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Assessing land-use and transport integration via a spatial composite indexing model

Assessing land-use and transport integration

Abstract: Achieving sustainable urban development is identified as one ultimate goal of many contemporary planning endeavours and has become central to formulation of urban planning policies. Within this concept, land-use and transport integration is highlighted as one of the most important and attainable policy objectives. In many cities, integration is embraced as an integral part of local development plans, and a number of key integration principles are identified. However, the lack of available evaluation methods to measure extent of urban sustainability levels prevents successful implementation of these principles. This paper introduces a new indicator-based spatial composite indexing model developed to measure sustainability performance of urban settings by taking into account land-use and transport integration principles. Model indicators are chosen via a thorough selection process inline with key principles of land-use and transport integration. These indicators are grouped into categories and themes according to their topical relevance. These indicators are then aggregated to form a spatial composite index to portray an overview of the sustainability performance of the pilot study area used for model demonstration. The study results revealed that the model is a practical instrument for evaluating success of local integration policies and visualising sustainability performance of built environments and useful in both identifying problematic areas as well as formulating policy interventions.

Keywords: Land-use and transport integration; sustainable urban development; composite index; spatial indexing; indicator

1. Introduction

Integration of land-use and transport decisions to achieve sustainable travel behaviour has been considered an integral element for sustainable urban development (Yigitcanlar and Dur 2010; Yigitcanlar 2010a). It would not be correct to state that before the popularity of urban sustainability concept, land-use and transport interaction had been scrutinised as strictly separate entities in planning (Yigitcanlar et al. 2008). However, it had been elaborated in the context of spatial interaction, and as a key factor of local economic development and community building (Van de Walle et al. 2004). Their interaction had not been elaborated in a way that fully covers a set of interrelated subjects, such as travel behaviour and patterns, residential choice, transport related environmental externalities, built environment and health relationship, and so on (Stead and Marshall 2001; Duvarci et al. 2011). Even though sophisticated land-use and transport models have been available for a long time, classical 'predict and provide approach' has prevailed in the planning practice due to the higher costs of making one of these models operational (Van de Walle et al. 2004). After inclusion of integration as an important policy objective in achieving the sustainable urban environment goal, land-use and transport interaction topic has become pervasive in regional and local plans (Yigitcanlar et al. 2007).

Having acknowledged the complex nature of land-use and transport interaction (Stead and Marshall 2001), which also stems from socioeconomic factors and personal predispositions, new research has focussed on disaggregate level analyses to better reflect the true nature of this relationship (Handy 2005). Accordingly, there are many exploratory, explanatory and simulation studies to embrace complex nature of land-use and transport interaction (Handy 2005; Bhat and Guo 2007). From the spatial interaction and equilibrium models, new land-use and transport interaction models have evolved into complex micro-analytic or agent-based simulations that are able to capture the change in urban settings according to development schemes (Maoh and Kanaroglou 2009). The main quality of these contemporary modelling approaches is that they analyse the influence of built environment attributes (e.g., density, location of services, land-use mixture, transport infrastructure and services) on aggregate or disaggregate level travel patterns taking into account demographic and socioeconomic variations, and activity patterns (Bhat and Guo 2007). They may also incorporate residential choice and resident attitudes (i.e., self-selection phenomenon) into the equation to better capture relationship between urban form and travel patterns (Handy 2005). However, it has not yet been possible to clearly purport to what extent built environment influences travel behaviour consolidating socioeconomic and behavioural parameters of this relationship. Moreover, local variations in model outcomes and different frameworks used to portray casual relationship for the same phenomenon are other drawbacks of explanatory studies (Stead and Marshall 2001).

In parallel to growing interest in urban sustainability matters, planning agencies have included land-use and transportation integration into local policy agenda and delineated general principles and best practice guidelines for the implementation (Minken et al. 2003; Yigitcanlar 2010b). For example, coordinating land-use and transportation has been considered as one of the primary responsibilities of Federal Highway Administration in the USA, which has given rise to a number of plans and programs initiated at state, metropolitan and city levels. In Australia, land-use and transport integration has been considered as one of the main strategies to reach the sustainable mobility goal, and was highlighted by the Department of Transport and Regional Services. In the EU, Land-Use and Transport Research cluster was initiated "to develop planning tools, assessment methodologies and best practices aimed at managing future transport demand through integrated land-use and transport policies, reducing individual motorised vehicle movements and encouraging greater use of collective and other sustainable transport modes" (EC 2004, p.11).

Even though conceptualisation of the main concerns varies regarding to local context and values, problem definitions and remedies saturate on a number of key land-use and transportation integration related issues and challenges. Thus, the objective of this paper is to address 'how land-use and transport integration challenges can be formulated and tackled in an assessment framework to assist local governments in designating planning decisions'. For this, the paper explores the indicator-based assessment method, develops a spatial indexing model, and elaborates and discusses the findings from a pilot study conducted in the Gold Coast, Australia, in 2012.

2. Materials and methods

2.1. Land-use and transport integration in the policy context

Land-use and transport integration is commonly referenced by state or local government planning agencies and has been included in regional plans worldwide. For instance, the Department of Infrastructure (DIP) states that "land-use, transport and employment integration all play key role in achieving social, economic and environmental sustainability... By shaping the development pattern and influencing the location, scale, density, design and mix of land-uses, integrated planning can create complete communities" (DIP 2009, p.101). Furthermore, the benefits of land-use and transport integration can be explained as "[it] reduces the need for travel; results in shorter journeys; provides safer and easier access to jobs, schools and services; supports more efficient land and existing infrastructure use; and maintains environmental benefits of compact development" (DIP, 2009, p.101).

In order to reflect on how the integration is conceptualised and what the common principles are, three well-known international approaches are reviewed. These are: (i) Land-Use and Transport Research's land-use and transport measures of TRANSport Planning, Land-Use and Sustainability (TRANSPLUS) project (Sessa, 2007)—from the EU; (ii) Smart Growth Network's smart growth principles (SGN 2002)—from the USA—and; (iii) Integrated land-use and transport planning principles of Queensland Government Department of Infrastructure and Planning (DIP, 2009)—from Australia. The main motivation behind this selection is to compare and contrast differences in continent-based urban and policy planning approaches. This review reveals the common principles of the integration as follows:

- Increasing compactness of settlements and their land-use mix;
- Planning new developments in close proximity to the existing urban services, most preferably as infill development;
- Encouraging active transport via design features;
- Enhancing public transport service and quality;
- Improving accessibility to urban services by alternative modes;
- Balancing travel costs of automobile and alternative modes;
- Changing travel behaviour by soft measures;
- Enhancing the character and amenity of the urban areas, and;
- Providing affordable housing.

These principles are common in at least two initiatives and clearly refer to urban form qualities in reaching a more environmentally sustainable travel patterns and community well-being goals. First five principles refer to 5D's of sustainable urban development (i.e., density, diversity, design, distance to transit and destination accessibility) (Cervero and Kockelman 1997; Bhat and Guo 2007) and are common in all initiatives. Provision of affordable housing, and promoting urban character and amenity are shared by given approaches, and overlaps with the sustainable communities, liveability and quality of life debates. A strong taxation measure to diminish automobile use is particularly intrinsic to the EU policies. These principles also frame the indicator selection process (i.e., what is important and how they can be demarcated?) and the expected outcomes of this composite indicator study (i.e., what are the practical implications to aid policy formulation?).

2.2. Indicator-based assessment method

The OECD defines indicators as “a parameter, or a value derived from parameters, which points to, provides information about, describes the state of a phenomenon/environment/area, with a significance extending beyond that directly associated with a parameter value” (OECD 2003, p.5). The main instrumental purpose of indicators is that “…by visualizing phenomena and highlighting trends, indicators simplify, quantify, analyse and communicate otherwise complex and complicated information” (Singh et al. 2009, p.10). Rydin et al. (2003) reported that early literature on sustainability indicators mainly focused on design of a framework and selection of relevant indicators. This approach unintentionally emphasised technical matters while subordinating the basic function of indicators, which is facilitating communication via active involvement of stakeholders. They also said that this led to a new research agenda in indicator initiatives, asserting the foremost quality of indicators as their direct linkage to policies. Essentially the main role ascribed to indicators is to provide policy-making support (Rassafi and Vaziri 2005; Singh et al. 2009).

Recently Tanguay et al. (2010) reviewed urban sustainability indicators considering the conceptual framework, indicator selection approach and number of indicators of some 17 studies. After reclassifying the indicators according to the 3Es of sustainability (i.e., environment, equity, economy), they found that selected indicators frequently take place in the intersections of the three tiers of sustainability due to the cross-domain nature of indicators. More than half of the indicators are contained in the social domain, directly or indirectly. In order to investigate the common approaches in land-use and transport integration literature, a content analysis was conducted by adopting the issue-based framework. Table 1 is a compilation of 28 urban and transport sustainability studies and over 1,000 indicators, where it is primarily formed via considering the three main themes of transport, built environment and externalities. These themes are separated into categories according to the general content of the studies reviewed as follows: (i) Transport (accessibility, mobility); (ii) Built environment (density, diversity, design); (iii) Externalities (pollution, resource consumption). The contents of these indicators are analysed and 47 indicator sub-categories formed according to their characteristics. The distribution of 790 indicators is provided in Table 1.

Table 1. Categorical distribution of indicators on built environment, transport and externalities

[INSERT TABLE 1 HERE]

Not surprisingly, a large group of indicators accumulates on three categories, mobility, pollution and resource consumption. This finding is very similar to the categorisation of Tanguay et al. (2010), such that, transport domain is predominantly represented by mobility patterns and sub-components of mobility (249 indicators); and a great deal of indicators are related to pollution (133) and resource consumption (189) referring to the externalities as a result of contemporary mobility patterns. While 69 indicators cover accessibility, there are 150 built environment indicators. When these two figures are combined, we can extract another dimension of the integration issue, which, in addition to the 3Ds (i.e., density, diversity and design) of urban form (Cervero and Kockelman 1997), encompasses the locations of destinations (Handy 2005). Importantly Table 1 clearly delineates the problem areas as well as revealing prominent indicator categories, which can be used to define a new set of indicators for assessment of another setting. Table 1 also constitutes the basis of the indicator selection process, which is elaborated in the following section.

2.3. Composite indices and spatial indexing methods

As an indicator-based assessment sub-type, the composite indicator refers to an aggregate metric derived from a set of indicators, which are selected to define a multidimensional, generally complex concept by using mathematical and statistical inference tools (Nardo et al. 2008; Yigitcanlar and Dur 2010). Recently, due to their simplicity, they have gained a great deal of attention and been used for various purposes, such as performance monitoring, benchmarking comparisons, public communication, policy analysis and decision-making (Nardo et al. 2008). Saisana (2005) clearly states “the temptation of stakeholders and practitioners to summarise complex and sometime elusive processes (e.g., sustainability, single market policy) into a single figure to benchmark country performance for policy consumption seems likewise irresistible” (p.308). As expected, the growing attention on indexing has led to proliferation of numerous examples. Bandura (2008) found that there were 178 different composite index initiatives worldwide. While the final product of some studies is a composite index, others produce a series of comparable sub-indices, which are grouped according to environmental, economic and social tiers (Saisana 2005).

There are vast numbers of composite index studies, which use more or less overlapping considerations. Nardo et al. (2008) summarise the process in the following 10 major steps, which are generally embraced by composite index studies. Among these steps, normalisation, weighting, aggregation and sensitivity analysis are considered as the most critical and the judgments made in these steps determine validity, reliability and practical value of the final outcome.

- Developing a theoretical framework;
- Selecting variables/indicators;
- Imputation of missing data;
- Multivariate analysis;
- Data normalisation;
- Weighting and aggregation;
- Robustness and sensitivity analysis;
- Decomposition of the composite index;
- Linking the composite index with other known measures, and;
- Presentation and dissemination of the index findings.

2.4. Pilot study

Much like North American ones Australian cities are also known for their urban and environmental issues (e.g., sprawling development) and land-use and transport integration has been at the hearth of the Australian Governments' agenda for quite sometime. Even though the model could also have been put into test anywhere else, due to the problematic built and natural environmental and population characteristics and urban policy dynamics, Gold Coast City is selected as a test bed for the model. Gold Coast is the second mostly populated urban area in the State of Queensland and South East Queensland, Australia, with almost 500,000 residents in 2010. It is expected to accommodate 1,000,000 people by 2030. As one of the most important tourism centres it attracts more than 10 million visitors annually owing to the long coastline, sub-tropical climate and a number of tourism theme parks. It has also been a popular real-estate destination for aging and retired population due to its climate and availability of developable land. Its close proximity to the state capital, Brisbane, and vast tourism potential has played an important role in its urban growth (Yigitcanlar et al. 2008).

Construction of high-volume transport systems (Pacific Motorway and railway) and increasing car ownership have been important factors, which gave pace to linear urbanisation along the coastline and the corridor between Brisbane and the Gold Coast. Since the area has a number of internationally recognised environmental qualities, after the 1990s, in order to address the sustainability issue, protection of ecological diversity and environmental assets (e.g., estuarine and marine systems, beaches and dunes, and native vegetation) has become pervasive in its planning schemes (Mahbub et al. 2011; Dizdaroglu et al. 2012). Moreover, the form and intensity of urban development, facilitating a sustainable economic base for the key sectors, provision of sustainable urban infrastructure, preservation of local characters and heritage, enhancing health of residents and housing affordability, and management of bush fires and landslides have been key issues of the planning schemes. Three Gold Coast suburbs (i.e., Coomera, Upper Coomera, and Helensvale) consisting 47 census collection districts (CCD) were selected as the pilot area. The main characteristics of these suburbs are as follows:

- They represent the general pattern of newly developed suburbs in the Gold Coast reflecting some specific features, such as low density, detached housing and auto dependent travel patterns, and so on;
- They consist not only of residential areas, but also other urban functions (e.g., commercial, industry and recreation), making it possible to study effects of different land-uses on various indicators;
- While Coomera and Upper Coomera can still be considered as periphery settlements with mostly residential characteristics, Helensvale has a relatively balanced distribution of commercial, industrial and residential uses due to its proximity to the Gold Coast central business district (CBD);
- Areas close to the current urban footprint have gained a more urbanised character (e.g., Helensvale and partially Upper Coomera). While some areas are still transitioning (e.g., peripheries of Upper Coomera), some others are planned for future development via conversion of Greenfields to urban parcels (e.g., Coomera).

2.5. Indicator selection

Indicator selection process involved a series of consecutive steps with the engagement of an expert panel that is specially formed for the study. The panel consists of 15 experts from the areas of urban planning, urban design, transport planning, transport engineering, environmental science, and civil engineering—five experts from the state government (Queensland Government), six from the local government (Gold Coast City Council), and four from the local university (Queensland University of Technology). Initially, a comprehensive indicator list is prepared by analysing a number of international studies as given in Table 1. The common themes and categories considering their concordance with land-use and transport sustainability topics were extracted via a content analysis. This comprehensive set of indicators is shared with the panel and asked them to evaluate each category and indicator according to topical relevance to international land-use and transport integration discourse and local policy objectives. According to the feedback obtained, a new version is produced and discussed iteratively in each meeting. The indicator list is then finalised basing on relevance, comprehensiveness and practicality of the indicators (Table 2).

Table 2. Measures and weights of the model indicators

[INSERT TABLE 2 HERE]

2.6. Data sources

Transport related data were collected from Queensland Government Transport and Main Roads (QTMR) and Gold Coast City Council (GCCC). QTMR provided road network data, household travel survey results of, 16,849 trips made in 2008, public transport stop locations and daily timetables, and traffic accidents data. The 2011 transport demand model results were acquired from the GCCC. Additionally, GCCC provided available parking space for employment centres, aerial images (data related to the design indicators were extracted by visual inspection of these aerials) and land-use plans. Journey to work, population and employment data were obtained from Australian Bureau of Statistics (ABS). A research team in Queensland University of Technology (QUT) collected air and stormwater pollution data for 11 sites in the pilot study area and provided mathematical equations to replicate pollution levels in the overall area. Lastly, land-use destination information that was used to calculate accessibility related indicators was extracted from the Internet by parsing data in two online business directories of Australia, Yellow Pages and White Pages. All data items were stored in a GIS database, with ArcGIS 9.3 used for all data analysis. Data was collected at either CCD or parcel level. Parcel level data was aggregated to the CCD, which is also the unit of analysis of the study. The CCD is the smallest geographic area defined in the Australian Standard Geographical Classification (ASGC), and it contains 225 dwellings on average. It also provides an approximation to neighbourhood level analysis (Baum et al. 2010).

2.7. Data imputation and multivariate analysis

Since all datasets were complete, no data imputation was required. In order to check the existence of high correlation, CCD level data was analysed. A correlation coefficient ratio 0.7 was taken as the threshold value. This analysis showed that there are five highly correlated indicator pairs as shown in Table 3. All accessibility indicators and traffic noise indicator data were at parcel level, and a further correlation analysis on original spatial scale revealed no indication of high correlation. This was due to the aggregation process from parcel to CCD level.

Table 3. Highly correlated indicator pairs

[INSERT TABLE 3 HERE]

2.8. Normalisation

Normalisation is a rescaling operation according to the reference points (min, max or average) and the direction of desirability (e.g., while less pollution values are desirable, the opposite is the case for accessibility) In this study, min-max normalisation was used to reflect the area-specific distribution of the indicator values and to present a relative scale according to the best and worst performers. A 5-point Likert scale was formed representing low, medium-low, medium, medium-high and high performance. This was calculated as follows:

$$I_{new} = \frac{I_{raw} - I_{\min}}{I_{\max} - I_{\min}} * 5 \qquad (1)$$

where *I* corresponds to the indicator value(s), *new, raw, min* and *max* subscripts denote normalised and original indicator value, and minimum and maximum range of the indicator values, respectively. While rescaling, the mode column in Table 2 was used to assign low or high performance values.

2.9. Weighting and aggregation

In composite index creation, weights are used to reflect relative importance of each indicator (i.e., trade-off between indicators), or to correct the information overlap of correlated indicators, to ensure that results do not display a bias (Hanafizadeh et al. 2009). Even though a number of alternative weighting methods exist in the literature, they can be grouped under three headings: (i) Statistical inference techniques (e.g., factor analysis, data envelopment analysis, unobserved component analysis); (ii) Expert opinions (Delphi, public opinion, budget allocation process, analytical hierarchy process, conjoint analysis); (iii) Equal weighting (Nardo et al. 2008). Weighting might be the most criticised aspect of composite indicator considering it carries value-dependent biases and, in some cases, weighting with linear aggregation causes substitution among indicators giving rise to acquiring overly-normalised index values (Hanafizadeh et al. 2009).

In order to reflect local level considerations, the indicator weightings were determined by the expert panel, which was familiar with the land-use and transport integration policies as well as urban planning processes in South East Queensland. For this, an expert survey was conducted by budget allocation process with our panel of experts—in total 15 experts. The purposive sampling technique was adopted due to the study scope and pilot study area selection. In the survey, the experts were asked to distribute 120 points first to each indicator category and then to each indicator. Following this, experts were asked to refine their scores according to the relative importance of each indicator by pairwise comparisons. Then, weights given by the experts were averaged as shown in Table 2.

Aggregation is employed to exert the final composite index figure. Considering its wide use and simplicity, linear addition was used as the principal aggregation scheme. The composite index was calculated according to the following formula:

$$CI = \sum_i I_i w_i \qquad i = 1, 2, ..., 24 \tag{2}$$

where CI is the composite index, I and w correspond to the normalised indicator score and weight of each indicator given by the experts, respectively.

3. Results and discussion

3.1. Performance of the pilot area

The spatial indexing model provides a summary metric, which can be used to rank different spatial entities according to their performance. As seen in the pilot implementation, the three study suburbs were ranked from highest to lowest as Helensvale, Upper Coomera and Coomera. The minimum and maximum composite scores were 1.54 and 3.51, respectively, and the average was 2.77. This implied that the performance of the pilot study area was at medium level on average. The best performing CCDs in the area can be employed as the best-case examples for other CCDs in the area. Figure 1 below illustrates the pilot study area's composite indicator performance. Generally, the suburb centres and their close surroundings performed better than the periphery areas mostly due to higher weights given to the transport and urban form category indicators. Thus, areas where dwelling density and vehicular circulation are higher perform better. Two CCDs, one in Upper Coomera and the other in Helensvale, present comparatively the best performance in the area (see map grids E5 and H9 on the map). The lowest composite scores were in the Western CCDs of Upper Coomera (see B8:C9 map grid range). The composite indicator scores range between 1.5 and 3.5. A great deal of Coomera yields lower scores, whereas the performance of Upper Coomera and Helensvale are similar.

[INSERT FIGURE 1 HERE]

Fig 1. Composite indicator scores of the pilot area

Descriptive statistics and area-based score ranges are listed in Table 4. Despite looking similar, a larger portion of Helensvale is covered with CCDs, whose scores are 2.5 and greater. Moreover, mean and median values of Helensvale are greater than Upper Coomera. Considering these, Helensvale presents the best performance in the pilot study area.

Table 4. Descriptive statistics and score range of the composite index

[INSERT TABLE 4 HERE]

The main problem of any composite index exercise is the substitution between indicator scores as the result of arithmetic aggregation, which obscures the fine details of location specific performances (Nardo et al. 2008). In order to detect this compensation effect, the category base scores were inspected, the main purpose being to provide a clear idea about which categories compensate each other more frequently and to what extent. Area distribution of the composite score ranges for each category are given in Figure 2.

[INSERT FIGURE 2 HERE]

Fig 2. Distribution of category level and overall composite scores

Figure 2 clearly shows the accumulation in the second and third bins. Furthermore, the high index scores of the externalities category compensate the low index values of the transport and urban form categories, which is a clear indication of over-normalisation due to substitution between the category scores. More specifically, the areas that performed better in either transport or urban form yielded low scores in externalities categories. This created a clear distinction between the suburb centres, where transport and built environment indicator values are higher and periphery areas, where pollution and traffic related externalities are at minimum. Furthermore, relatively higher weights of the transport and urban form categories, and the great portion of the area covered with lower scores (i.e., range 0 to 3) in the accessibility, mobility, density/diversity and design categories shift the composite scores to the average and below average performance bins (note the frequency of the ranges of 1-2 and 2-3 in Figure 2). This also implies that densification together with the ideal land-use mix in accordance with local employment characteristics can yield an increase in composite scores of transport and urban form categories.

3.2. Sensitivity analysis

The main aim of sensitivity analysis is to reflect on robustness of model results by testing the alternatives against the decisions made on the previous stages of composite indicator creation. There are three critical factors that require re-evaluation: (i) Normalisation; (ii) Weighting; (iii) Aggregation. The model originally is formed through using min-max normalisation, expert opinion weighting, and linear additive aggregation. The alternatives to these methods are two normalisation (i.e., benchmark-based, z-score) and weighting (i.e., equal weighting, factor analysis) schemes, and an aggregation (i.e., geometric) approach. In this section, the results of the variance-based sensitivity analysis technique are reported by reflecting on the variance of overall rank change of CCDs once the model is reformulated with these alternatives. Nardo et al. (2008) suggested this technique owing to its advantageous properties over other techniques, for example, they can be used in "exploring whole range of variation of the input factors, [...] to distinguish the main and interaction effects, [...] and are model-free (i.e., suitable for non-linear and non-additive models)" (p.121). This technique simply involves: (i) Selection of input factors (X_i; e.g., normalisation, weighting and aggregation for this model); (ii) Generating a Monte Carlo sample (*N*) with all combinations of the input factors; (iii) Calculating the resulting Y^l (model output) for each X_i^l in the sample (l=1,2,3,...,N); (iv) Computing first order (S_i) and total (S_{Ti}) effects of each input factor. The first order effect corresponds to the singular contribution of each factor to the overall variance and equals the ratio of the variance of each input factor (V_i in Eq.3) to the overall unconditional variance (*V(Y)* in Eq.3).

$$S_i = \frac{V_{X_i}(E_{X_{-i}}(Y \mid X_i))}{V(Y)} = \frac{V_i}{V(Y)} \quad (3)$$

where *Y* is the model output, V_{X_i} is the variance of input factor X_i and $E_{X_{-i}}(Y \mid X_i)$ is the expected value of the model output by fixing the value of input factor X_i to x_i^*. Total effect is a measure that takes into account the singular and interaction effects for each input factors are computed as follows:

$$S_{Ti} = \frac{V(Y) - V_{X_{-i}}(E_{X_i}(Y \mid X_{-i}))}{V(Y)} = \frac{E_{X_{-i}}(V_{X_i}(Y \mid X_{-i}))}{V(Y)} \quad (4)$$

Due to the overlapping interactions among sets of input factors, sum of total effect is greater than 1 (i.e., $\sum S_{Ti} \geq 1$). After calculating S_i and total S_{Ti} , Nardo et al. (2008) advised another simple measure to reveal the power of interaction between input factors (i.e., S_{Ti} - S_i). For all three input factors, a Monte Carlo simulation was formed to yield a 95% confidence level for the standard error. All three measures of the variance-based sensitivity analysis of the average absolute rank change of the CCDs are given in Table 5.

Table 5. First order and total effects of the input factors to the model outputs

[INSERT TABLE 5 HERE]

In Table 5, the total variation caused by singular effects of normalisation and weighting factors is 91% (i.e., 0.9132), and the weighting is the most influential in absolute rank change of the CCDs. Only a limited part of the total variation, fewer than 9%, is not explained by the input factors, being a consequence of the interaction between input factors. This is also confirmed with the values in the last column of the table, where all differences are smaller than the first order effect. The average and standard deviation of the absolute rank change are 3.7 and 3.75, respectively. The influence of weighting and normalisation is extreme for two CCDs in the area whose absolute rank change as wide as 23 (average and standard deviation of the absolute rank changes are 6.86 and 10.22, respectively).

4. Conclusion

In this paper, we aim to address the research question of 'how can land-use and transport integration challenges be formulated and tackled in an assessment framework to assist local governments in designating planning decisions?' The results reported in the paper reveal that the spatial indexing model is a practical instrument for evaluating success of local land-use and transportation integration policies and visualising sustainability performance of built environments. The spatial indexing model provides a summary metric, which can be used to rank different spatial entities according to their performance. Hence, the model is useful in identifying problematic areas, which leads authorities then to formulate relevant policy interventions.

In terms of applicability, the model outcomes can help to demarcate areas according to their performance and to decide on the best option satisfying a number of planning objectives, such as interconnected walkable neighbourhoods, a good mix of urban uses and services, densification around employment centres, and so on. This might help local planning departments to delineate most effective locations to apply suggested urban form strategies of the planning scheme. Furthermore, this model can be employed in public consultation and local sustainability programs (e.g., taxation or incentive programs). This can lead more interaction between planning departments and the public in terms of prioritisation of the infrastructure provision, appraising urban development and benchmarking of community's sustainability goals (e.g., user says). As it is hard to detect the compensation between indicator values in overall composite score, category level aggregation (i.e., accessibility, mobility, density/diversity, design, pollution, resource consumption) can provide more insights about, which policy can be applied more effectively for the area. Moreover, a number of indicators of this model rely on traffic estimates and provide benchmarks related to these estimates. Once available, the outputs of similar travel demand models can be easily incorporated to provide further insights about better utilisation of traffic estimates. In overall, this model can contribute the local governments to effectuate sustainable transport and urban development policies by providing an easy-to-use metric, and thus, contributes significantly to the sustainability of the environment.

As criticised by some (Gasparatos et al. 2008), the use of indicators as assessment method is reductionist in nature. It reduces the multi-dimensional and generally complex phenomena into one or a few quantitative metrics, which can cause subordination or dismissal of important considerations and limit the discourse. Moreover, the composite indicator developed in this study uses linear aggregation which allows trade-off among indicators (i.e., poor performance in one indicator can be compensated by a better performance in another) which can obscure the critically problematic aspects of the subject matter. In order to overcome these issues, each step followed in indicator selection and composite indicator creation processes should be made transparent and the compensation among indicators should be discussed with stakeholders (Saisana et al. 2005). Furthermore, the result of the sensitivity analysis points out the most influential input factors of the model.

Even though the indexing model is a promising one, it has a critical drawback, it only gives a momentary or static picture of neighbourhood level sustainability considering land-use and transport related indicators. The most valuable improvement to the model would be inclusion of a 'scenario evaluation capability' to provide a dynamic snapshot of the study areas taking into account changes in the indicator values, more clearly, inclusion of a module that can reveal what type of urban development and transport system alternatives or combinations may create the best outcome in terms of urban form and mobility patterns. This is an area that our future research focuses on.

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