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From Comparative and Statistical Assessments of Liveability and Health Conditions of Districts in Hong Kong towards Future City Development

Yan Ling Chi [1,†] and Hugo Wai Leung Mak [1,2,3,*,†]

[1] Department of Geography, The University of Hong Kong, Pokfulam, Hong Kong, China; u3546774@connect.hku.hk
[2] Department of Electrical and Electronic Engineering, The University of Hong Kong, Pokfulam, Hong Kong, China
[3] Department of Mathematics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
* Correspondence: hwlmak@ust.hk
† These authors contributed equally to this work.

Abstract: Liveability is an indispensable component in future city planning and is practically linked with the health status of individuals and communities. However, there was nor comprehensive and universal district-level framework for assessing liveability due to geospatial and social discrepancies among different countries. In this study, using Hong Kong, a highly dense and international city as an example, the Liveability and Health Index (LHI-HK) consisting of 30 indicators was established, with 21 of them related to education, economy, housing, walkability/transport, environment, and health facilities aspects, while the health conditions of citizens in individual districts were examined by other 9 indicators. Respective scoring allocation was determined by statistical reasoning, and was applied to quantify the connections between liveability and health among the 18 districts of Hong Kong in both 2016 and 2019. Temporal changes of spatial features could be traced by this quantitative framework, and obvious correlations between liveability and health were attained, with R values of 0.496 and 0.518 in 2016 and 2019, and corresponding slopes of 0.80 and 0.88, respectively. Based on the statistical results, it was found that Sai Kung and Kwun Tong are the most and the least liveable district of Hong Kong in 2019. The LHI-HK index was well-validated by renowned AARP liveability index and The California Healthy Places Index (HPI), with R values of 0.90 and 0.70, and the potential uncertainties due to data projection were less than 2.5% for all districts, which implicates its relevancy and appropriateness in conducting similar spatial assessments in international cities. Further, both favorable and unfavorable spatial arrangements of each of the 3 district types in Hong Kong were identified, namely residential, commercial, and industrial districts. This opens new windows in enhancing liveability and health status within communities, with the aim of promoting the sustainability of cities in the long run.

Keywords: Liveability and Health Index (LHI-HK); statistical scoring framework; geospatial and data analytical assessment; environmental impacts; urban development; sustainability and liveable neighborhood

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Citation: Chi, Y.L.; Mak, H.W.L. From Comparative and Statistical Assessments of Liveability and Health Conditions of Districts in Hong Kong towards Future City Development. *Sustainability* **2021**, *13*, 8781. https://doi.org/10.3390/su13168781

Academic Editor: Marichela Sepe

Received: 30 June 2021
Accepted: 30 July 2021
Published: 5 August 2021

1. Introduction

The concept of liveability has begun to attract worldwide attention since the 1970s [1,2], and is comprised of multi-dimensional criteria and measures, thus, it is tremendously difficult to lay down an explicit definition, or to quantify the degree of liveability objectively [3]. Generally speaking, a liveable city attempts to equip individuals of specific communities with strong sense of satisfaction and well-being, mainly via the incorporation and enhancement of existing environmental, geospatial, and social characteristics and facilities, via infrastructural planning, reducing population density within each community, enhancing the aesthetics of surrounding environment, accessibility, ensuring the provision of basic necessities and services, as well as outlying feasible land-use distributions during city planning processes [4]. According to [5], the formation of "liveable cities" requires the global cooperation of different governments and multiple-level organizations, with the aim of fulfilling the United Nations (UN) Sustainable Development Goals, which emphasize on promoting good health conditions and well-being, responding to climatic changes, and creating a harmonious living environment for human settlement [6]. The liveability of built environment and impervious surface is also crucial in improving the quality of life of residents [4], however, the yearning and desiring for liveability could actually vary among time and spatial contexts. Thus, there has been no coherent standard, benchmarks, nor theoretical framework to assess "liveability", because different cities impose different emphases and weighting factors towards the individual liveability aspect [2]. Based on the "concept of places" as proposed in [7], liveability encircles different socio-economic components, and particularly embodies the characteristics of community and home; while transportation and street-level spatial features are also considered as important ingredients of liveability, and are often connected with urban planning [8,9]. To narrow down the concept of liveability, extra attention has been paid to environmental perspectives, which can be summarized as sustainability, quality of life, and place, where place generally refers to the environmental features that each individual can interlink with nature [10]. Moreover, the authors of [11] investigated liveability with a housing perspective and defined a liveable community as a safe and secure spatial region, and space being equipped with affordable housing and sufficient transport options. To account for these multi-dimensional perspectives, the U.S. Partnership for Sustainable Communities has set up 6 liveability principles in 2014, namely, diverse choices of transportation, support neighborhood, value communities, competitiveness of the economy, affordable housing, and policies coordination [12]. These dimensions have generally been applicable for conducting spatial assessments and reviewing the strengths and deficiencies of cities in terms of liveability. Nevertheless, due to urbanization, the trend of empirical studies has shifted more to socio-economic side, particularly for Eastern countries. Governments from Eastern cities and some Eastern researchers examine liveability via both physical and socio-cultural dimensions, and consider public governance, security and stability as crucial factors, apart from the aforementioned 6 principles [13].

In modern societies, the concept of liveability has always been connected to health status. The idea of healthy cities was launched by the World Health Organization (WHO) in 1986, when respective Healthy Cities Programmes (HCP) were set-up in more developed countries, like the United States and Canada, to offer basic healthcare and hygiene service, and to develop health-supportive campaigns that could effectively promote good living qualities [14]. Physical, psychological, and social health conditions were also being placed at the topmost item of the agenda of urban development [15]. For Hong Kong, despite the recognized importance of health, the first Healthy Cities project actually began in Tsueng Kwan O (a new town in the Sai Kung district) in 1997 and was led by the Haven of Hope Christian Service, a local non-governmental organization [16]. Despite the direct linkage between the two concepts, "liveability" and "health", previous research has only focused on connecting health and selected liveability components, for example, education and environment [17–20]. In particular, as illustrated in [21,22], unfavorable indoor housing conditions could lead to different physical and mental health problems, like asthma and respiratory infections, and could diminish indoor air quality, while the more frequent use of vehicles and the lack of safe walkways could potentially result in additional health risks towards vulnerable groups [20]. Nevertheless, the presence of urban green spaces like green roofs, parks, and community gardens provide space for local citizens to conduct more physical activities and reduce environmental noise pollutions, thus enhance the health qualities of citizens [23]. Further, positive correlation was found in between schooling and satisfactory health conditions [18], and favorable health conditions could increase individual's income level and upgrade one's socio-economic status in long run [24]. However, the potential statistical connection between overall liveability levels (or district-wise liveability) with health qualities was seldom investigated, especially for urban high-rise cities, thus inducing the first research gap that motivates current study [25].

In recent decades, different indices and quantitative approaches have been developed to rank cities based on their individual performance in different liveability dimensions. Highlighted measures include the Global Liveability Index (GLI) by the Economist Intelligence Unit (EIU) [26,27], Mercer Quality of Living Survey [28], Organization for Economic Cooperation and Development (OECD) Better Life Index (BLI) [29], which published a ranking list of the top liveability cities on an annual basis. Based on EIU assessment, which ranks cities based on their relative performance in 30 quantitative and qualitative factors selected from 5 different categories [26], the top three most liveable cities in 2019 were Vienna, Melbourne, and Sydney [30], while Hong Kong ranked only the 38th under the same assessment framework, despite its extraordinary performance in natural environment and public transportation [1]. Similarly, Mercer's Quality of Living Survey was predominantly designed to evaluate the living quality of over 460 global metropolises, with the aid of totally 39 indicators; while the OECD BLI quantifies the living standard of local residents in 35 OECD nations via an interactive online platform, in terms of 11 socio-dimensions [31]. This index is unique because users can freely impose different weightings on various indicators, which means that the scoring framework is subjecting to the decision of users, thus may take subjective opinions into account during model development. Further, controversies and disputes arising from practical implementation of frameworks easily exist. General public would question the methodologies of mark calculation and the imposition of different weightings to individual indicator [32], which could result in scoring discrepancies. For example, Melbourne ranked top in the EIU assessment framework, but was only placed the 18th in the Mercer's Quality of Living Survey [33]. On top, the usage of a single numerical value to quantify liveability performance might not be comprehensive [32], thus it is vital to include the most appropriate liveability dimensions and constraints for conducting spatial assessments.

For Hong Kong, the government has made concerted efforts to promote liveability at the district level, especially in recent years. The Clean Air Plan was formulated and published in 2013 to combat air pollutions originated from transports, power plants, and non-road mobile machinery, with the aim of reducing public health risks [34]. Then, consultancy studies were initiated by the Transport Department in 2017, to acquire realistic spatial profiles of Hong Kong via appropriate liveability scoring techniques, which can transform Hong Kong into a pedestrian-friendly and walkable city [35]. Moreover, the Long-Term Housing Strategy Annual Progress Report released in 2020 also targeted at identifying suitable land for reclamation and providing sufficient housing units in the next 10 years to satisfy housing demands and improve district-wise liveability conditions [36]. This means that liveability has already been embraced into the forthcoming city planning agenda of Hong Kong, which can easily be visualized from the building blocks of the Hong Kong 2030+ document [37]. Although there are many available liveability assessment frameworks applicable in East Asia, these methods only display the total score of each city, but without explicit explanation of the scoring process, while very few studies have actually concerned the relationships between district-wise liveability and health performance of urban high-rise cities like Hong Kong. Therefore, this study attempts to fill these observable research gaps, via the development of the Liveability and Health Index (LHI-HK). This new index can examine liveability conditions of all 18 districts of Hong Kong and evaluate the correlation between liveability and health scores obtained by districts. Based on in-depth statistical analyses, some spatial features that enhance liveability and health status of selected districts were identified, which could provide urban planning recommendations to high-rise urban communities, as a result constitute to better health conditions in the future.

In this paper, Section 2 describes the spatial characteristics of the study area, Hong Kong; the data collection processes; the methodologies of setting up the quantitative LHI-

HK framework; and all detailed mathematical formulation adopted. Then, Sections 3.1–3.3 provide a list of factors applied throughout the framework development process, followed by the liveability and health performance of all Hong Kong districts based on consistent grading criteria, together with the temporal changes observed from 2016–2019. Next, spatial variabilities and favorable practice that enhance liveability of individual district are discussed in Section 4.1. The newly established LHI-HK was also validated by two renowned indices in Section 4.2, namely the AARP and the California Healthy Places Index (HPI), while potential numerical uncertainties due to projection were derived in Section 4.3. All these have confirmed the applicability of this framework into conducting spatial liveability assessments. Some limitations and potential extensions of the current study are highlighted in Section 4.4. A short summary of current research and some recommendations on enhancing the sustainability of cities is provided in Section 5, with the aim of creating a liveable, harmonious, and healthy community via different spatial land-use contexts.

2. Data Collection and Methodologies

2.1. Study Area

Hong Kong (Longitude from 113°49′–114°31′ E; Latitude from 22°35′–22°8′ N), situated in the south-eastern coastal region of China, has a total area of 1106.81 km^2, and covers the New Territories, the Kowloon Peninsula, Hong Kong Island, Lantau Island, and 262 outlying islands [38,39]. Figure 1 shows the map of Hong Kong, with each of the 18 districts and respective population densities clearly indicated. As of 2020, only 24.9% of its available land has been fully developed or utilized, as public and private residential land, rural settlement, industrial land, commercial land, government, institutional, and community facilities, and railways, while around 65.4% of available land were categorized as either grassland, woodland, or shrub-land, which need long-term land use planning for appropriate utilization [40]. To assess the liveability performance of individual district in Hong Kong, various socio-economic attributes must be taken into consideration, in particular, from aspects like housing, education, surrounding environmental conditions, and accessed facilities. From the latest figure in 2019, Hong Kong has a population of around 7.5 million, with a population density of around 6880 people per km^2. Kwun Tong situated at the Kowloon Peninsula is the most densely populated district of Hong Kong, while Islands, North, and Tai Po in the New Territories are the least dense [39]. In terms of education status in 2016, over 40% of population aged 15 and over in Central and Western and Wan Chai had received post-secondary education, followed by Eastern, Kowloon City, Islands, and Yau Tsim Mong. On the contrary, relatively less residents in inland districts (i.e., the New Territories) received higher education trainings. Similarly, such spatial variabilities also exist in terms of economic status as of 2016—the median monthly domestic household income of districts in Hong Kong Island (including Central and Western, Wan Chai, Eastern, and Southern) and Sai Kung are higher than districts in the New Territories and Kowloon, for example, Yuen Long, Tuen Mun, Kwai Tsing, Wong Tai Sin, Sham Shui Po, and Kwun Tong. The former districts earned more than HK $45,000, while the districts in the latter group only received an average of HK $25,000 per month [41]. In terms of meteorological conditions, the temperature could vary a lot among different seasons. In particular, Hong Kong usually has rainy and hot summers, with temperature exceeding 31 °C, and the highest rainfall is often detected in between June to August, however, its temperature can drop to under 10 °C during winters [39].

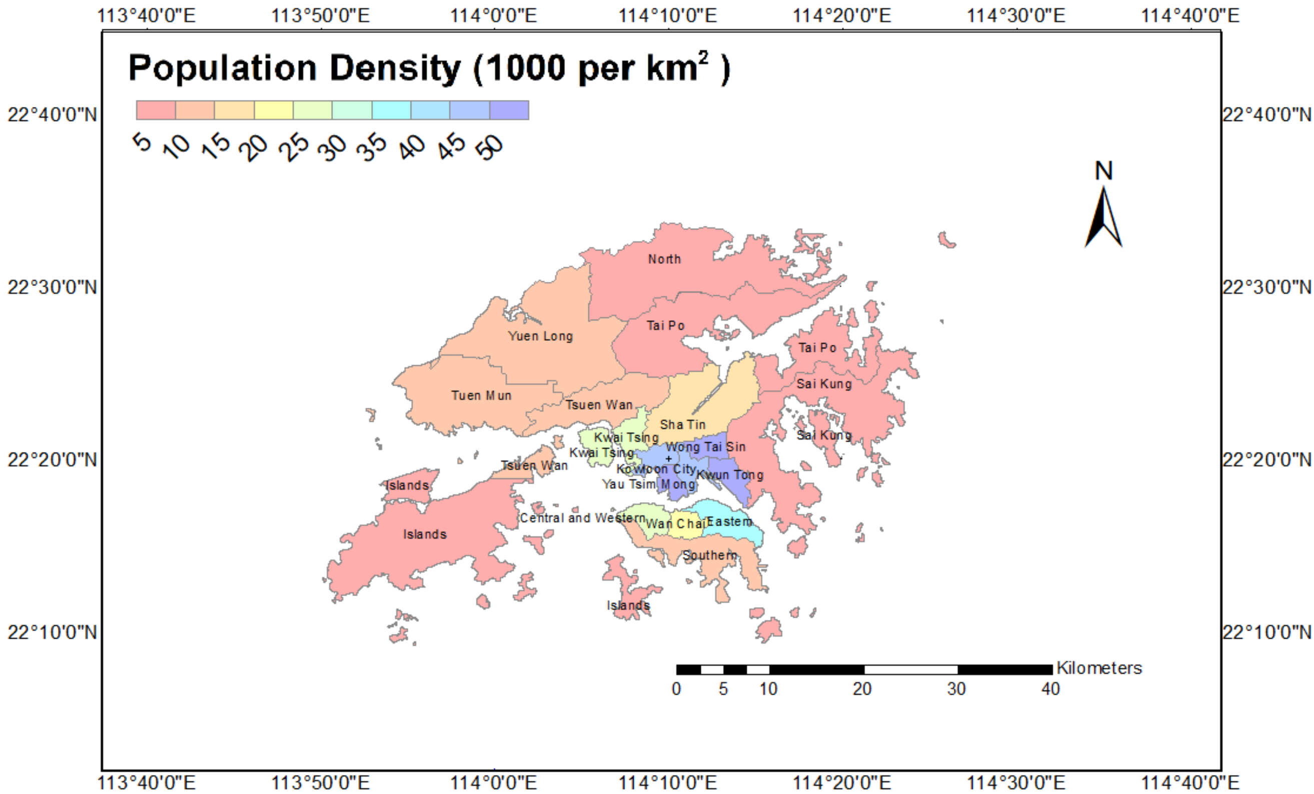

Figure 1. Population densities of 18 districts of Hong Kong, with color bar ranging from 0 people per km^2 to 54,000 people per km^2. The New Territories: Islands, North, Sai Kung, Sha Tin, Tai Po, Tsuen Wan, Tuen Mun, Yuen Long, and other outlying islands; Kowloon: Kowloon City, Kwai Tsing, Kwun Tong, Sham Shui Po, Wong Tai Sin, and Yau Tsim Mong; Hong Kong Island: Central and Western, Eastern, Southern, and Wan Chai.

2.2. Data Collection and Categorization

2.2.1. Overview of Data Collection for LHI-HK Development

In this study, we focus on collecting reliable datasets of indicators that could effectively assess district-wise liveability conditions, as well as health status of residents within the individual district. The collected information and attributes were then converted into numeric for setting up the LHI-HK index, via statistical and spatial considerations. All liveability and health indicators adopted in this study generally satisfy several criteria as follows: (1) The information should be readily available either in reliable sources or collected from recognized surveys; (2) The attribute could be quantified and inter-compared based on objective statistical metrics; (3) The indicator could effectively reflect the liveability and/or health qualities of each district, and has been verified in local context, as well as in other modernized cities.

To maintain the reliability of the LHI-HK framework, most input data are secondary hand data, and were obtained from either government organizations, academic institutions, and citizens' inputs within the regular Population Census. Some were based on participants' response of the "Open Space Opinion Survey" conducted by the Civic Exchange in 2018 [42]. In total, 21 liveability and 9 health indicators were adopted to evaluate the liveability, sustainability, and district-wise environmental and socio-economic conditions in each of the 18 districts. These 30 indicators have been shown to possess particular importance in Hong Kong context, as explained in the following paragraphs. To better group these indicators, and to observe the interdependence and performance of each perspective, the 21 liveability indicators were categorized in 6 representative categories, namely Education, Economy, Housing, Walkability/Transport, Environment, and Health Facilities, while the 9 health indicators assessed both physical and mental health conditions. Further, to account for potential periodic changes and spatial features that have taken place in recent years, this study collected information of both 2016 and 2019, whenever possible. However, due to the irregular updating of websites, the acquisition and latest updates of some indicators as of 2019 were not available. For those cases, we refer to the latest available data entries from respective secondary sources. For example, the record of "Number of old and valuable trees" and "Number of greening and landscape assets" were last updated on 12 May 2020 and 26 June 2018, and the record of "Number of hospitals, specialist outpatient clinics, and general outpatient clinics" under the Hospital Authority (HA) were based on datasets from 2016–2017 and 2018–2019. Further, the "Total length of walking tracks" of each district was last revised on 1 January 2021, while the "Total number of sports facilities" was updated in either 2019 or 2020. The details of all these 30 liveability and health indicators adopted in LHI-HK framework, together with their official and unofficial sources were enlisted in Table S1.

2.2.2. References and Local Contexts of 6 Liveability Categories

This study attempts to study the overall statistical connections between liveability criteria and health status, which was seldom explored in literature. Nevertheless, previous studies have focused on assessing the potential relationship between each liveability category and health, and included more preferred spatial features that could promote sustainability and resilience of a community.

As highlighted in [17,43], education is a significant determinant of liveability, and education level is closely connected with morbidity and mortality. People with lower educational attainment tend to possess poorer health conditions throughout their lives [43]. On the contrary, more educated group can acquire better opportunities and medical resources, which result in better physical and psychological health status [44]. For Hong Kong context, the government has provided 12 years of free education to all students [45], thus, this study only focuses on investigating the proportion of people having received post-secondary education or above.

For Economy, employment rates could effectively symbolize social gradients of our community and affect both mental and physical health conditions [17]. Further, working hours is a unique indicator in Hong Kong, because its average number of working hours (i.e., 42 h per week) has exceeded international standard, and is even higher than that in South Korea (41 h), Japan (38 h), the United States (37 h), and the United Kingdom (36 h) [46]. The long working schedule could result in negative physical health impacts, such as higher risks of hypertension, obesity, coronary heart diseases, as well as associated physiological pressure and mental health challenges like insomnia [47], therefore, heavy emphasis should be imposed on this indicator when conducting liveability assessments in Hong Kong.

In terms of housing, Hong Kong is especially famous for its expensive housing price, mainly due to the scarcity of land [48]. The median price of a property in Hong Kong is around 20 times of annual median household income of the working force [49]. The rental market of Hong Kong is equally expensive, thus, people could only rent a small place with huge rents [50]. It was observed that Hong Kong citizens can only settle in restricted areas, because of high demand for housing but with limited supply in the housing market [48], thus homeownership and housing types could likely influence the liveability of the surrounding environment, as well as mental health conditions [51].

The role of transport is significant for promoting sustainable city development, as an easily accessible transportation network could better support human activities, like the accessibility to health and social service [17]. Further, possessing a walkable neighborhood environment could also facilitate mobility and bring favorable environmental impacts, like the reduction of greenhouse gases [17]. Hong Kong was ranked the first in Urban Mobility Index 2.0, and its public transportation system is high performing despite the high-density spatial context [52]. The connection between transportation system, walkability, liveability, and health was further incorporated in this study.

Moreover, research in the United Kingdom has shown that people who can gain access to green space will generally encounter less depression, while exposure to traffic noise and pollution will result in respiratory diseases like asthma, chronic, and heart diseases [19]. The latter conclusion has already been verified within Hong Kong context, via the advanced data analytic framework for assessing street-level traffic emission variabilities and evaluating its connection with undesirable health effects [53]. Due to dense morphologies and complex urban structures, vehicular pollutants are usually being trapped in between the tall buildings situated on two sides of a road, which result in street canyon effect and the lack of proper air ventilation [34]. This could possibly cause devastating physical health impacts to pedestrians. Further, Hong Kong is also suffering from Urban Heat Island (UHI) effect, which is not merely an environmental problem, but could be a potential hazard for public health, because hot weather can lead to heatstroke and cardiovascular diseases [54]. For example, Hong Kong has experienced an average daily temperature of 33 °C or above in more than 30 days of 2019, accompanied by an upsurge number of hot nights during the same period [54]. Thus, the average temperature, population density, and air pollution figures of 18 districts were also included in LHI-HK framework development.

Finally, for health facilities, as remarked in the case study of Melbourne in [43], distance to medical clinics, accessibility to different services like community centers and hospitals within Australia, and other indicators have been incorporated into analyzing liveability in the neighborhood context. As for Hong Kong, similar spatial coverage of health services as provided by HA are Chinese medical services, rehabilitation, pharmacy, and physician consultation [55]. Its healthcare system is at a worldwide leading position, because of its ease of accessibility, affordability, and the provision of comprehensive and lifelong health services [56]. Hence, appropriate indicators have also been included in current spatial and district-wise assessment framework.

2.3. Data Handling and Scoring Framework

2.3.1. Overall Development of Liveability and Health Index-Hong Kong (LHI-HK)

The LHI-HK development relies on quantitative and statistical approaches, while in-depth spatial analyses and the identification of urban planning work conducted in different district types were explored in qualitative means. Upon the collection of information of all 21 liveability and 9 health indicators in 2016 and 2019 whenever possible, projection technique was first applied to fill in missing data entries of some indicators in 2016 or 2019, despite some foreseeable uncertainties were observed. The estimation was conducted by calculating the percentage change of respective quantities during the 2011–2016 period, together with some assumptions imposed. Next, district-wise scores of each indicator within the LHI-HK framework were calculated based on one or two of the three scoring methods, namely (1) Proportion to the largest value; (2) Standard score approach; and (3) Relative score approach (see Section 2.3.3). This is with reference to approaches in handling education and financial data, like predicting performance of an individual student in a test or estimating future stock price based on available data entries [57–59]. Then, 3 case studies were set up to determine the best mathematical formula for assessing liveability conditions of Hong Kong districts. The rationales of respective case studies were explained in Section 2.3.4, while the health score was simply the weighted sum of all scores obtained in the health indicators. Finally, both liveability and health scores were normalized, for the purpose of conducting systematic comparisons, and for identifying the potential linkage between these two important concepts of sustainable city development. It is remarked that some indicators would not possess huge fluctuations within few years' time, for example, total number of sports facilities, total length of walking tracks, and the number of greening and landscape assets, thus the latest available datasets have been directly adopted for statistical assessment. Figure 2 shows the flowchart of this study, from the development of LHI-HK framework to both quantitative and qualitative assessments conducted.

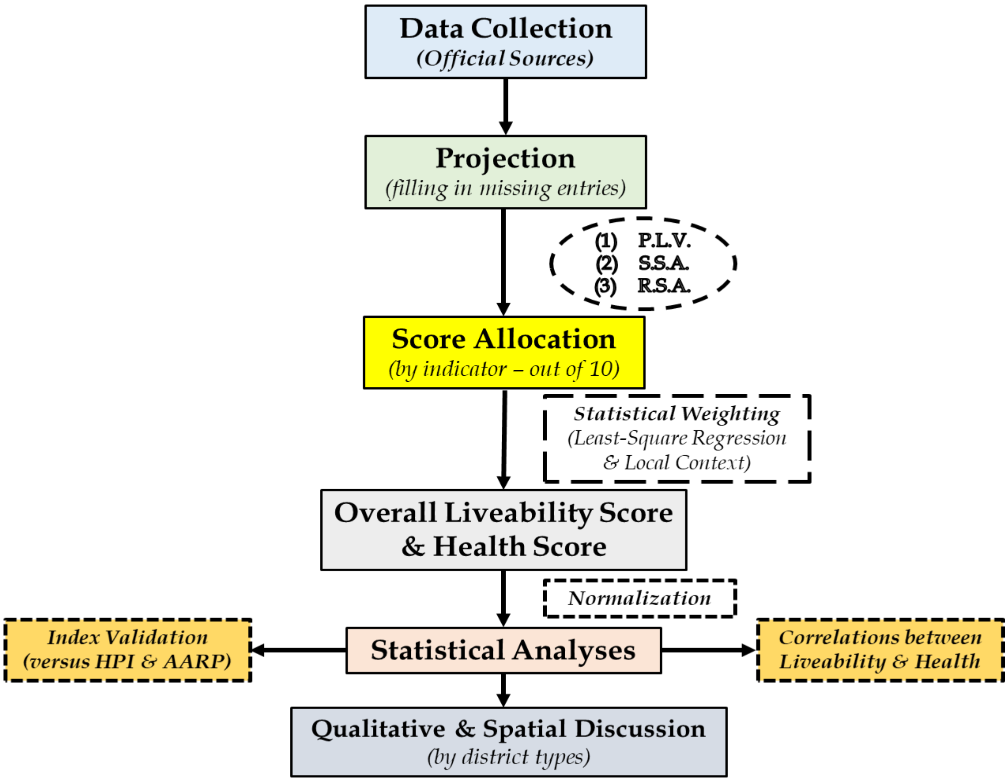

Figure 2. Overall flowchart of LHI-HK framework—Collection of datasets; Scoring Process; Statistical Analyses, Qualitative and Spatial Discussions, with Techniques and Approaches in dotted boxes. P.L.V.: Proportion to the Largest Value; S.S.A.: Standard Score Approach; R.S.A.: Relative Score Approach; HPI: The California Healthy Places Index (the United States); AARP: AARP Liveability Index.

2.3.2. Projection of Missing Entries

The raw liveability and health data collected from different sources (as indicated in Table S1) were first inputted into the database for appropriate score allocation (discussed in Section 2.3.3). Although the data entries of most attributes are complete, 3 liveability indicators consist of missing entries in 2019, namely "Median rent to income ratio (%)", "Proportion of domestic households owning the quarters they occupy (%)", and "Proportion of working population with place of work in same district of residence (%)". Therefore, a scientific approach of filling in all these missing entries is necessary for investigating the periodic changes of liveability and health performance from 2016 to 2019, before raw values were converted into scores via different scoring methods.

In this study, we imposed an assumption that the annual percentage change of these 3 concerned quantities is the same throughout the entire investigated period. Based on the corresponding numerical figures of 2011 (V_{2011}) and 2016 (V_{2016}) obtained from Population By-Census of Hong Kong [60,61], the missing entries in 2019 (V_{2019}) were computed by Equation (1), based on the concept of "linear trend model" in statistics [62] and "inverse distance weighting interpolation" in Numerical Analysis [63]. Here, P denotes the overall percentage change that took place during the previous 5-year period (i.e., from 2011–2016), and it is assumed that the percentage change observed was distributed equally among the years.

$$\begin{cases} P = \frac{V_{2016} - V_{2011}}{V_{2011}} \times 100\% \\ V_{2019} = V_{2016} \cdot \left(1 + \frac{P}{5} \times 3\right) \end{cases} \tag{1}$$

Despite the feasibility to estimate numerical figures of these several parameters in 2019, the linearity assumption may not be true in general. Therefore, the potential uncertainties within the projection process could be brought forward to the final evaluation of district-wise liveability performance. The uncertainty assessments and effects towards final statistical results were outlined in Section 4.3.

2.3.3. Development of Scoring Approaches

After obtaining necessary information for spatial assessment, consistent scoring methodologies are crucial for reflecting relative liveability performance of the 18 districts, and for distinguishing high achievers from relatively low performers. In general, the highest score that the best district could obtain in each indicator was kept at 10, and districts with better performance should receive higher scores than their "competitors". However, for some indicators, the raw numerical values of all districts were very close to each other (e.g., average temperature), or when the performance was actually represented as an inverted distribution (e.g., higher pollution figures or poverty rates in a district actually indicated worse liveability and/or health qualities), thus the concept of "standard score" and the range of scores that the 18 districts could achieve have to be properly defined, based on local contexts. Here, special scenarios like the missing entries at particular district, or the existence of attributes within only 1 year was first handled by "Relative Score Approach (R.S.A.)", followed by either "Proportion to the Largest Value (P.L.V.)" or "Standard Score Approach (S.S.A.)" as appropriate. For the 9 health indicators, scores were calculated either by S.S.A or directly adopted from scores assigned by Civic Exchange [42].

(*a*) *Proportion to the Largest Value (P.L.V.)*

In this study, 5 indicators in 2016 (and 9 indicators in 2019) directly adopted the P.L.V. approach for score conversion, with 10 marks assigned to the best performing district in Hong Kong, i.e., the one that attained the highest value within that measure. This is with reference to the concept of "Numerical Rating Scales" originated from education applications [64]. Some selected indicators include "Educational characteristics (%)", "Median monthly household income from all households (HK$)", "Proportion of domestic households owning the quarters they occupy (%)", and "Number of hospitals, specialist outpatient clinics, and general outpatient clinics under HA". The score of district i (where $i = 1, 2, \ldots, 18$) (S_i) of these indicators is calculated as in Equation (2), where V_i and $V_{\max}$ are the raw values of district i, and the maximum value attained by all Hong Kong districts within that liveability indicator:

$$S_i = \frac{V_i}{V_{\max}} \times 10 \quad (2)$$

(*b*) *Standard Score Approach (S.S.A.)*

The S.S.A. will only be applied to indicators that consist of raw values of all 18 districts, and that fit into one of the two scenarios, namely indicators (1) with sufficiently close enough scores among all 18 districts, i.e., the distribution of scores has an interquartile range of less than 5 (e.g., average temperature); or (2) the scores to be assigned vary inversely as the raw values of the indicators (e.g., $PM_{2.5}$ concentrations, Noise pollution figures). The idea of such scoring approach was again originated from education applications [65]. With sufficiently large number of students in class, teachers can use the S.S.A. approach to assess individuals' relative performance in a test when compared to class mean and understand the deviation behind. The procedures are described as follows:

1. Arrange the raw values of all 18 districts (V_i, where i = 1, 2, ... , 18) for concerned liveability or health indicators, in descending order.
2. Evaluate the mean (μ) and SD (σ) of the distribution obtained in Step 1.
3. Compute the standard score (Z_i) of individual district by Equation (3):

$$Z_i = \frac{\text{Raw value } - \mu}{\sigma} \quad (3)$$

4. Determine the maximum possible score (M_H) and the minimum possible score (M_L) assigned to the best-performing and worst-performing districts, based on the importance of that indicator in Hong Kong context. Detailed criteria and concerned indicators are shown in Table S2. The range of (M_L, M_H) of individual indicator ranges from (2, 10) to (5, 10).
5. Determine the score to be allocated to district *i* (M_i), by assuming that the variation of scores could effectively capture spatial discrepancies of liveability performance in all 18 districts, and proportionality holds. The formulation is as shown in Equation (4), where Z_i, $Z_{\max}$ and $Z_{\min}$ denote the standard score of district *i*, the maximum standard score, and the minimum standard score attained by all districts of Hong Kong, respectively.

$$M_i = M_L + \frac{Z_i - Z_{\min}}{Z_{\max} - Z_{\min}} \times (M_H - M_L) \tag{4}$$

Remark 1: *For indicators with inverted distributions, Equation (5) was applied instead of Equation (4), because it is assumed that the district with higher standard score performs worse in that dimension. The definitions of all notations in Equation (5) are exactly the same as in Equation (4):*

$$M_i = M_H - \frac{Z_i - Z_{\min}}{Z_{\max} - Z_{\min}} \times (M_H - M_L) \tag{5}$$

In this study, a total of 9 liveability indicators (for 2019) or 11 liveability indicators (for 2016), and all 6 physical health indicators directly adopted the S.S.A. scoring method, as listed in Table S1.

(*c*) *Relative Score Approach (R.S.A.)*

R.S.A. was adopted when some entries or records were missing in one of the investigated time period, for example, there was no pollutant concentration data available in Southern, North, and Sai Kung in 2016, because the air quality sensors in these districts did not start operation until 2017 [66]. Thus, a relative score must be first assigned to concerned districts, based on the "relative" values as compared to the best-performing district in 2019. The procedures are described as follows:

1. The missing entry of the concerned district (represented by district *i*) in 2016 was estimated by Equation (6), with $V_{2016,i}$, $V_{2019,i}$, $V_{2016,\max}$ and $V_{2019,\max}$ representing the missing attribute of district *i* in 2016, available attribute of district *i* in 2019, value of that attribute in the best-performing district in 2016, and in 2019, respectively.

$$V_{2016,i} = \frac{V_{2019,i}}{V_{2019,\max}} \times V_{2016,\max} \tag{6}$$

2. After obtaining $V_{2016,1}, V_{2016,2}, \ldots, V_{2016,18}$ of concerned attributes, the scores of each of the 18 districts in 2016 were calculated by S.S.A., as described in (b).

(*d*) *Scoring and Assigning Values for Exceptional Cases*

First, although the interquartile range of "Number of greening and landscape assets" and "Number of hospitals, specialist outpatient clinics, and general outpatient clinics under the HA" were 2.75 (i.e., less than 5), the raw values of 18 districts were quite separated from each other; thus it is easy to distinguish the relative performance of each district. Therefore, the P.L.V. scoring approach was adopted.

Next, indicators like "Working hours", "Median floor area of accommodation (m^2)", and "Walking as main mode of transport to place of work (for working population with fixed place of work)" only consisted of data in 2016, but not in 2011. As a result, projection (see Section 2.3.2) could not be conducted due to the incompleteness of data entries. For these cases, the scores assigned in 2016 were directly transferred to 2019. On the contrary, raw data record of "Number of old and valuable trees", "Noise pollution (% of people exposed to traffic noise exceeding 70 dB)", "Number of greening and landscape assets", "Total length of walking tracks", and "Total number of sports facilities" were only available in 2019 (or in 2020 or 2021), but not in 2016, due to the irregular updates of data record. Thus, scores of these 5 indicators assigned in 2019 (or in 2020 or 2021) were directly adopted for statistical analyses in 2016, and we assume that the relative performance of these large-scale facilities would not have huge discrepancies within the 3-year period.

(*e*) *Score Allocation of available Health Indicators*

All 6 physical indicators adopted the S.S.A. scoring method, and the score distributions range from "2 to 10" to "5 to 10", depending on respective importance within local context. The detailed score range of each indicator is as shown in Table S2. For mental health indicators, the Civic Exchange has conducted a survey, seeking citizens' opinions regarding level of satisfaction towards quantity and beauty of open space, trees, plants, and landscaping [42]. Within that survey, citizens were allowed to fill in integral scores from 0 to 10, with 0 representing "completely dissatisfied", while "10" representing "completely satisfied". This is in line with our scoring assumptions, thus the scores of the 3 health indicators were directly adopted in the LHI-HK framework.

2.3.4. Determination of Multiplying Factors via Statistical and Spatial Means

Based on the scoring approaches introduced in Section 2.3.3, each district was assigned a score (out of 10) for each liveability and health indicator. However, it is important to note that different weighting factors should be introduced to each of the 21 liveability indicators, which were determined based on its potential connection with health status, the consideration of local context in densely populated Hong Kong, and the insights acquired from existing literature.

To determine the most suitable mathematical formula for assessing liveability conditions of individual district in Hong Kong, 3 case studies were first explored, to calculate liveability scores, and to sort out the relation with health status of the 18 districts. It was implicitly assumed that the health scores achieved were objective, which was a valid assumption because majority of scores were obtained from reliable sources. Case Study 1 assigned equal weights to all 21 liveability indicators, thus could not provide realistic and meaningful conclusion within local contexts of Hong Kong. Therefore, case studies 2 and 3 were established to enhance the applicability of our LHI-HK framework, for quantifying the actual statistical connection between liveability and health. These cases first obtained the R values between each liveability indicator and overall health performance of all 18 districts, then determined the appropriate multiplying factor imposed to each liveability indicator. Case study 3 is generally more applicable in Hong Kong, because it has also considered local geographical and spatial features. In particular, housing problems like high property prices and small unit size are unique morphological characteristics of Hong Kong, thus relatively heavier weights should be imposed to "Median floor area of accommodation" and "Median rent to income ratio". Further, Hong Kong is also well-known for its long working hours and high population density [67], which has possibly led to physical and mental health risks and diminished the liveability and sustainability of the community. Thus, higher weightings should be applied to these concerned attributes. For environmental indicators, the report from Clean Air Network has mentioned that the NO_2 pollution of Hong Kong has not improved throughout the past 20 years, with an average roadside NO_2 concentration of 96 $\mu g/m^3$ in 1998, and 98 $\mu g/m^3$ in 2015 [68], imposing huge environmental and health risks at neighborhood levels. The accumulation of O_3 in Guangdong has also caused prolonged impacts on the air quality of Hong Kong and is considered a critical regional issue in recent years [34]. Pollution levels of these chemicals are still not within worldwide targeted limits by 2019 [69], thus easily affect livelihood and sustainability of the society. Therefore, sufficiently high weightings must also be applied to all these attributes. Table 1 below shows the multiplying factors applied to different liveability indicators within each of the 3 case studies explored in this study.

Table 1. Three case studies (as test-cases) for determining the multiplying factors imposed on each liveability indicator, and the selection of one of these approaches for assessing district-wise liveability conditions in Hong Kong, based on the LHI-HK framework.

R Value	Case 1	Case 2	Case 3
$R \geq 0.5$	1	3	*6*
$0.4 \leq R < 0.5$	1	3	*5*
$0.3 \leq R < 0.4$	1	2.5	*4*
$0.2 \leq R < 0.3$	1	2	*3*
$0.1 \leq R < 0.2$	1	1.5	*2*
$R < 0.1$	1	1	*1*
Exceptional indicators (Spatial Consideration)	-	-	*5 for the following indicators:* • Working hours • Median rent to income ratio • NO_2 concentration • O_3 concentration

R value: correlation coefficient—the statistical metric attained in the best-fit line of the concerned liveability indicator against overall health scores (N = 18) (see Section 2.4). *N*: number of data points, i.e., the 18 districts.

2.3.5. Normalization

Based on the concept of "linear combination" in mathematics, the overall liveability $(L_{i,O})$ and health scores $(H_{i,O})$ of district i (without normalizing) were expressed as a weighted sum of the numeric scores obtained within each indicator [70] and were calculated as in Equation (7). Here m_j represents the multiplying factor imposed to the jth liveability indicator, as determined from the best combination of the 3 case studies shown in Table 1. Detailed discussion of m_j is provided in Section 3.1 and Table S3. Here, $0 \leq L_{i,j},\ H_{i,k} \leq 10$, as determined by scoring approaches introduced in Section 2.3.3. Further, it is assumed that all health attributes are equally important in Hong Kong context, therefore the overall health score of all districts is simply the sum of scores (out of 10) attained in each health indicator.

$$\begin{cases} L_{i,O} = \sum_{j=1}^{21} m_j \cdot L_{i,j} \\ H_{i,O} = \sum_{k=1}^{9} H_{i,k} \end{cases} \tag{7}$$

With the aim of standardizing the base scores of liveability and health, normalization was applied, with full score pre-set to be 100 for both quantities. After this process, it suffices to determine whether the slope of the best-fit line between the two quantities is close to 1, and whether the distribution of "normalized liveability $(L_{i,N})$ and health scores $(H_{i,N})$" are uniformly distributed. Equation (8) shows the two formula for calculating $L_{i,N}$ and $H_{i,N}$, with L_F and H_F represent the full liveability and health scores that a district could achieve after the application of weightings to individual indicators.

$$\begin{cases} L_{i,N} = \frac{L_{i,O}}{L_F} \times 100 \\ H_{i,N} = \frac{H_{i,O}}{H_F} \times 100 \end{cases} \tag{8}$$

2.4. Metrics for Statistical Assessments

In this study, different statistical metrics have been applied for multiple purposes. First, without considering the importance of selected liveability indicators in local context, the multiplying factors imposed, as described in Section 2.3.4, were determined mainly by the *R* values obtained from the best-fit line between the desired indicator and overall health performance of all 18 districts. The *R* value of a linear plot ranges from −1 to 1 (inclusive): Having an *R* value of –1 implicates that the two quantities are absolutely and negatively correlated. In contrast, absolutely positive correlations result in an R value of 1. In this study, we assume that an R value exceeding 0.5 implicates a strong correlation between the concerned liveability indicator and health status within Hong Kong. Furthermore, this statistical metric is also adopted to assess the connection between $L_{i,N}$ and $H_{i,N}$ in 2016 and 2019, as well as the inter-comparison of the newly developed LHI-HK framework with other well-known liveability indices.

Other than R values, the slope of the best-fit line represents the steepness of the causal linear relationship: Positive (Negative) slope means that the increase in quantity positioned on the x-axis will likely lead to an increase (decrease) in the quantity of y-axis. On top, p-value, Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and Mean Bias Error (MBE) have also been considered when assessing respective statistical performance. If p-value < 0.05, then the null hypothesis of the original assumption can be rejected, thus the statistical relationship developed becomes valid. RMSE evaluates the error between observed values and corresponding values on the best-fit line, with lower RMSE being more favorable; MAE provides insights of whether the two sets of data are far away from each other; while MBE estimates averaged bias for regression purposes. More significant linear correlation between the two quantities is obtained when the MBE is lower [71–73]. The corresponding formula of these statistical parameters are as shown in Equations (9)–(11), where O_i and P_i represent the observed health score and predicted health performance of district i, based on the linear regressed equation.

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{18}(P_i - O_i)^2}{18}} \tag{9}$$

$$\text{MAE} = \frac{1}{18}\sum_{i=1}^{18}|P_i - O_i| \tag{10}$$

$$\text{MBE} = \frac{1}{18}\sum_{i=1}^{18}(P_i - O_i) \tag{11}$$

3. Results

3.1. Determination of Multiplying Factors and Selection of Case Study

Based on the study of correlations obtained from the linear fit between each of liveability indicator and overall health performance, it was found that only 1 liveability indicator possessed an R value higher than 0.5, that is, the "Median floor area of accommodation (m)". Further, 3 liveability indicators have R values in between 0.4 and 0.5, and in between 0.3 and 0.4, respectively. These include "Median monthly household income from all households (HK$)" (0.417), "Poverty Rate (%)" (0.410), "Population density (people/km^2)" (0.461), "Educational characteristics" (0.378), "Labor force participation rate (%)" (0.353), and "NO_2 concentration (μg/m^3)" (0.384). Following this, 1 indicator had R value in between 0.2 and 0.3, while 5 more indicators with R values in between 0.1 and 0.2 could be found. Then, corresponding multiplying factors within different case studies were determined based on Table 1. As for Case Study 3, the local geographical and morphological contexts were highlighted (as discussed in Section 2.3.4), thus the multiplying factors imposed to the 4 "exceptional indicators" were kept at 5, regardless of whether the corresponding R value lied within the interval of $0.4 \leq R < 0.5$. The detailed slopes and R values obtained in respective best-fit line, as well as multiplying factors imposed on all these 21 liveability indicators $(\{m_j : j = 1, 2, \ldots, 21\})$, were shown in Table S3. Some strange correlations acquired will be explored in Section 4.4, which served as part of the limitations of this study. The Analytic Hierarchy Process (AHP) proposed in [74] was adopted here to represent the entire scoring framework, and the weighting assigned to each individual liveability indicator. AHP has been widely applied in many daily life aspects, for example, identifying suitable and available sites for groundwater recharge and dams [75,76], handling problems of conflict managements [77], making wise decisions by identifying ultimate goals, then breaking down complicated decisions and opportunities into different parameters [76].

Further, via the calculation of different weighting of attributes within an index, potential suitable sites and final decisions can be uniquely determined [75,76], while the assigned weightings can be determined from various studies, intensity of the parameters, and geographical context [76]. Here, AHP of this study began with the goal of this study, followed by listing out different liveability categories and weighting assigned to each indicator, then eventually to alternatives (i.e., the candidate of the most liveable district of Hong Kong), as shown in Figure 3 below.

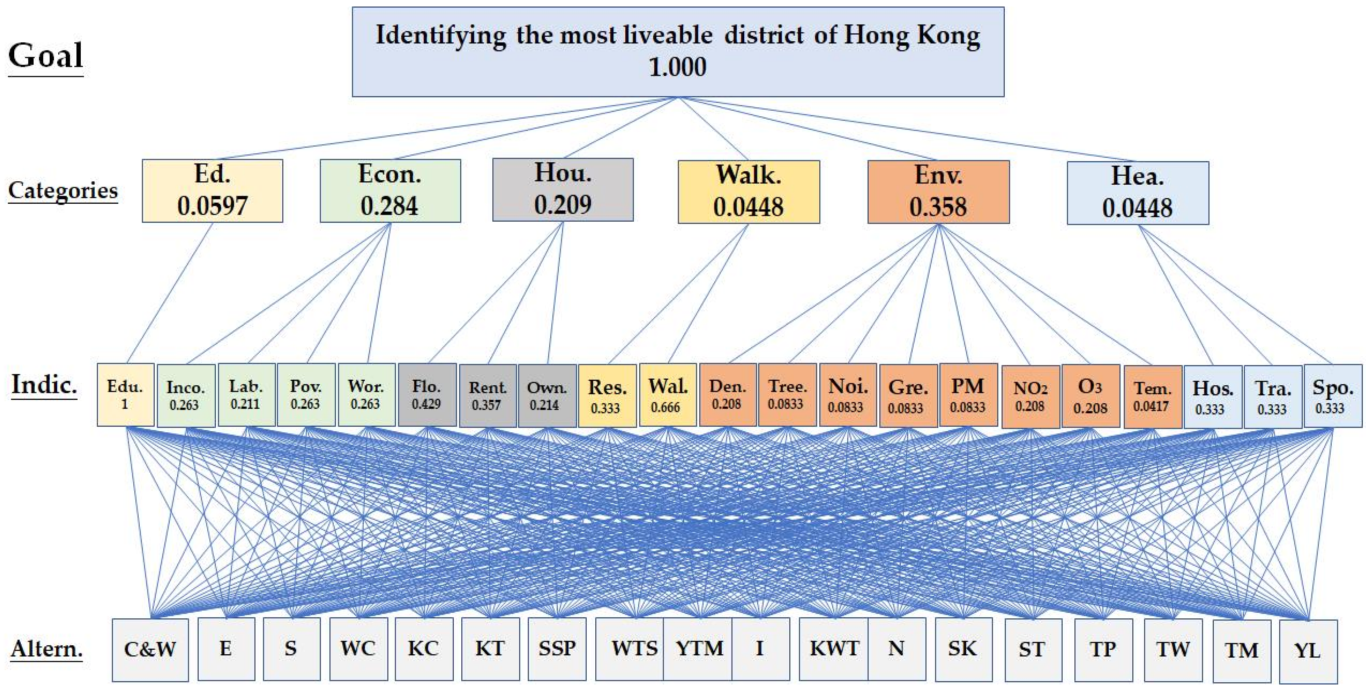

Figure 3. Analytic Hierarchy Process (AHP) of this study, for identifying the most liveable individual district of Hong Kong. Ed.: Education; Econ.: Economy; Hou.: Housing; Walk.: Walkability/Transport; Env.: Environment; Hea.: Health Facilities; Edu.: Educational characteristics (Percentage of citizens having post-secondary education: degree-both sexes) (%); Inco.: Median monthly household income from all households (HK$); Lab.: Labor force participation rate (%); Pov.: Poverty rate (%); Wor.: Working Hours; Flo.: Median floor area of accommodation (m^2); Rent.: Median rent to income ratio (%); Own.: Proportion of domestic households owning the quarters they occupy (%); Res.: Proportion of working population with place of work in the same district of residence (%); Wal.: Walking as main mode of transport to place of work (for working population with fixed place of work) (%); Den.: Population density (people/km^2); Tree.: Number of old and valuable trees; Noi.: Noise pollution (% of people exposed to traffic noise exceeding 70 dB); Gre.: Number of greening and landscape assets; PM: $PM_{2.5}$ concentration ($\mu g/m^3$); NO_2: NO_2 concentration ($\mu g/m^3$); O_3: O_3 concentration ($\mu g/m^3$); Tem.: Average temperature (°C); Hos.: Number of hospitals, specialist outpatient clinics, and general outpatient clinics under the Hospital Authority (HA); Tra.: Total length of walking tracks (m); Spo.: Total number of sports facilities; C&W: Central and Western; E: Eastern; S: Southern; WC: Wan Chai; KC: Kowloon City; KT: Kwun Tong; SSP: Sham Shui Po; WTS: Wong Tai Sin; YTM: Yau Tsim Mong; I: Islands; KWT: Kwai Tsing; N: North; SK: Sai Kung; ST: Sha Tin; TP: Tai Po; TW: Tsuen Wan; TM: Tuen Mun; YL: Yuen Long.

Next, the overall liveability scores ($L_{i,O}$) of all districts in 3 different case studies were calculated as in Equation (7), and then were normalized to obtain corresponding $L_{i,N}$'s in 2019, following the approach stated in Equation (8). Based on the resulting best-fit lines of "Health scores vs Liveability Scores" in these 3 case studies, it was observed that the weighted sum of liveability scores in all case studies of 2019 demonstrated significant statistical connections with district-wise health status. The slopes and R values got enhanced after the application of multiplying factors to more "important" and "spatial dependent" liveability indicators, from 0.65 (Case Study 1) to 0.88 (Case Study 3) for slopes, and from 0.331 (Case Study 1) to 0.518 (Case Study 3) for R values, as shown in Figure 4. This indicates that Case 3 of Table 1 is the most appropriate scoring approach for conducting liveability assessment within Hong Kong context.

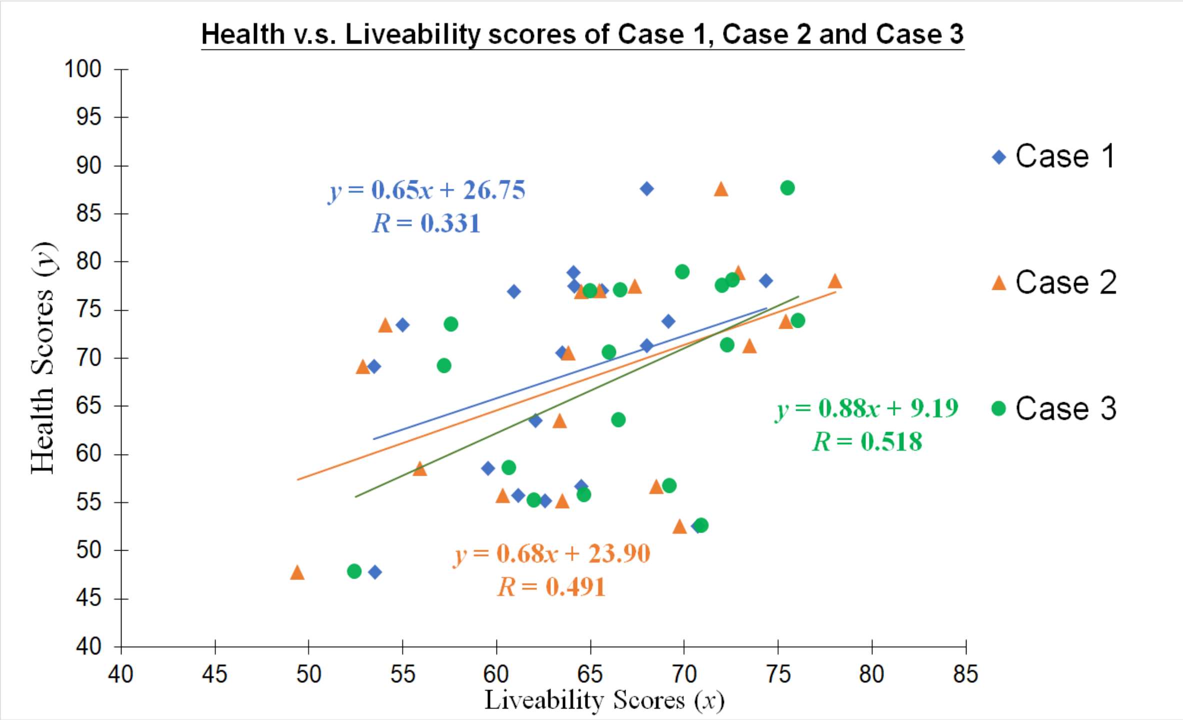

Figure 4. Health scores versus Liveability scores of Hong Kong districts based on different case studies, together with equations of best-fit line and R values of linear fits shown.

3.2. Liveability and Health Performance of All Districts

Table 2 shows the weighted scores of all districts in each of the 6 liveability categories, based on the raw data collected or estimated in 2016 and 2019, and the application of LHI-HK framework illustrated in Figure 2, i.e., different multiplying factors have been imposed to different indicators. The respective health scores and associated rankings of both quantities were also displayed. After obtaining $L_F = 670$ and $H_F = 90$, the scores of each individual district were normalized for conducting statistical comparison. Figure 5 shows the spatial map of Hong Kong, with its overall liveability and health scores in 2019 clearly indicated.

Table 2. Liveability scores of each of the 6 categories, and Health scores of all 18 districts in 2016 and 2019, after appropriate multiplying factors have been applied to each liveability indicator, together with corresponding rankings of liveability and health.

District [$R_{L,\,2016}$;$R_{L,\,2019}$;R_H]	Ed. (40) *	Econ. (190) *	Hou. (140) *	Walk. (30) *	Env. (240) *	Hea. (30) *	Health (100) **
Hong Kong Island							
Central and Western [3; 3; 3]	**38.62 (39.56)**	**153.65 (149.18)**	76.97 (74.62)	**28.78 (28.78)**	179.25 (178.29)	16.10	78.10
Eastern [8; 8; 14]	29.61 (27.97)	153.00 (153.17)	104.53 (103.37)	17.86 (17.77)	135.72 (147.87)	13.93	56.66
Southern [5; 4; 9]	23.91 (24.49)	137.22 (140.59)	102.61 (102.90)	14.73 (14.96)	187.82 (186.83)	14.96	71.31
Wan Chai [7; 7; 2]	40.00 (40.00)	150.85 (149.56)	91.11 (89.15)	21.46 (21.24)	156.86 (157.17)	11.50	78.87
Kowloon							
Kowloon City [13; 11; 10]	27.77 (28.85)	139.69 (142.36)	88.66 (89.19)	16.68 (16.86)	143.35 (145.66)	18.58 (19.58)	70.57
Kwun Tong [18; 18; 18]	**15.08 (15.08)**	**106.17 (96.35)**	**78.02 (78.93)**	17.83 (17.90)	**118.52 (125.07)**	18.38	47.72
Sham Shui Po [16; 16; 8]	21.52 (20.74)	111.32 (121.75)	**72.09 (72.86)**	18.14 (18.31)	136.40 (138.29)	**13.94**	73.46
Wong Tai Sin [17; 17; 11]	**14.80 (15.51)**	**114.89 (115.15)**	93.10 (93.76)	**11.87 (11.99)**	**123.17 (131.91)**	15.36	69.14
Yau Tsim Mong [14; 14; 16]	27.31 (28.85)	120.38 (121.11)	72.23 (71.01)	27.51 (27.67)	150.08 (153.50)	13.50	55.18
New Territories							
Islands [1; 2; 1]	27.49 (25.01)	150.38 (144.35)	123.18 (123.95)	14.81 (14.50)	188.49 (184.30)	14.21	87.67
Kwai Tsing [15; 15; 13]	14.71 (14.99)	118.92 (118.06)	80.97 (81.57)	14.23 (14.24)	152.34 (155.87)	21.92	58.54
North [11; 9; 5]	15.26 (15.77)	98.28 (105.40)	100.62 (100.74)	17.21 (17.40)	189.43 (187.28)	19.83	77.06
Sai Kung [2; 1; 7]	25.10 (26.32)	**155.41 (167.72)**	**120.53 (121.73)**	**10.78 (10.86)**	166.45 (165.41)	17.70	73.80
Sha Tin [6; 6; 17]	23.82 (23.18)	139.38 (133.53)	103.81 (104.16)	12.46 (12.49)	176.63 (177.57)	24.49	52.59
Tai Po [10; 12; 6]	19.95 (20.83)	110.22 (112.06)	103.00 (102.09)	17.64 (18.34)	178.96 (170.67)	11.62	76.98
Tsuen Wan [4; 5; 4]	24.83 (24.49)	159.37 (159.75)	104.08 (102.94)	16.84 (17.09)	166.01 (167.15)	11.35	77.48
Tuen Mun [9; 13; 15]	16.83 (16.03)	125.63 (112.51)	107.47 (107.61)	17.57 (17.76)	167.05 (163.55)	16.08	55.77
Yuen Long [12; 10; 12]	16.18 (16.56)	105.94 (115.52)	111.91 (112.70)	12.78 (12.96)	175.21 (169.76)	17.28 (18.28)	63.48

Ed.: Education; Econ.: Economy; Hou.: Housing; Walk.: Walkability/Transport; Env.: Environment; Hea.: Health Facilities; $R_{L,\,2016}$ Ranking of Liveability in 2016; $R_{L,\,2019}$ Ranking of Liveability in 2019; R_H Ranking of Health. Bolded numerical figures in the Table were described in this section. * All scores are corrected to 2 decimal places, and the numerical figures outside (inside) brackets represent scores of 2016 (2019). ** Normalized Health Score.

Based on the latest scores and rankings as shown in Table 2 and Figure 5, Sai Kung ranked the first in 2019, followed by Islands and Central and Western, in terms of liveability. Their normalized liveability scores (out of 100) were 76.08, 75.57, and 72.62, respectively. Sai Kung outperformed all or most of the other districts in terms of Economy and Housing, and excelled in different liveability criteria as at 2019, for example, "labor force participation rate", "poverty rate", "proportion of domestic households owning the quarters they occupy", "population density", "noise and air pollution", despite its poorest performance in walkability/transport due to its remote geographical location. Islands performed equally well in terms of liveability and health assessments throughout both years and obtained full scores in terms of "number of greening and landscape assets", "population density", and "median floor area of accommodation" in 2019, which clearly showcased its sustainable and decent neighborhood environment for human settlement. Central and Western came the 3rd in both liveability and health, and did particularly well in terms of education, economy, walkability/transport dimensions, for example, with the highest proportion of educated residents, sustainable and user-friendly footbridges that connect one building to another and possess the largest number of old and valuable trees and favorable environment for human activities.

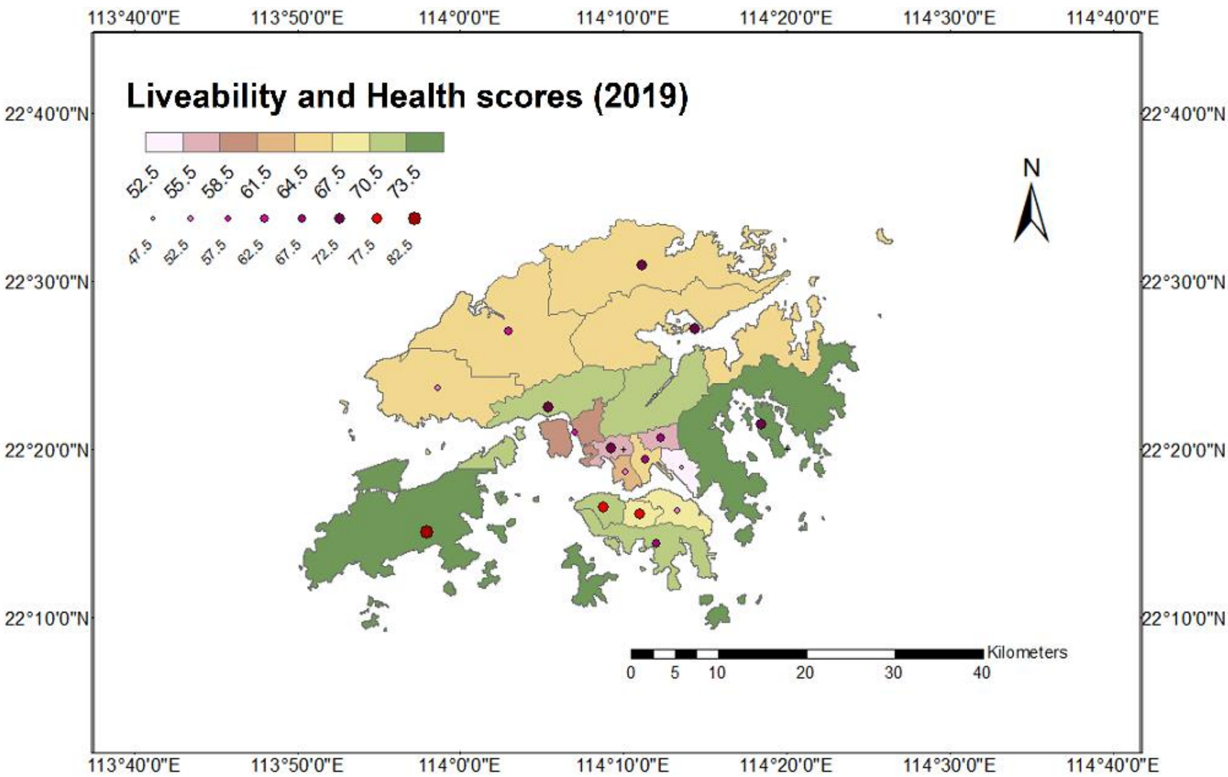

Figure 5. Spatial map of the Liveability (represented by shaded areas) and Health (represented by dots) performance of all Hong Kong districts in 2019. *C&W*: Central and Western; KC: Kowloon City, KT: Kwun Tong; SSP: Sham Shui Po; WC: Wan Chai; WTS: Wong Tai Sin; YTM: Yau Tsim Mong.

On the contrary, Sham Shui Po, Wong Tai Sin, and Kwun Tong had the worst liveability performance in both 2016 and 2019. Out of all 18 districts, only Kwun Tong's overall liveability score decreased after the 3-year period, while its health score was also significantly lower than other 17 districts of Hong Kong. In terms of the 6 liveability categories, Kwun Tong was within the last 4 positions in Education (right before Kwai Tsing), Economy, Housing (before Yau Tsim Mong, Sham Shui Po, and Central and Western), and Environment in 2019. Its overall score in Environment (i.e., air and noise pollution, population density, greening assets and features) was obviously lower than most of the districts in both 2016 and 2019, which could imply that Kwun Tong is not a good district to live in. On top, although Sham Shui Po and Wong Tai Sin performed poorly in terms of liveability, they came the 8th and the 11th in health assessment. This may be attributed to the government's efforts in paying extra attention to the elderly, by providing medical care and supports to these two ageing districts, which eventually enhance the mental health conditions of residents. In particular, the promotion and implementation of "ageing-in-place" was established in redeveloped public rental housing estates of these districts, at micro, meso and macro scales throughout the past decades [78,79]. Nevertheless, the housing conditions at Sham Shui Po were still having room for improvement, which could be reflected from its lowest score in "median floor area of accommodation", and there were insufficient walking tracks and sports facilities that could deteriorate liveability within the district. As for Wong Tai Sin, it was categorized as one of the most elderly districts in Hong Kong, however there were insufficient community centers and ancillary facilities like handrails, escalators, and elevators, while residential care, recreational facilities, and walking tracks within the district were also missing [80]. Further, residents of the district generally received less education, thus constituted to lower household income and higher poverty rates. All these lowered its liveability scores in Education, Economy, Walkability/Transport, and Environment.

3.3. Temporal Changes in Liveability Performances

For the higher achievers, Sai Kung had improvements during the 3-year period, increased from 74.03 (ranked the 2nd) to 76.08 (ranked the 1st) marks out of 100. The improvements could be observed in 5 liveability categories, except with a slight decrement in terms of Environment score (from 166.45 to 165.41 out of 240). Conversely, its main competitors, Islands and Central and Western have undergone a mark reduction of 2.36% and 1.39% from 2016 to 2019. In particular, the Education, Walkability/Transport, Environment, and Economy scores of Islands have decreased by 9.02%, 2.09%, 2.22%, and 4.00%; while the Central and Western suffered mark reduction of 3.05% and 2.91%, in terms of Housing and Economy, respectively.

For other districts, Kowloon City (from 64.89 to 66.05), Yuen Long (from 65.57 to 66.52), and North (from 65.77 to 66.63) have shown improvements in terms of liveability scores. In particular, the enhancement of Health Facilities, Education, and Economy in Kowloon City were 5.38%, 3.89%, and 1.91%, respectively. Similarly, the scores of Yuen Long in Economy, Health Facilities, Education, Walkability/Transport have increased by 9.04%, 5.79%, 2.35% and 1.41% accordingly. In contrast, the Economy and Education scores of Tuen Mun had suffered a huge decrease, by 10.44% and 4.75%, thus constituted to the drop in ranking, from the 9th in overall in 2016 to the 13th in 2019. The corresponding scores decreased from 67.26 to 64.71. The detailed normalized liveability scores of all 18 districts in 2016 $(L_{2016-i,N})$ and 2019 $(L_{2019-i,N})$, and the changes of scores (ΔL_N) could be found in Table S4.

Further, when connecting $L_{2016-i,N}$ and $L_{2019-i,N}$ of all districts with corresponding health scores $(H_{i,N})$ via least-square regression, it is well noticed that the slope and R value in the linear fit of 2019 are higher than that in 2016, and is accompanied by the reduction of RMSE, MBE, and MAE. The p-values of both linear fits are below 0.05, thus the statistical correlations obtained are statistically significant. The improvement of statistical performance actually reviews the local government and respective district council's efforts in creating a more liveable and healthy environment for human settlement, travelling and community engagement, however, the actual effectiveness of these policies are yet to be reviewed. Table 3 shows the values of all aforementioned statistical metrics obtained from both linear fits, and details of these metrics were described in Section 2.4.

Table 3. Selected statistical metrics of the linear fits between normalized liveability and health scores in 2016 and 2019.

	Equation (y = mx + c) *	*R Value* **	*RMSE* **	*MAE* **	*MBE* **	*p-Value* **
2016	$y = 0.80x + 14.86$	0.496	9.48	8.18	−0.001	0.0314
2019	$y = 0.88x + 9.19$	0.518	9.35	8.20	−0.00009	0.0233

* The equation of the best-fit line, via least square fitting, with x and y representing the normalized liveability score and health score, and m and c are the resulting slope and y-intercept. ** Slopes, y-intercepts, RMSEs and MAEs are corrected to 2 decimal places, while MBEs and p-values are corrected to 1 significant figure and 3 significant figures, respectively.

4. Discussion and Limitations

4.1. Spatial Features and Enhancement of Liveability in Different District Types

The 18 districts of Hong Kong can be categorized into 3 main types, namely, residential districts, commercial districts, and industrial districts, based on their land-use patterns and population figures. Out of these 3 district types, 3 districts (i.e., Sai Kung, Kwun Tong, and Kwai Tsing) were extracted for spatial analyses. First, Sai Kung consists of more than 6% of the total population in Hong Kong [81] and is regarded as a "residential district", while Kwun Tong is a commercial and residential district, because 33% of land-use zonings have been utilized for residential purposes and 7% for commercial use [82]. Kwai Tsing is regarded as an industrial district, with 9% of its land use zonings being used for industrial purposes.

4.1.1. Residential District: Sai Kung

Based on the LHI-HK framework, Sai Kung is a high achiever of both liveability and health, which is constituted by concerted efforts of citizens, local district councils, and government's development plans. One of its new towns, Tseung Kwan O, has incorporated recreation and conservation features during the construction of low-density residential areas, with the aim of combating problems of population growth and high population density [83]. In particular, controls of building height towards waterfront areas were imposed, and a breezeway system was designed in The Hong Kong Velodrome Park to channel seasonal prevailing breezes, sea winds, and valley winds [84]. In addition, the overall architectural design of buildings was to facilitate airflow, enhance ventilation, reduce the trapping of pollutants within street canyons, and to provide more open space to citizens. All these reduce the NO_x emissions and pollutant concentrations of Sai Kung [53], with an average NO_2 concentration of only 29 $\mu g/m^3$ detected in roadside monitoring stations [85]. Further, the government is promoting cycling as an alternative to private vehicles for short distance travel, which can also serve as the transport mode to connect with public transport, offices, and residential flats. Thus, there are 22 km of cycle tracks and 5,799 bicycle parking spaces within Sai Kung, with 1,388 of them situated near to the 5 Mass Transit Railway (MTR) stations in the district [86]. At the same time, joint efforts between the Transport Department, the Transport and Housing Bureau, and District Council attempted to provide more cycling facilities and racks [87], hence improving district-wise air quality and enhancing citizen's public health qualities [88].

Sai Kung also consists of numerous islands, beaches, country parks, and hiking trails (e.g., MacLehose Trail, Sai Kung Country Park East and West), which serve as a leisure hub for local residents to get connected with natural environment [89]. The presence of natural sceneries, together with the provision of transportation services, have enhanced the linkage between people, space and nature, thus increasing its liveability score within the LHI-HK assessment. To further maintain good health conditions within the district, expansion of healthcare service and implementation of mental health projects have been conducted in recent years, for example, the "Sunshine with Me", "Happy Living Community Campaign", "Age-friendly City Project", "Brain Big Fun Sai Kung 2018", to cope with needs of different age groups, especially for teenagers, women, and elderlies. The built environment also consists of walkways to provide a comfortable neighborhood environment for pedestrians, and to encourage community engagement [90–92].

4.1.2. Commercial and Residential District: Kwun Tong

Based on the LHI-HK framework, Kwun Tong is regarded as the least liveable district of Hong Kong. Apart from suffering from high poverty rate (i.e., 19%) and population density (with 61,500 people/km^2) [93,94], it has low scores in air quality and other environmental indicators. Further, 21.86% of the working population of Hong Kong reside in Kwun Tong, which causes high demand for traffic. However, the limited provision of roads has exacerbated traffic congestions in road junctions during peak hours, thus leading to devastating air pollution and environmental problems [95], as reviewed by the extraordinarily high roadside $PM_{2.5}$ and NO_2 concentrations observed in different parts of the district [53,85]. Moreover, kerbside activities like loading and unloading take place in different major roads of the district (e.g., Hing Yip Street and Wai Yip Street), and the associated illegal parking problems have influenced normal traffic flow and road capacity [96], because existing road network is ineffective to manage the transformation of district from an industrial to a commercial one. All these have seriously diminished the liveability and sanitary conditions of Kwun Tong.

The pedestrian environment of Kwun Tong is also poor, as reviewed by its poor performance within environmental assessments of the LHI-HK framework, for example, the lack of greenery and open spaces. The massive pedestrian flow towards commercial buildings, transition of land use from industrial to commercial purposes, and the presence of kerbside activities have also interfered the normal functioning of sidewalks and back alleys [96]. Aforementioned problems arise because the current situation is not expected in the original spatial planning documents of Kwun Tong. In the 1950s, the public facilities and road network was only planned to accommodate around 50,000 people, however there are now around 1 million citizens commuting to the place for school and work on daily basis [97], thus the traffic flows have exceeded the maximum carrying capacity of roads, which pose health risks to motorists and pedestrians [97]. As a result, Kwun Tong has obtained a poor liveability score.

To ameliorate its liveability conditions, the highlighted campaigns and projects have been conducted within the district, for example, the Kwun Tong Town Centre Project and Energizing Kowloon East. These redevelopment projects demolished old buildings, broadened walkways, enhanced existing roads, and allotted additional areas for community facilities, green space, and for transportation purposes [98]. The restructuring of street networks, like the incorporation of more traffic lanes aim at alleviating traffic congestions [95]; while the addition of pedestrian signals, new footpaths, and street arts strive for promoting the walkability, greenness, and attractiveness of Kwun Tong, as a result creating more business initiatives for the entire district [96,99].

4.1.3. Industrial District: Kwai Tsing

Kwai Tsing ranked the 15th in terms of liveability in both 2016 and 2019 based on the LHI-HK framework. People living in this district generally have low educational attainment, which constitute to lower household income and higher poverty rate. The dissatisfactory socio-economic status and air qualities have worsened its liveability performance when compared with other districts of Hong Kong. In particular, its NO_2 concentration was the highest among all 18 districts in both 2016 (59 $\mu g/m^3$) and 2019 (54 $\mu g/m^3$) [85]. In addition, the excessive vehicular traffic flow and industrial activities within the district also lead to heavy roadside pollutions; while huge vessel emissions and ship berthing often take place in the 5th most hectic container port in the world, the Kwai Tsing Container Terminals, thus resulting in the highest NO_2 and SO_2 concentrations among all districts [100]. As a result, health challenges were posed to Kwai Tsing citizens, for example, higher risks of suffering from respiratory diseases and premature mortality due to exposure to air pollutants [101].

Regarding the health performance, Kwai Tsing ranked the 13th among all districts, despite concerted efforts being put into place to improve its health and sanitary conditions. Again, this is because Kwai Tsing is one of the elderly districts of Hong Kong, which consists of 16% of elderlies (65 years old or above), and 60% of residents actually live in public housing estates. Meanwhile, their low economic status has weakened their expenditure and purchasing powers, especially on health products and medical services [102]. The government and its District Council had set up the first district-wise health center in 2019, which provides rehabilitation, free health risk assessments, and prevention services to residents [103], with focus placed on the elderly group and the grassroots of Kwai Tsing. The strengthening of primary healthcare services has steered a step forward to promote a healthy neighborhood environment within Kwai Tsing.

4.2. Validation of the LHI-HK Framework

Within the LHI-HK framework, different multiplying factors have been imposed to individual liveability indicator, so that the local geographical and socio-economic characteristics could be better captured, and their connection with health could also be easily reviewed. To validate the appropriateness of this newly established framework for spatial assessments, the renowned AARP Liveability Index and The California Healthy Places Index (HPI) are selected for statistical comparisons. The former one adopts equal-weighting scheme to each category of liveability indicators [104], with the aim of conducting measurements at neighborhood levels of cities in the U.S.; while the latter one applies the prescribed weighting scheme to a total of 8 categories of action areas, namely economic (32%), education (19%), transportation (16%), social (10%), neighborhood (8%), housing (5%), clean environment (5%), and healthcare (5%), then evaluates the statistical relationship between these action areas and life expectancy [105].

For validation purposes, an equal weighting scheme was applied to all 21 liveability indicators preset in the LHI-HK framework, thus constituting to the AARP scores of each district in Hong Kong. Next, to follow the scoring approach of HPI, the 21 LHI-HK indicators were grouped into corresponding HPI action areas (as shown in Table S5), then the aforementioned weighting of each action area was applied to obtain the HPI scores of all 18 districts. Figure 6 shows the statistical correlations and best-fit lines obtained by the inter-comparison of LHI-HK scores, AARP scores of HK, and HPI scores of HK. For LHI-HK versus HPI, the resulting R value and slope are 0.70 and 0.53; while for LHI-HK versus AARP, a higher R value of 0.90 is attained, and the slope is much closer to unity. Overall, strong associations between these 3 indices or framework could be observed, which have implicitly confirmed the applicability and potential extension of our established LHI-HK framework to densely populated cities. On top, the framework developed in this study has properly incorporated socio-economic and environmental indicators that constitute to good health, as reviewed by the clear statistical relationships obtained between "liveability" and "health" in Hong Kong, a city with complex land use patterns and compact urban morphologies.

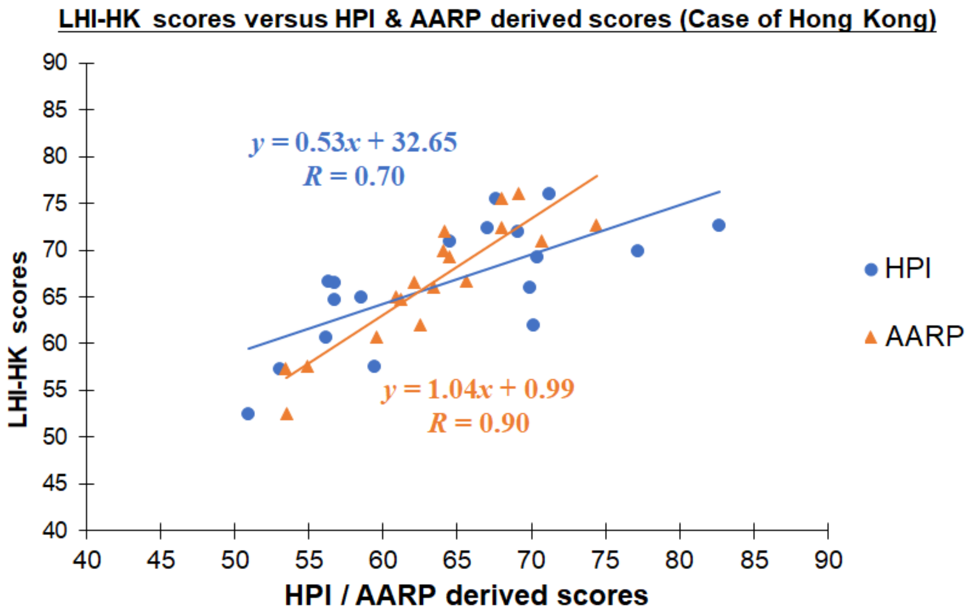

Figure 6. Statistical correlations between LHI-HK scores, HPI, and AARP derived scores, obtained via prescribed scoring framework and linear regression techniques (Blue circles: LHI-HK versus HPI; Orange triangles: LHI-HK versus AARP).

4.3. Potential Uncertainties Resulting from Projection of Missing Entries

In Section 2.3.2, corresponding trends during the 2011–2016 period were used to approximate the 3 liveability indicators that possessed missing entries in 2019. Two of them belong to Housing category, while the remaining one belongs to Walkability/Transport. To quantify the potential uncertainties caused by such "approximation", and to trace for changes in overall district-wise liveability scores and rankings of Hong Kong districts, the analysis of error propagation in Physics disciplines [106] was adopted to investigate the possible discrepancy and accuracy of the estimated figures of these 3 indicators.

Recall from Equation (1) that P_j can be obtained by calculating the percentage change of indicator j from 2011 to 2016, thus the error of estimating P_j (δP_j) is calculated as in

Equation (12), with both $\delta V_{2011,j}$ and $\delta V_{2016,j}$ equal to 0.05, because the raw values of these 3 liveability indicators in 2011 and 2016 are all corrected to 1 decimal place.

$$\delta P_j \approx P_j \times \sqrt{\frac{\left(\delta V_{2016,j}\right)^2 + \left(\delta V_{2011,j}\right)^2}{\left(V_{2016,j} - V_{2011,j}\right)^2} + \left(\frac{\delta V_{2011,j}}{V_{2011,j}}\right)^2} \tag{12}$$

Then, expanding the second equation of Equation (1), the error of the jth indicator in 2019 ($\delta V_{2019,j}$) can be approximated as in Equation (13):

$$\delta V_{2019,j} \approx \sqrt{\left(\delta V_{2016,j}\right)^2 + \left(P_j \cdot V_{2016,j}\right)^2 \cdot \left[\left(\frac{\delta V_{2016,j}}{V_{2016,j}}\right)^2 + \left(\frac{\delta P_j}{P_j}\right)^2\right]} \tag{13}$$

By combining Equations (1), (12) and (13), $\delta V_{2019,j}$ can be expressed solely in terms of $V_{2011,j}$, $V_{2016,j}$, $\delta V_{2011,j}$ and $\delta V_{2016,j}$.

$$\delta V_{2019,j} \approx \sqrt{\left(\delta V_{2016,j}\right)^2 + \left(\frac{V_{2016,j} - V_{2011,j}}{V_{2011,j}} \cdot V_{2016,j}\right)^2 \cdot \left[\left(\frac{\delta V_{2011,j}}{V_{2011,j}}\right)^2 + \left(\frac{\delta V_{2016,j}}{V_{2016,j}}\right)^2 + \frac{\left(\delta V_{2016,j}\right)^2 + \left(\delta V_{2011,j}\right)^2}{\left(V_{2016,j} - V_{2011,j}\right)^2}\right]} \tag{14}$$

Now, considering the fact that the score assigned to district i and indicator j ($L_{i,j}$) via both P.L.V. and S.S.A. depends on its relative performance as compared with the highest achiever, we have $\delta L_{i,j} = \delta V_{2019-i,j}$ for i = 1, 2, 3, ... ,18, and j = 1, 2, 3. Hence, the overall potential uncertainties of liveability score ($\delta L_{i,O}$) in district i resulted from the projection of these 3 indicators can be estimated as in Equation (15):

$$\delta L_{i,O} \approx \sqrt{\left(\delta L_{i,1}\right)^2 + \left(\delta L_{i,2}\right)^2 + \left(\delta L_{i,3}\right)^2} = \sqrt{\sum_{j=1}^{3} \left(\delta V_{2019-i,j}\right)^2} \tag{15}$$

Finally, note that the 3 indicators contribute 90 marks out of 670 marks for liveability assessment, while normalization must be conducted as in Section 2.3.5, the maximum actual uncertainty ($\delta L_{i,O-\max}$) in terms of normalized score is calculated as shown in Equation (16).

$$\delta L_{i,O-\max} = \frac{\delta L_{i,O} \times 90}{670} \times 100 \tag{16}$$

After conducting the uncertainty assessment by following the aforementioned procedures, $\delta L_{i,O-\max}$ of all 18 districts range from 1.586% in Island to 2.193% in Tai Po, with an average of 1.949% and SD of 0.157% attained. Suppose the uncertainty is either being added to or subtracted from the normalized liveability score of respective districts, the overall R value of the linear fit between health and liveability performance of all districts will remain at 0.518, and has a slight increase to 0.519, respectively. This indicates that the statistical uncertainties due to the application of temporal projection in 3 liveability indicators are negligible. However, it is interesting to observe that after such uncertainty adjustment is applied, the ranking of North and Yuen Long swap, while other districts remain unchanged. North has a maximum of 1.635% adjustment, as compared to 2.008% for Yuen Long, thus, its liveability rank will likely drop from the 9th to the 10th after the adjustment. Nevertheless, this section has again verified that the LHI-HK framework is numerically reliable, though slight discrepancy of ranking was found. When more historical datasets of these 3 liveability indicators are available, further error analyses can be conducted to assess the reliability of our numerical and statistical techniques in different scenarios.

4.4. Potential Limitations and Insights of Current Study

First, as observed from Table S3, negative correlations were found between 6 liveability indicators with health scores of Hong Kong. For "Median rent to income ratio", it has been suggested that rent to income ratio serves as a measure of housing affordability [107], while it was previously verified that expensive housing costs in high-dense living environment will likely create emotional stress to individuals, and negatively affect both physical and mental health conditions of citizens [108]. As for "Proportion of working population with place of work in same district of residence", as suggested in [109], if people's activity area is only limited to their residential neighborhoods, they will likely experience social and spatial confinement, and even suffer from mental depression. In terms of "O_3 concentration", due to the chemical coupling of NO_x and O_3, the reduction of NO_2 concentration on ground will lead to the increase in O_3 concentration [110], thus it is of no surprise to obtain such casual statistical relationship when connected with health scores.

Second, the raw data source of liveability and health qualities in Hong Kong is rather restricted and kept confidential. Therefore, this study has adopted mental health data collected from the survey conducted by the Civic Exchange [42]. Although the 21 indicators within the LHI-HK framework could effectively reflect the liveability conditions of Hong Kong districts, they may not be comprehensive enough when the framework is extended to other cities. In particular, the impacts of social cohesion, social supports, crime and safety, and citizens' views towards the government should also be included. However, some of these attributes are sensitive, and may only be adopted for political or administrative purposes, i.e., will not be released to public. Therefore, results collected from unofficial questionnaire and interviews can also be incorporated in the future, to reflect the realistic social conditions of districts. Further, delays in releasing the latest data to the public could also hinder the advancement of health qualities and mental well-being of citizens. Thus, it is highly recommended that the authority and relevant departments can enhance and promote the concept of data openness [111], update respective information in a timely manner, and take into account of unofficial data sources for policy implementation. At the same time, more organizations and local communities can install remotely sensed instruments like wind and ozone LiDARs at local scales to govern wind flow dynamics and pollution [112], then combine them with algorithmic based satellite retrieval methods to understand how changing land use patterns could result in better environmental conditions [113], as a result improving overall liveability conditions in the city, district, and neighborhood scales.

Lastly, strange correlations were found in the assessment process, for example, negative correlations shown between "total number of sports facilities" and "number of hospitals, specialist outpatient clinic, and general outpatient clinic under the Hospital Authority (HA)" and health performance. Regarding sports facilities, a possible reason that could explain the unusual causal relationship might be related to the long working hours of Hong Kong, therefore, the working population might not have sufficient time for entertainment and leisure. Thus, the presence of sports facilities may not lead to direct health benefits in Hong Kong context. With regard to the second indicator, patients may not have received timely care, due to the lack of medical personnel and overloaded public healthcare services in Hong Kong [114], which result in unsteady service quality and the negative correlation. Further investigations can be done to determine a more accurate explanation of these strange statistical correlations.

5. Conclusions

In this study, the Liveability and Health Index-Hong Kong (LHI-HK) was established to link up a total of 30 socio-economic indicators from 6 different disciplines, namely Education, Economy, Housing, Walkability/Transport, Environment, and Health Facilities, to assess the current liveability and health status of Hong Kong. Upon the application of different scoring approaches and multiplying factors that reflect statistical significance and importance of local geographical contexts, it was shown that normalized liveability and health scores were positively associated, with slopes higher than 0.8, and R values of around 0.5 for both 2016 and 2019 cases. Improved statistical metrics from 2016 to 2019 symbolize the government's efforts in infrastructural planning, promotion of sustainable and green neighborhood environment. Within the study, Sai Kung and Kwun Tong (with normalized liveability scores of 76.08 and 52.49 out of 100) were the most and the least liveable district of Hong Kong, and Islands is the healthiest district. Based on different land-use distributions, good and bad existing spatial arrangements of 3 key district types were identified. The validation between LHI-HK with the renowned AARP liveability index and HPI in California, and corresponding error analyses showed that our newly established index could provide fair and meaningful spatial assessments in high density cities like Hong Kong.

Overall, this study has complemented the research gap of connecting liveability and health status from both quantitative and qualitative approaches. Selected favorable spatial features could also enhance thermal comfort of individual district, for example, roadside vegetation [115], urban greening features [116], and environmental friendly architectural design features. Further, for ageing districts or towns, the revitalization of existing old buildings and the promotion of "ageing-in-place" [117,118], like the PMQ in Central and Western, can enhance the vibrancy of the concerned district. To conclude, the developed LHI-HK framework and corresponding numerical indices show great potential for worldwide applications, with the goal of establishing a self-belonging, liveable, healthy, sustainable, and resilient community in long run.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/su13168781/s1, Table S1: Details of the 21 liveability indicators and 9 health indicators in the LHI-HK framework (for the Hong Kong context), Table S2: Determination of score range of Liveability and Health Indicators that adopted the Standard Score Approach (S.S.A.), based on previous literature and the consideration of local contexts in Hong Kong, Table S3: Statistical parameters obtained from the best-fit line between each LHI-HK Liveability Indicator versus Overall Health Score, and the respective multiplying factors imposed to each of these indicators in Case Study 3 (See Section 2.3.4 and Table 1), after local contexts are being considered, Table S4: Overall normalized liveability scores of all 18 districts of Hong Kong in 2016 and 2019, together with the changes and percentage changes of scores, and changes in rankings from 2016 to 2019, Table S5: The categorization of 21 LHI-HK liveability indicators for the liveability assessment prescribed by The California Healthy Places Index (HPI) (i.e., with 8 action areas). Corresponding weighting scheme of HPI framework is as shown.

Author Contributions: Conceptualization, H.W.L.M.; methodology, H.W.L.M. and Y.L.C.; software, Y.L.C. and H.W.L.M.; validation, H.W.L.M. and Y.L.C.; formal analysis: H.W.L.M. and Y.L.C.; investigation: Y.L.C. and H.W.L.M.; data curation, Y.L.C. and H.W.L.M.; writing—original draft preparation, Y.L.C. and H.W.L.M.; supervision, H.W.L.M.; funding acquisition, H.W.L.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was partially funded by HKU Seed Fund for Basic Research for New Staff, grant number 104005930.

Institutional Review Board Statement: The study was conducted according to prescribed guidelines, and approved by the Human Research Ethics Committee (HREC) of HKU (Code: EA200004, approved on 6 August 2020).

Data Availability Statement: Interested readers may contact the corresponding author for acquiring relevant datasets generated in this research study.

Acknowledgments: This paper is an extended and modified version of the dissertation of Y.L.C.

Conflicts of Interest: The authors have no conflict of interest, nor competing financial interests that could have influenced the work reported in this paper.

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