the elderly, by optimizing the daily movement paths and adapting to changing living requirements. As a flat apartment with moderate space, the design of example 1 is more suitable for the elderly to live. By contrast, the large indoor area and multiple floors of example 1 make the elderly feel stressed and difficult to move around at home.

However, the advantages of example 1 are also prominent. Housing example 1 performs well in the IEQ. To be more specific, example 1 performs better than example 2 in aspects of sunlight and noise. Since example 1 is in a single-family house community, there are no high-rise buildings around, helping example 1 achieve a long duration of direct sunlight. The suburban area is far away from urban noise sources, making example 1 get a good acoustic environment. Moreover, the thermal environment of example 1 seems similar to example 2. In detail, example 1's thermal environment mainly benefits from the local mild climate, but the local climate of example 2 is cooler, its thermal performance mainly relies on the building envelop with better thermal insulation effect. Currently, most Chinese homes are equipped with basic equipment and fire equipment to meet requirements of the elderly's daily life and avoid danger. And the emergency equipment for the elderly is common in nursing homes or other professional care facilities for the elderly, such as emergency phones and push buttons in bedroom and toilet, but it is rarely equipped in ordinary housing. In recent years, smart equipment has emerged. Part of smart equipment is specially designed to prevent the elderly from danger and injuries automatically, such as automatic fire extinguishing device, automatic alarm system, IoT-based fall detector (Mrozek, Koczur, & Malysiak-Mrozek, 2020), IoT-based health monitor system (Hosseinzadeh et al., 2020). But, owing to the current high expense of the installation and low technology acceptance by the elderly (Chen & Chan, 2014), much smart equipment has not yet been popularized in ordinary Chinese families.

(2) The comparison in micro-level

The sub-HAFIs of two housing examples are quite close in their micro-level, but the detailed age-friendly performances are not similar. In terms of weights in Table 7, the safety within the micro-level area affects the age-friendliness more than functional zone and walkability. Example 1 has better functional area and walkability than example 2, while the safety score of example 1 is lower than example 2. The different performances are largely caused by the ownership of the micro-level housing. Generally, the micro-level area of single-family house is the private outdoor space belonging to residents, but the micro-level area of apartment in the high-rise building is the public space.

So, in example 1, the elderly can optimize the functional zones according to particular demands or preferences. For example, the width of entrance areas can be extended, and the ramp can be set considering the needs of the wheelchair. Differently, the micro-level of example 2 refers to the public space within the building. The design and setting of functional zones, like elevators, building entrances and corridors, are already determined by designers and property developers, sometimes lacking enough considerations about age-friendly issues. Regarding safety in micro-level, the safety issue in micro-level area of example 1 is in charge of the household. Conversely, property management companies are responsible for high-rise buildings' safety by providing professional safety services for residents. Thus, example 2 performs better in the aspect of safety, which is the most important in the age-friendly performance of housing.

(3) The comparison in meso-level

In terms of the multi-spatial framework of housing (Fig. 3), the meso-level of housing refers to the nearby community, neighborhood, or block. The different weights of indicators in meso-level contribute diversely to housing age-friendliness. The sub-HAFI of example 2 is better than example 1, because example 2 gains better scores of three high weighted indicators, including walkability, accessibility to facilities and safety.

Neighborhood development is one of determining factors of meso-level age-friendliness. Example 2 is located in a central area community well developed with ample facilities offering their daily necessities and better public security. Due to the high population density in the central area, the neighborhood facilities have been developed for a long time, and residents' life and property safety would be paid more attention. On the contrary, the neighborhood of suburban area is not developed as maturely as that in the central area in the above aspects, which affect the elderly's life within the meso-level area heavily. Finally, the community services in China mostly rely on the promotion and financial support from local governments (Chen & Han, 2016). Generally, the more developed cities have started the development of community services earlier. Housing example 1 is in the provincial capital, the local government has begun to offer some food programs for the elderly living in example 1 by government procurement. The local government of example 2 only proposed the plan of community services, but has not implemented it yet.

(4) The comparison in macro-level

The sub-HAFI in macro-level evaluates citywide medical infrastructure and intercity transportation infrastructure. Due to the declining physical health of the elderly, the citywide medical infrastructure is necessary for the elderly to deal with severe or sudden diseases. But the elderly's demands for the intercity journey are small in daily life. As the weights of two indicators, the performance of citywide medical infrastructure contributes more to the age-friendliness in macro-level. Example 1 performs better than example 2 in both two aspects.

The age-friendly performance in macro-level is determined by the development level of cities and the citywide housing location. More citywide medical infrastructure and intercity transportation infrastructure are available to the elderly living in the provincial capital than the small city. But, most civil infrastructures are clustered in central areas of the city, so the elderly living in central areas (example 2) can access more conveniently than suburban areas (example 1). Therefore, the accessibility of example 1 is slightly worse than example 2 due to the larger urban scale of the provincial capital, making up for example 2's deficiencies of availability of citywide infrastructure.

(5) The overall comparison

Based on the above discussion, example 1 (a single-family house in the suburban area) performs better than example 2 (an apartment of high-rise building in the central area) only in the macro-level. According to the weights of spatial levels in the multi-level assessment, the housing age-friendliness of the macro-level is the least important to the elderly, because the discomfort of housing in the macro-level would not impact the daily life of the elderly frequently. However, sub-HAFIs in the other three spatial levels are quite significant to the overall age-friendliness of housing. Owing to functional impairment and declining mobility, the elderly commonly shrink their main activity scope to the area within home, building, and neighborhood. The age-friendly performance in the nano-level, micro-level and meso-level contribute more to the overall housing age-friendliness.

5.2 Recommendations

The multi-level assessment of housing age-friendliness benefits not only users like the elderly, but also the implementers like local governments and developers of housing projects. How the multi-level assessment works in actual practice is elaborated from two aspects: the HAFI and the assessment items of age-friendliness.

(1) The HAFI can be used as evidence to provide appropriate housing to the elderly.

The HAFI is valuable to stakeholders for reference. The housing index quantifies the overall age-friendly performance of housing, showing how suitable the housing is to support individuals' later life. The HAFI is concerned with the elderly's requirements in all age periods. The housing with a higher HAFI is more likely to support the elderly's daily activities well in all stages of later life; otherwise, this housing is suitable for early-aged adults. In the early aged stage, the elderly are generally in good physical condition, so that they can accomplish activities of daily living (ADLs) and most instrumental activities of daily living (IADLs) independently, such as accessing shopping centers in the long-distance, climbing stairs, mowing the lawn. As the physical condition of the elderly declines gradually with their age, some ADLs and IADLs would become beyond bearing capacity, and the housing with a lower HAFI would not be sufficient to support independent lives anymore. By referring to HAFI, the elderly who dislike moving to a new house would pick housing with a higher index.

Experts' opinions determine the weight of each housing sub-HAFI of spatial levels, which means the HAFI is supported by experts' knowledge and experience in the field of age-friendly housing. It is reasonable that HAFI is authoritative enough to reflect the perception of most people. Local governments can identify which regional deficiencies should be concerned more during urban design and renewal, for accommodating the elderly better. Furthermore, in the practice of public housing, the proportion of middle-aged or aged applicants keeps increasing, and more people have to age in public housing. Local governments can implement the multi-level assessment of age-friendliness, and adopt the HAFI for reference to allocate suitable public housing to aged applicants (Wadu Mesthrige & Cheung, 2020). And housing developers can use the HAFI as the index to find out which housing needs to be improved to accommodate the elderly.

However, special preferences of a few seniors should not be neglected totally. Sub-HAFIs of spatial levels are offered for the further filter. The threshold value can be set according to personal requirements. The housing alternative would be filtered out once its sub-HAFI is below the threshold value. For example, the elderly with high requirements on outdoor activities and social communication can set a threshold value for the sub-HAFI of meso-level, filtering the housing whose sub-HAFI is below this threshold value.

To sum up, results of the multi-level assessment of age-friendliness offer the HAFI and sub-HAFIs of spatial levels, which have kinds of functions in practice. The elderly can select appropriate housing from alternatives by referring to the HAFI and sub-HAFIs, for guaranteeing their later life quality. The HAFI also helps local governments and property developers to know about the age-friendly performance of large amounts of housing quickly and then make decisions about housing allocation and retrofits.

(2) The assessment indicators and scoring standard can be used as a supplemental guideline for developing high-quality age-friendly housing.

At present, many cities have to cope with the issue of “double aging”, which means the population aging and building stock aging at the same time[4]. New housing should be designed and constructed

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[4] https://static1.squarespace.com/static/591e6a001b631bff6312f919/t/5d89affc87e82e702f513c8f/1569304663088/f+HKIP+Journal+33.pdf

in a more age-friendly way, and old housing should be retrofitted to improve the living environment for the elderly. On the basis of existing guidelines, the indicators and scoring standard of the multi-level assessment of age-friendliness can be regarded as a further checklist to develop age-friendly housing. Assessment indicators manifest the housing components that influence the elderly's independent life quality, while weights of indicators inform which housing components should be emphasized more in the process of design or retrofit. Detailed requirements on different housing components can refer to the scoring standard of the multi-level assessment of age-friendliness.

The detailed items and weights of the multi-level assessment help planners and designers to find out which elements should be given priority to ensure the housing age-friendliness and how to improve the initial design efficiently. For instance, regarding designing or retrofitting the housing in the micro-level, safety and walkability items should be guaranteed foremost, such as adequate lighting at night for the elderly with declining eyesight, visual and audible alarm for the elderly with declining eyesight or hearing.

6. Conclusions

6.1 Theoretical implications

Previous researches lacked the assessment of housing age-friendliness, and consideration of variances of significance among different spatial scales during the evaluation of age-friendly performance. To fill the research gap, this study contributes to developing a comprehensive multi-level assessment of HAFI to reflect the housing age-friendliness based on the proposed multiscale spatial framework.

The multiscale spatial framework of housing regards the housing performance in multiple spatial levels, consisting of nano-level, micro-level, meso-level, and macro-level. Under this framework's guidance, the new multi-level assessment of housing age-friendliness is developed quantitively evaluating the age-friendly performance of housing in spatial levels. Moreover, given that the multi-level assessment requires multi-source housing data, this study adopts BIM and external data sources to help compute the HAFI. This multi-level assessment is applied in two different housing examples to verify the feasibility and validity of the assessment and its computation process.

6.2 Practical implications

This study provides an effective method to assess the housing age-friendliness, which is quite helpful for stakeholders in practice. The assessment results, namely the HAFI and sub-HAFIs of particular housing, are the reliable evidence for the individual to select housing and local government to assign suitable public housing to aged applicators. Meanwhile, designers, planners, and property developers can utilize the multi-level assessment of age-friendliness as a supplementary guideline to develop age-friendly housing by referring to assessment indicators and the scoring standard.

The multi-level assessment of age-friendliness contains many indicators in different spatial levels, potentially leading to difficulties in obtaining data in practice. Traditionally, users of the housing assessment have to extract the data from amounts of paper drawings, electronic drawings, and urban planning. If the multi-level assessment of age-friendliness is implemented in the traditional way, more human resources for data collection and calculation and more time for avoiding manual errors are inevitable. Therefore, BIM is adopted instead, because the data stored in BIM is easy to query, seldom has manual errors, also supports diverse computer simulations. The primary function of BIM is to make the computation process faster and more concise, then facilitate the implementation of the multi-level assessment of age-friendliness in practical applications.

Furthermore, the successful implementations in two housing examples manifest that the multi-level assessment of age-friendliness can adapt to different housing types well. As mentioned in section 3.2, the official standards released latest are regarded as baselines of housing assessments, and the scoring standard should be various to comply with local official standards. Therefore, all flexible indicators of multi-level assessment of age-friendliness are marked to facilitate international users from different regions. They only need to reset the numbers of flexible indicators in the scoring standard according to their local standards.

6.3 Limitations and future work

Actually, BIMs of old housings are absent or with low LOD. Much necessary digital housing information, that cannot be retrieved from its BIMs, has to be supplemented from other data sources. It hinders from implementing the BIM-enabled multi-level assessment of age-friendliness in as-built housing. Fortunately, many researchers are working on the automatic generation of BIMs for as-built buildings via 3D laser cameras, and this hindrance is getting eliminated.

Furthermore, this study focuses on proposing the multi-level assessment of housing age-friendliness, and computing the HAFI by taking advantage of digital data of BIMs. Restricted by the article length, this study integrates BIM and multi-source data to calculate HAFI, but does not realize the automatic approach to compute HAFI and sub-HAFIs. Besides, determining a threshold value of HAFI is necessary to judge whether the housing is eligible for aging-in-place. Since the approach to set the threshold value of HAFI is out of the scope of the study, this study only makes a comparative analysis of between HAFIs of housing examples. As a result, our subsequent studies would concentrate on developing an automatic computation approach to realize the BIM-based automatic multi-level assessment of housing age-friendliness, and also proposing the method to determine the threshold value of HAFI for housings in different regions.

Appendix

Table A1

The scoring standard of the multi-level assessment of age-friendliness

Spatial level	Indicator	Sub-indicator	Scoring standard	Score	
				Example 1	Example 2
Nano-level **(NA)**: Home	**NA_1** Affordability	-	0 – Housing price-to-income ratio is more than 20. 2/4/6/8/10 – Housing price-to-income ratio is less than 20/15/12/10/6.	2	4
	NA_2 Interior design	Indoor floors	10 - Single floor/equipped exclusive elevator. Deducting 2 points one more floor of housing, such as duplex apartments, skip floors, loft, villa, etc.	6	10
		Layout	2 – The floor plan has the corridor with rooms off. 6 – The floor plan also has an entrance hall with rooms off. 10 – The floor plan also has an open plan of living room, dinning room and kitchen.	6	10
		Space*	Adding the following items together: 2 – Housing size is over 50 m^2. 2 – Housing size is less than 150 m^2. 1/2/3/4 – The width of passage and doorway is over 900/1200/1350/1800mm.* 2 – Outdoor private space in housing.	6	7
		Barrier-free design*	Adding the following items together: 2 – Non-slip floor. 2 – Floor without drop height. 2 – Entrance ramp. 2 – Handrail. 2 – Dry wet depart in the bathroom.	8	10
	NA_3	Lighting*	Adding the following items together: 5 – Artificial lighting system.	10	10

	Indoor environment quality (IEQ)		0/2/5 – The illuminance of nature lighting is over 300 lux in less than 50%/50-75%/over 75% area.		
		Sunlight*	0/5/10 – The duration of direct sunlight is less than 2 hours/2-4hours/more than 4 hours in winter solstice*.	10	5
		Thermal environment*	Adding the following items together: 1/3/5 – Location is in the cold and severe cold zone/hot-summer and cold&warm-winter zone/mild climate zone. 1/3/5 – Average heat transfer coefficient (U) is over 1/0.5-1/less than 0.5.	6	6
		Ventilation*	0/5 – The ventilation area is less than 5%/more than 5% of floor area*. 5 – Equipped ventilators.	10	10
		Noise*	0/2/5 – No/1-2/over 3 noise sources within 500 meters (including traffic noise, industrial noise, building construction noise, social life noise). 0/5 – The living room is/isn’t close to the elevator.	10	7
	NA_4 Equipment	Basic equipment*	Adding the following items together: 2.5 – Drain system. 2.5 – Electrical system. 2.5 – Water system. 2.5 – Gas system.	10	10
		Safety equipment	Adding the following items together: 5 – Fire safety equipment. 5 – Emergency equipment.	5	5
		Smart equipment	0 – No smart equipment indoors. 10 – Sensors/detectors/IoT or other smart systems equipped indoors.	0	0
Micro-level **(MI)**: Building/ House	**MI_1** Functional zone	Rest/activity area	0– No rest area is set in public space of buildings. 10 – The rest area is set in public space of buildings.	10	0
		Entrance area*	Adding the following items together: 5 – The rampway, automatic door, and other barrier-free facilities is set in the entrance area of buildings. 5 – The width of the entrance is over 1300 mm.	10	10
		Corridor*	0 - The width of the corridor and doorway is less than 900 mm. 4/6/8/10 – The width of corridor and doorway is over 900/1200/1350/1800mm.*	10	10

	MI_2 Walkability	Circulation pattern	Adding the following items together: 2/5 - The pattern of horizontal circulation is loop or radial/chain. 2/5 - The vertical circulation is via stairs/elevators.	10	10
		Pedestrian-friendly design	Adding the following items together: 2 - Non-slip floor. 2 - Floor without drop height. 2 – Ramp. 2 – Handrail. 2 – Others.	8	6
		Direction signage	Adding the following items together: 4 – Necessary direction signage is set. 3 – Contents of direction signage are clear and easy to understand. 3 – The size of direction signage is big and visible.	4	4
	MI_3 Safety	Entrance guard	0 – No entrance guard. 10 – Security guards or electrical guard system.	5	5
		Lighting at night	Adding the following items together: 5 – Enough natural lighting. 5 – Artificial lighting system.	5	10
		Danger alarm and escape route	Adding the following items together: 5 – Danger alarms are set for danger warning (smoke detector, fire alarm, etc.) 5 – The signages and maps of escape routes are shown clearly.	10	10
		Warning sign	Adding the following items together: 4 – Necessary warning sign is set. 3 – Contents of warning sign is also clear and easy to understand. 3 – The size of warning sign is also big and visible.	4	7
Meso-level **(ME)**: Community/ Neighbor-hood/Block	**ME_1** Walkability	Pedestrian amenities	0 – No pedestrian paths/sidewalks/trails for walking. 5 – Main streets have paths/sidewalks/trails for walking. 10 – All streets have paths/sidewalks/trails for walking, or specific walking ways are set.	5	10
		Crosswalk	Adding the following items together: 2 – Traffic signal. 2 – Zebra crossing.	4	6

		2 - Enough traffic signal time. 2 – Audible traffic signals. 2 – Push-to-walk button.		
	Topography	0 – Rugged. 5 – Slight rugged. 10 – Flat.	5	10
	Outdoor seating	0 – No rest place. 5 – Few outdoor seating alone sidewalks. 10 – Regular outdoor seating alone sidewalks.	5	0
	Street signage	2 – Necessary direction signages are set. 6 – Contents of direction signages are clear and easy to understand. 10 – The size of direction signages are big and visible.	6	10
ME_2 Accessibility to facilities	Entertainment and exercise facility	0 – No parks, green spaces, exercise facilities, community centers, and other entertainment and exercise facilities with walking distance (500 meters). 2 points per entertainment and exercise facility.	4	10
	Shopping facility	0 – No groceries, markets, shopping centers, and other shopping facilities within walking distance (500 meters). 5 points per shopping facility.	10	10
	Medical facility	0 – No drugstores, pharmacies, community clinics, hospital outpatient and other medical facilities within walking distance (500 meters). 2 points per medical facility.	10	10
	Transportation stop	0 – No public transportation stop within walking distance (500 meters), like bus stops, subway stations, and ferry terminal. 5 points per transportation stop.	10	10
	General facilities	0 – No bank, laundry store, bookstore, library and other facilities providing general services within walking distance (500 meters). 2 points per general facility.	10	10
ME_3 Community service	Food programs	0 – No food programs provided in community/neighborhood. 5 – Particular food programs provided in community/neighborhood. 10 – A series of food programs provided in community/neighborhood.	5	0

		Community-based care services	0 – No IADL services provided in community/neighborhood. 5 – Particular IADL services provided in community/neighborhood. 10 – A series of IADL services provided in community/neighborhood.	5	0
	ME$_4$ Safety	Traffic safety	Adding the following items together: 4 – Lmited speed. 4 – Average daily traffic. 2 – Guardrail on the main streets.	8	10
		Warning sign	Adding the following items together: 4 – Necessary warning sign is set. 3 – Contents of warning sign is also clear and easy to understand. 3 – The size of warning sign is also big and visible.	0	7
		Lighting at night	0 – No streetlamps within the community/neighborhood. 5 – Number of streetlamps within the community/neighborhood is adequate. 10 – Number of streetlamps at regular intervals within the community/neighborhood is adequate.	10	10
		Crime	0/5/10 – The annual crime rate is over 1/between 0.5 and 1/ less than 0.5 per 100 thousand.	10	10
		Security and police service	Adding the following items together: 5 – Security services (security guards, electrical guard system, CCTV, etc.) provided within the neighborhood. 5 – Police services (emergency call boxes, police patrol, policy station, etc.) provided within the neighborhood.	10	10
Macro-level **(MA)**: District/ Region/ City	**MA$_1$** Citywide medical infrastructure	Availability	0 – No district-wide infrastructure (medical infrastructure). 2 points per district-wide infrastructure.	10	4
		Accessibility	Shortest distance to citywide care infrastructure (municipal hospitals, city hall, and other municipal services). 10 – 2km. 8 – 5km. 6 – 10km. 4 – 20km. 2 – More than 20km More than 20km.	6	10

	MA_2 Intercity transportation infrastructure	Availability	0 – No coach stations, railway stations, airports and other intercity transportation hubs. 2 points per intercity transportation hub.	10	6
		Accessibility	Shortest distance to citywide care infrastructure (municipal hospitals, city hall, and other municipal services). 10 – 2km. 8 – 5km. 6 – 10km. 4 – 20km. 2 – More than 20km.	6	8

Notes: * depends on local standards, this example refers to the Chinese national building standards: "*Uniform standard for design of civil buildings*" (GB 50352-2019), "*Residential building code*" (GB 50368-2005), "*Code for the thermal design of civil building*" (GB 50176-2016), "*Standard for urban residential area planning and design*" (GB 50180-2018).

Table A2

The fuzzy-AHP questionnaire for the **spatial levels**

Code	E. Imp. (9,9,9)	V. Imp. (6,7,8)	S. Imp. (4,5,6)	M. Imp. (2,3,4)	Indicator A	Eq. Imp.	Indicator B	M. Imp. (2,3,4)	S. Imp. (4,5,6)	V. Imp. (6,7,8)	E. Imp. (9,9,9)
1					Functional zone		Walkability				
2					Functional zone		Safety				
3					Walkability		Safety				

Note: please mark with one symbol in the blank of each line based on your consideration.

Table A3

Example of fuzzy-AHP questionnaire for indicators of **micro-level**

Code	E. Imp. (9,9,9)	V. Imp. (6,7,8)	S. Imp. (4,5,6)	M. Imp. (2,3,4)	Spatial level A	Eq. Imp.	Spatial level B	M. Imp. (2,3,4)	S. Imp. (4,5,6)	V. Imp. (6,7,8)	E. Imp. (9,9,9)
1					Nano-level		Micro-level				
2					Nano-level		Meso-level				

3	Nano-level	Macro-level
4	Micro-level	Meso-level
5	Micro-level	Macro-level
6	Meso-level	Macro-level

Note: please mark with one symbol in the blank of each line based on your consideration.

Table A4

The envelop information of housing examples 1&2

Envelop	Example 1	Example 2
Exterior wall	Brick; polystyrene insulation; dense concrete, dense plaster. (U=0.550)	Cast-in-place reinforced concrete wall; insulated composite external formwork (SXPS core); cement mortar; white flax color stone. (U=0.300)
Roof	Asphalt; screed; dense concrete; dense plaster. (U=2.024)	C20 fine aggregate concrete; waterproof layer; C20 fine aggregate concrete; extruded polystyrene board; cement expanded perlite; reinforced concrete. (U=0.370)
Floor	Vinyl floor covering; screed; concrete. (U=1.250)	Floor tiles; cement mortar; C15 fine aggregate concrete; extruded polystyrene panels; reinforced concrete laminated slab. (U=0.470)
Window	Arched window with double glazing - clear/low-E (e=0.05) glass. (U=1.987)	Window with low-e triple glazing (U=1.455)

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: