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Transit Orientation: More Than Just Coverage—A New Method for the Assessment of Transit and Development Co-Location

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Abstract

This paper presents a new method for assessing transit and development co-location and applies it to a case study. Co-location is a core element of transit oriented development. It is currently assessed by designating activities within a given distance from transit as “close to transit” and calculating the activity density of these catchment areas or the share of activities within them. However, transit demand decreases with distance, so distribution of activities within transit catchment areas matters in addition to average density. The main contribution of the new method is explicitly assessing density distribution within transit catchment areas. It is based on the notion that density should not increase with distance from transit. Case study results demonstrate the method’s ability to compare station areas based on aggregate indicator values, while also providing maps of disaggregate and spatially explicit co-location performance. This fine-grained analysis allows planners to identify potential future development areas. Results are compared to commonly used indicators for station area intensity and proximity of activities to transit. An important conclusion is that the new method should be used in combination with an intensity indicator.

Transit oriented development (TOD) is an important planning paradigm (1–3). A key goal of TOD – engrained in its very name – is orienting development toward transit. This co-location of transit and development can be achieved by locating activities where they are close to transit, or by creating transit where activities are located.

Co-location is important because the distance transit users are willing to travel (often by walking) to/from a transit stop is limited, and the share of people willing to walk to/from a stop decreases with distance (4–10). The exact form of this distance-decay of transit demand depends on factors including trip purpose, service characteristics, sociodemographic characteristics, and context. However, it is clear that the distance to/from a transit stop is one of the main factors determining the probability that potential transit users will actually use transit.

Co-location is commonly considered in TOD planning, land use transport integration analysis, or direct demand models for transit because of its importance. The most common approach is to define a catchment area – the area within a certain threshold distance (Euclidean or network) from a transit stop – and to designate all activities within this area as “close to transit”, and all other activities as “not close to transit”. This

approach is inadequate because of the influence of distance on potential transit users’ travel behavior.

This paper presents a new method for assessing transit and development co-location that accounts for the importance of proximity. It is organized into four parts. Part one describes current practices for co-location assessment and derives a research gap. Part two introduces a new indicator for co-location assessment. Part three applies the indicator in a case study. Part four presents the conclusions.

Co-Location Assessment

Application Scenarios

There are three applications for co-location assessment:

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1. planning support, by using the results as pointers for possible interventions;
2. normative or incentive policies, prescribing or encouraging a certain standard of co-location;
3. evaluation and learning.

As a planning tool, co-location indicators can help generate ideas and support decision-making when making changes to transit systems, the built environment, or both. Examples include analyzing existing or proposed co-location strengths and weaknesses or rating alternative proposals. As a policy tool, threshold values for co-location indicators could be developed and used as a condition for granting a building permit, for incentives such as a floor area bonus, or for transit subsidies. As an evaluation and learning tool, co-location assessment can shed light on how well co-location goals of executed projects have been achieved or highlight particularly successful cases that can serve as models for new developments.

Existing Approaches

Transit and development co-location assessment appears in the literature in different contexts. Most prominently, it is used as an independent variable in direct transit demand models (7, 11), as an indicator in studies on the share of people with access to transit (12), and in TOD evaluation (13).

The most common approach for assessing co-location is to evaluate transit proximity by defining catchment areas within a fixed distance from stations. This is essentially an “all-or-nothing approach” (7, p. 1084) as any activity within the catchment area is considered to have transit access (and to potentially generate demand), while all activities beyond the threshold distance are considered to not have transit access (and not to generate any transit demand). The rationale for using a threshold is the notion of “maximum acceptable walking distance”. The most common way of evaluating co-location is thus measuring intensity of catchment areas (e.g. density or number of activities), particularly for direct demand models. Other approaches capture proximity of activities to transit by calculating ratios, for example between the number of activities within two catchment areas defined using different distances such as 300 and 1200 m (13), or by analyzing the share of all activities located within a given threshold distance from transit (12). In any case, the exact distribution of activities or density is not considered in these methods for assessing co-location.

The problem with these “all-or-nothing” approaches is that transit demand decreases with increasing distance from transit (4–10). This means there is no fixed threshold distance people are willing to walk, but rather a continuous decay of transit demand with increasing distance.

Thus, the influence of density on transit demand is determined by the exact distance of activities from transit rather than by the number of activities located within the threshold distance. In other words, transit demand depends not only on the average density of activities within transit catchment areas, but also on its distribution, or “articulated density” (3, p. 155).

In practical terms this means “concentrating housing and employment within several hundred feet of a rail station will produce far more riders than placing the same amount of development a half-mile away” (11, p. 286). In addition, it implies that existing approaches “cannot reflect the greater tendency to use public transport when the distance within the station catchment area is shorter. ... They are not able to reflect the impact on travel of concentrating housing and employment at a longer/shorter distance from the station in cases where these developments are located within the station catchment area” (7, p. 1084).

Empirical evidence that density distribution within station catchment areas affects ridership is provided by Gutiérrez, Cardozo and García-Palomares (7). They developed a direct transit demand model that weights activities in transit station catchment areas by their distance from the station. Their model systematically produces better results than the all-or-nothing approach used by previous models. However, the distance-decay weighted regression applied by Gutiérrez et al. does not allow for the explicit assessment of co-location performance, such as comparing two different station areas or two alternative development scenarios for one station area based on their density distribution (7). Furthermore, it does not provide spatially explicit information about the causes of high or low co-location performance.

In summary, there is currently no approach that directly evaluates activity or density distribution around transit stations with regard to transit and development co-location.

Density Distribution Assessment

To address this gap, this research developed a method for assessing density distribution within transit catchment areas. One possible approach for assessing density distribution would be to recognize that transit demand decreases with increasing distance from stops, and therefore an ideal density distribution would locate all activities “as close as possible” to stops. An example is the indicator used by Provincie Noord-Holland and Vereniging Deltametropool (13). It calculates the share of activities located within 300 m of a station compared to all activities located within 1200 m from the station. This indicator could be further developed using several distances within the catchment area and averaging the

share of activities within each distance. Any such “the closer the better” assessment would render the best result if all activities were located very close to transit – with either empty land between stops or very small stop spacing. However, using the notion of “the closer the better” as a general guideline for achieving co-location of transit and activities is problematic for three main reasons.

First, transit demand depends on many factors other than density and its distribution, among them the quality of the built environment. Concentrating all activities within a very small area around transit stops and leaving “gaps” in-between would lead to strong overcrowding in developed areas, and there is no evidence that this would create a high quality urban environment.

Second, proximity to transit can increase nuisances such as noise. Therefore, some potential transit customers might prefer to live a few hundred meters from a station instead of as close as possible.

Third, even if extreme concentration was generally desirable, it could still have negative impacts on overall transit demand, depending on future development demand and maximum densities (e.g. because of future building codes or developer behavior). There are two cases to be considered:

1. If all future development demand could be absorbed by the area directly around a transit stop (here called “core area”, e.g. all land located within 300 m of a stop), it would be ideal from a transit perspective to locate all activities inside this core area. In this case, locating activities beyond the core area would redistribute density away from transit and thus decrease transit demand because of higher distances to transit.
2. However, if not all future development demand could be absorbed by the core area around a stop, limiting development to this core area would not be beneficial from a transit perspective. In such a case, development further away from transit is fully added to development within the core area, and thus still increases overall patronage, even if it creates less transit rides per activity.

This consideration needs to be undertaken at a corridor or even metropolitan level. However, as both future development demand and future maximum densities are not normally predictable, and the situation at the corridor or metropolitan level might be unknown when analyzing one specific station area, it seems unwise to generally limit development to the core areas very close to transit stops. However, this means that it is necessary to consider the importance of proximity in some other way.

In short, a better quality criterion than “the closer the better” is needed, one that considers the uncertainty of

possible densities and demand for activities, as well as environmental problems stemming from extreme concentration of development around transit stops.

This paper proposes using the criterion that activity density should not increase with distance from a transit stop as a basis for creating a new method for assessing co-location. An assessment based on this notion would render the best result for any situation that has an even density distribution or increasing density toward transit stops. Thus, it is less prescriptive about concentration around transit stops than the “the closer the better” approach, but still penalizes concentration away from transit stops.

The proposed indicator assesses density distribution within a station area but does not consider the magnitude of density. This means that a station area could achieve a good indicator result even if it contained very few activities, as long as these activities were concentrated around the station. As density distribution and high average densities are both important for transit, the paper’s proposed density distribution indicator should be used in combination with an intensity indicator such as average density or absolute number of activities in the station area. As these intensity indicators are commonly used, the remainder of this article focuses on density distribution indicators. The combination of density distribution with intensity indicators should be examined in further research.

Indicator for Density Distribution

Concept

This research translated the basic criterion that density at any point should not be larger than it is on average at points located closer to a transit stop into an indicator to assess density distribution for co-location of transit and activities. This was operationalized by comparing density at every point within the catchment area of a transit stop with the average density at all points located closer to that stop (“inwards density”), and with the average density at all points within the same catchment area that are located further away from that stop (“outwards density”).

Density Representation

To operationalize the indicator, the catchment area of a transit stop is represented with raster cells for which both the network distance to the respective transit stop and the activity density are calculated. As data on activities is normally available for points (e.g. number of jobs or inhabitants per address), these data must be transformed into a continuous representation of density (essentially a density value per raster cell). Such a density surface is

generated using kernel density estimation, which represents variation in population or services (14–17).

The basic idea is to estimate density at point s based on data points s_i (each point representing, e.g., an activity or a person) by weighting them with distance d_i between s and s_i so that data points further away from s contribute less to the estimated density at s . This analysis is conducted using all data points s_i with d_i smaller than a so-called bandwidth h . The distance weight is applied with a kernel function $k(\cdot)$, which must integrate to one so that the overall count of activities estimated with the kernel within an analysis area remains the same as when simply summing up the number of points within that area.

A typical kernel for geographic density estimation (14, 17, 18) is the quartic function based on Silverman (19); it is the only available kernel in ArcGIS Spatial Analyst (20, 21) and one of the available options in QGIS (22), GRASS GIS (23), and SAGA (24). The kernel density estimation using a quartic kernel can be formulated as follows (14):

$$\hat{p}(s) = \sum_{d_i \leq h} \frac{3}{\pi h^2} \left(1 - \left(\frac{d_i}{h}\right)^2\right)^2 \quad (1)$$

in which $\hat{p}(s)$ is the estimated density at point s (in absolute terms, i.e., the sum of all \hat{p} equals the total number of points) and n is the number of data points s_i that fulfil $d_i \leq h$. Thus, the summation is over all pairs s and s_i in which d_i does not exceed h . In this approach, data with counts (e.g. of activities or people per point) can simply be treated as multiple data points at a single location (18).

Indicator Formulation

The performance of density distribution with respect to co-location is measured for catchment area T of transit stop t . First, the entire developable surface of T is covered with raster grid cells m_k , and performance is evaluated for each cell. Subsequently, performance for T is obtained as the average performance of all cells $m_k \in T$.

For each cell m_k within T , activity density $\hat{p}(m_k)$ is estimated using kernel density estimation as described in Equation 1 and the pedestrian network distance between transit stop t and cell m_k , $d(t, m_k)$, is measured. Using this information, density $\hat{p}(m_k)$ is compared to the average “inwards” and “outwards” densities within T from the position of m_k , $\hat{p}_{in}(m_k)$ and $\hat{p}_{out}(m_k)$. The results of this evaluation, denoted $c_{in}(m_k)$ and $c_{out}(m_k)$, respectively, are within the range $[0, 1]$, with the value of 1 representing the best outcome and 0 the worst. Results are computed using the ratio between the “inwards” density and $\hat{p}(m_k)$ and between $\hat{p}(m_k)$ and the “outwards” density:

$$c_{in}(m_k) = \begin{cases} 1, \hat{p}(m_k) \leq \hat{p}_{in}(m_k) \\ \frac{\hat{p}_{in}(m_k)}{\hat{p}(m_k)}, \text{ otherwise} \end{cases} \quad (2)$$

and

$$c_{out}(m_k) = \begin{cases} 1, \hat{p}(m_k) \geq \hat{p}_{out}(m_k) \\ \frac{\hat{p}(m_k)}{\hat{p}_{out}(m_k)}, \text{ otherwise} \end{cases} \quad (3)$$

with the “inwards” average density defined as

$$\hat{p}_{in}(m_k) = \frac{\sum_{l|d(t, m_l) < d(t, m_k)} \hat{p}(m_l)}{\sum_{l|d(t, m_l) < d(t, m_k)} 1} \quad (4)$$

and the “outwards” average density as

$$\hat{p}_{out}(m_k) = \frac{\sum_{l|d(t, m_l) > d(t, m_k)} \hat{p}(m_l)}{\sum_{l|d(t, m_l) > d(t, m_k)} 1} \quad (5)$$

The results of the two evaluations are averaged as

$$c_{total}(m_k) = \frac{1}{2}(c_{in}(m_k) + c_{out}(m_k)) \quad (6)$$

For the innermost cell, \hat{p}_{in} has no value. Therefore, only c_{out} is computed, and $c_{total} = c_{out}$. For the outermost cell, this is reversed, that is, only c_{in} is computed, and $c_{total} = c_{in}$.

The density distribution within T is evaluated using the average performance of all cells m_k within T . The performance for T is thus:

$$C(T) = \frac{1}{K} \sum_{k=1}^K c_{total}(m_k) \quad (7)$$

in which K is the number of cells within T . $C(T)$ is in the range $[0, 1]$, with 1 representing the best and 0 the worst performance of T with respect to co-location. The indicator value does not represent an absolute quantity; rather, it is a comparative measure.

Comparing density at raster cell m_k to both “inwards” and “outwards” average densities (Equations 4 to 6) is necessary to consistently capture the effects of “gaps” within the density distribution. For example, if we assume a situation in which density is very low and uniform within the catchment area of a stop, but there is one high-density activity concentration located far away from the stop. Comparing density of raster cells only to the “inwards” average density, all points located closer to the stop than the concentration, and all that are further away, would achieve very good results (their density is not higher than the average “inwards” density). Thus, the average result over all points would be good, which does not reflect the situation. By also comparing raster

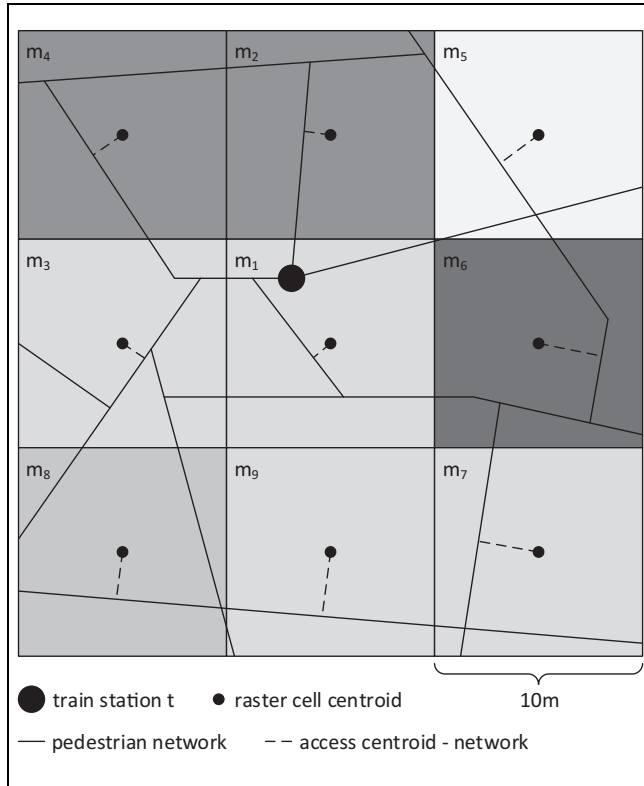


Figure 1. Generic example with nine raster cells of 10 x 10 m around a train station; darker shade of raster cell depicts higher density (see Table 1 for exact values).

cell density to average “outwards” density, results for all points located closer to the stop than the concentration are bad (because their density is lower than the average “outwards” density), and the effect of the isolated activity concentration is accounted for in the overall result.

Generic Example

Figure 1 depicts a generic example with one railway station and nine raster cells. Distance from a cell to the railway station is measured as the combination of the shortest path from the cell centroid to the pedestrian network and the network path from that access point to the railway station. Cells are denoted m_1 to m_9 , with increasing distance to the station.

Density $\hat{p}(m_k)$ was assigned randomly to demonstrate the mechanism of the indicator. Table 1 contains the input values as well as the intermediate results for the indicator computation, as well as the indicator results. Note that the average of c_{total} in Table 1 is $C(T)$ for the generic example.

Indicator Interpretation

The indicator result shows how well transit and development are co-located within a transit stop area based on

the distribution of activity density. At the stop area level, a maximum result value of 1.0 indicates that density is at no point within that area higher than the average density of all points located closer to the stop, and also at no point lower than the average density of all points within the stop area located further from the stop. In other words, a value of 1.0 is achieved if either there is uniform density within the stop area or there is a continuous decrease of density from the stop outwards. Any result value below 1.0 on the stop area level indicates some deviation from this “best case”—the closer to 0.0, the stronger the deviation. A “worst case” result value of 0.0 at the stop area level indicates a continuous increase in density with distance from the stop.

If the stop-level result is below 1.0, indicator values for individual raster grid cells are analyzed with result maps to examine how and where density distribution deviates from the “best case”. Low indicator values in a specific area point at one of three possible states:

1. density is higher than on average closer to the transit stop;
2. density is lower than on average further away from the transit stop; or
3. both.

For an unambiguous interpretation, indicator result maps need to be complemented with density distribution maps. In general, the most common reasons for low indicator values in a specific area are either comparatively low density close to a stop or comparatively high density far from a stop. While some of these cases could be identified solely based on a density distribution map, the indicator result map allows for the systematic assessment of distribution – that is, it considers density at every point relative to density at all other points, thus highlighting some areas deviating from a “best case” density distribution that are not easily identifiable on the density map.

Case Study

Overview

The municipality of Zaanstad in the Netherlands was selected as a case study for applying the co-location indicator. Zaanstad is located north of Amsterdam and is part of its metropolitan region. It is expected to attract a significant share of metropolitan growth, because of its proximity to Amsterdam and high level of railway accessibility. Zaanstad has six railway stations with travel times of between 12 minutes (Zaandam) and 25 minutes (Krommenie-Assendelft) to Amsterdam central station and frequencies of between four and ten trains per direction and hour. Transit oriented development is a general goal of Dutch planning and is particularly pressing in

Table 1. Input Values and Indicator Results for Generic Example in Figure 1

k	$d(t, m_k)^a$	$\hat{p}(m_k)^b$	\hat{p}_{in}^b	\hat{p}_{out}^b	c_{in}	c_{out}	c_{total}
Cell no.	Distance from cell centroid to stop	Density of cell	Average inwards density	Average outwards density	Inwards evaluation result	Outwards evaluation result	Total evaluation result
1	8.00	1.50	–	2.40	–	0.63	0.63
2	8.50	3.80	1.50	2.20	0.39	1.00	0.70
3	11.00	1.30	2.65	2.35	1.00	0.55	0.78
4	14.50	3.60	2.20	2.10	0.61	1.00	0.81
5	17.50	0.50	2.55	2.50	1.00	0.20	0.60
6	23.50	4.60	2.14	1.80	0.47	1.00	0.73
7	27.00	1.20	2.55	2.10	1.00	0.57	0.79
8	29.00	2.60	2.36	1.60	0.91	1.00	0.95
9	29.50	1.60	2.39	–	1.00	–	1.00
Avg.	18.72	2.30	2.29	2.13	0.80	0.74	0.78

Note: 1 m = 3.281 ft; 1 m² = 10.764 ft²; avg. = average; – = values that are not available because of the inner- and outermost cell.

^aIn m.

^bIn activities / 100 m²; $\hat{p}(m_k)$ is chosen randomly.

the metropolitan areas such as Amsterdam, where roads are often at capacity.

To plan future development strategies, it is essential to know where co-location is already good and where it could be improved. Therefore, the case study compares co-location performance for station areas using the proposed indicator. Station areas are defined as the area around a station reachable within 1200 m using the pedestrian network. Results are compared based on $C(T)$ per station area as well as maps of the disaggregated raster cell results $c_{total}(m_k)$. The case study area with its six stations is depicted in Figure 2.

As the case study should illustrate the potential of using the proposed indicator for co-location assessment, indicator results are also compared to established indicators for co-location.

Data and Implementation

Railways. Railway stations were imported from the “Informatiesysteem Knooppunten” (“information system transport nodes”) (25). Railway lines for visualization are based on cadaster data (26).

Pedestrian Network. The pedestrian network was extracted from OpenStreetMap data (27). Missing pedestrian crossings across roads represented with more than one line in the data or between offset sidewalks were added manually based on satellite images (28).

Activities. The number of residents was obtained from Statistics Netherlands (CBS) as hectare grid data for the year 2014 (29). The number of jobs was obtained from

the job register LISA per four-digit-postcode for the year 2015 (30). Postcode areas for the year 2015 were obtained from ESRI Nederland (31).

Activities were distributed to addresses within the respective hectare grid cell (residents) or postcode area (jobs). Address data were obtained from the cadaster (32) for the year 2016, including usage category and floor area per address. Inhabitants were distributed to addresses with residential use, while jobs were distributed to all other addresses. Distribution weight was determined using the floor area per address.

Built-Up Area. In the context of the case study, large portions of land within a 1200 m network distance from a railway station are not actually developable – namely green spaces and water. To account for this, the analysis has been conducted for “built-up” areas only, that is, all land excluding green spaces and water. For this, public space distribution (33) and building footprints (32) have been obtained from cadaster data. The built-up area within the 1200 m station areas is depicted in Figure 2.

Computation. The proposed indicator was calculated using QGIS version 2.18.7 (34) for data management and visualization, GRASS GIS version 7.2.0 (35) for network analysis, and R version 3.2.2 (36) for data analysis. Additional indicators shown in Table 2 were computed with R using the same dataset. Density was estimated with SAGA tool “Kernel Density Estimation” (24) within the QGIS Processing Toolbox using a quartic kernel (as shown in Equation 1), a bandwidth of 100 m, and a raster resolution of 10 x 10 m.



Figure 2 Overview of case study area.

Results

Table 2 contains co-location indicator results as well as additional indicators for the six case study station areas. The density distribution and respective indicator results on grid-cell level per station area are depicted in Figure 3.

The additional indicators in Table 2 reflect common approaches to co-location assessment:

- number of activities within the 1200 m station area—a measure of intensity;
- average density of the built-up area within the 1200 m station area—also a measure of intensity, considering differences in station area size;

- share of activities located within 300 m from the respective station in all activities located within the 1200 m station area—a measure of station proximity of activities;
- average distance from activities within the 1200 m station area to the station—also a measure of station proximity of activities.

Furthermore, Table 2 includes a simple ranking of the station areas according to the different indicators used.

Discussion

The proposed indicator clearly shows Koog aan de Zaan as the station area with the best co-location (indicator

Table 2. Overview of Results for Station Areas

	Krommenie-Assendelft	Wormerveer	Zaanse Schans	Koog aan de Zaan	Zaandam-Kogerveld	Zaandam
<i>New co-location indicator</i>						
Co-location indicator result C(T)	0.81	0.80	0.72	0.88	0.75	0.83
Rank	3	4	6	1	5	2
<i>Number of activities within station area</i>						
Number of inhabitants in 1200 m ^a	14565	7388	7621	13222	6203	12653
Number of jobs in 1200 m ^a	3387	2567	4335	1162	4656	8564
Number of activities in 1200 m^{a,b}	17951	9955	11956	14384	10858	21217
Rank	2	6	4	3	5	1
<i>Average density of station area</i>						
Built-up area within 1200m ^a [100 m ²]	19390	11610	14153	14545	11613	19970
Average density of 1200 m station area (built-up^c) [act. / 100m²]	0.93	0.86	0.84	0.99	0.94	1.06
Rank	4	5	6	2	3	1
<i>Share of activities within 300m in station area</i>						
Number of activities within 300 m ^a	553	346	415	1230	322	2641
Share of activities within 300 m in 1200 m^d	0.03	0.03	0.03	0.09	0.03	0.12
Rank	3	3	3	2	3	1
<i>Average distance to station</i>						
Average distance to station from activities within 1200 m station area [m]	840.67	836.27	801.39	720.73	785.02	726.03
Rank	6	5	4	1	3	2

Note: 1 m = 3.281 ft; 1 m² = 10.764 ft².

^aPedestrian network distance from station.

^bActivities = inhabitants + jobs.

^cOnly built-up area is counted for area computation.

^dShare of activities within 1200m station area that are located within 300m station area.

value 0.88). The station areas of Zaandam (0.83), Krommenie-Assendelft (0.81), and Wormerveer (0.80) represent the middle field, while Zaandam-Kogerveld (0.75) and Zaanse Schans (0.72) have the lowest co-location performance.

The density map of the best-performing station area, Koog an de Zaan (Figure 3g), shows a very uniform density distribution, and a slight decrease in density with distance from the station. To understand why the station area has not achieved an indicator value of 1 despite this, it is necessary to consult the map of indicator results per grid cell (Figure 3h). This map reveals the locations of areas with low performance. Together with the density map, this allows for a more detailed interpretation: very low indicator values occur only in areas with very low density that are located southwest of the station, at the northwestern fringe of the station area, and along the railway infrastructure. These locations are also apparent on the density map. However, there are further areas with an indicator value below 1. For example, activity concentrations in the southwest and southeast of the station area exceed the average density of all points closer to the station – a conclusion not directly apparent from the density map.

The density distribution of the worst-performing station areas Zaandam-Kogerveld (Figure 3i) and Zaanse

Schans (Figure 3e), shows both strong activity concentrations and low-density areas. However, given the highly irregular pattern, the density maps alone do not provide clear information about the main contributors to the overall low indicator values: which parts of the station areas perform particularly badly, and which do not? Indicator result maps (Figure 3, f and j) show that in Zaanse Schans, the lowest indicator values occur in areas with very low densities (at various distances from the station), whereas in Zaandam-Kogerveld, the lowest indicator values occur both in areas with high (far from the station) and low densities (also at various distances from the station). However, not all activity concentrations located toward the fringe of the two station areas (as apparent on the density distribution maps) entail particularly low indicator values. These are some of the additional insights provided by the indicator maps which would not be apparent simply from the density distribution maps.

The indicator result maps are particularly useful for identifying where interventions could have the highest potential effect on overall station area co-location performance. The specific type of intervention depends on boundary conditions (e.g., can transit or development be altered, or both?). However, there are some common

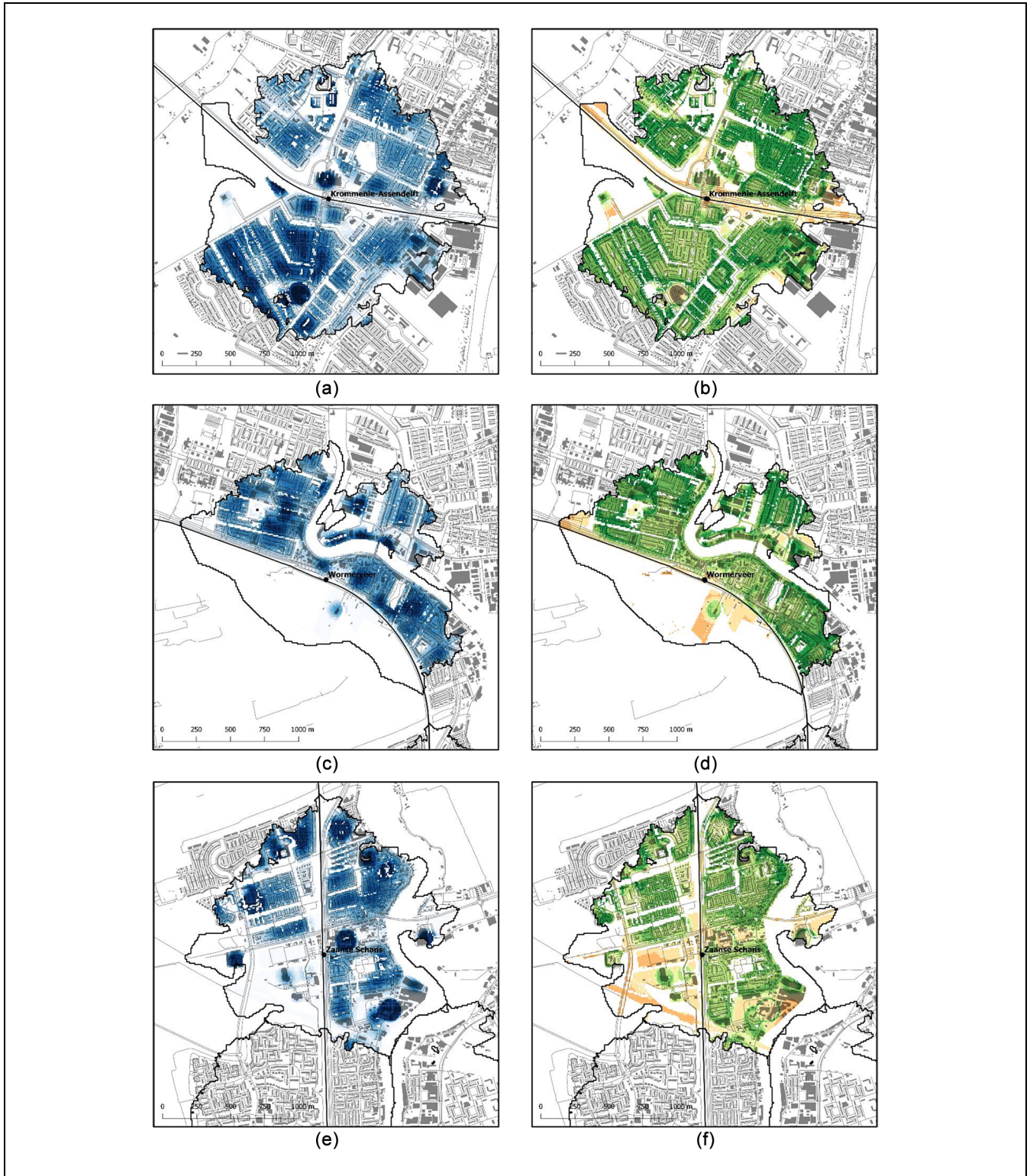


Figure 3. (continued)



Figure 3. Density distribution $\hat{p}(m_k)$ and co-location indicator result $c_{total}(m_k)$ per grid cell within station areas: (a) Krommenie-Assendelft: density distribution, (b) Krommenie-Assendelft: co-location indicator, (c) Wormerveer: density distribution, (d) Wormerveer: co-location indicator, (e) Zaanse Schans: density distribution, (f) Zaanse Schans: co-location indicator, (g) Koog aan de Zaan: density distribution, (h) Koog aan de Zaan: co-location indicator, (i) Zaandam Kogerveld: density distribution, (j) Zaandam Kogerveld: co-location indicator, (k) Zaandam: density distribution, (l) Zaandam: co-location indicator, and (m) legend.

rules. Areas close to a station with a low co-location performance value should be considered for densification. For low-performing high-density areas far from stations, access and egress paths to/from transit should be made as direct and as comfortable as possible. If changes to transit are considered, these areas are possible focus points for future stops.

The other co-location indicators shown in Table 2 lead to a different station area ranking compared to the indicator developed in this research. For example, the indicator number of activities within the 1200 m station area reflects two aspects: the size of the station area (depending on pedestrian network and proximity of other stations) and the intensity of its land use. It shows large differences between station areas. The ranking order differs almost completely from the proposed indicator; this is expected since intensity does not consider activity distribution within station areas at all. The other intensity indicator, average station area activity density, shows much smaller differences between station areas because it accounts for their size. It leads to a third ranking order. Again, this is expected, since the three indicators reflect very different aspects of co-location.

The share of activities within 300 m of the station compared to all activities within the 1200 m station area reflects station proximity based on an arbitrary threshold distance. It leads to the same ranking for the first two places as average density but does not lead to differences between the remaining four stations. Last but not least, the average distance to the station within the 1200 m station area – also a station proximity indicator – is the only alternative indicator that has the same ranking order as the new indicator for the top two station areas, but it shows strong differences at the bottom end of the ranking. The two proximity indicators lead to a different ranking order than the proposed indicator and this reflects that, by accounting for density distribution, the proposed indicator considers more than simply the proximity to the station.

Conclusion

The proposed indicator developed in this research enables planners to evaluate the quality of station area transit and development co-location. The indicator can be complemented with maps of the results at a grid cell level to identify specific locations where co-location is strong or weak. This second analysis can be used to draw conclusions about locations for interventions such as densification or new stations. These conclusions can inform decision-makers about where to focus more detailed research.

Existing indicators for co-location assessment do not provide a similar level of detail – neither in their input

for calculating results, nor in their possibilities for the presentation and interpretation of results. Intensity indicators (number of activities, average density) do not reflect density distribution within a station area at all. These indicators tend to simply show that the more centrally a station is located and the more urbanized the surrounding urban fabric, the better the value. Accordingly, they rank Zaandam station area first, which is located closest to central Amsterdam and is considered as the most urban station area. Proximity indicators consider density distribution to some extent. However, the 300 m share only assesses density based on one cut-off distance; therefore, inside the areas within 300 m and between 300 and 1200 m from the station, it does not assess distribution. Yet, there is an important difference whether development is concentrated at 400 or 1100 m from a station. Average distance to the station is ultimately the result of density distribution and thus considers distribution somewhat. However, it also depends on the extent of the station area (which can be reduced because of non-developable land or overlapping station areas), and it is hard to disentangle these influences. None of the other indicators allow for the spatially explicit interpretation of results, which means they do not help users understand the reasons why a certain station area performs well or badly.

On the other hand, all of the indicators discussed in this paper contain important information. In particular, the intensity indicators complement the proposed density indicator developed in this research. Importantly, the proposed indicator only reflects density distribution, regardless of the magnitude of density. Therefore, it is best used in combination with an intensity indicator.

The proposed indicator could be refined in three ways. First, the definition of built-up area used in the case study requires further development. In particular, large areas dedicated to transport infrastructure repeatedly show as performing badly in Figure 3. On the other hand, some transport infrastructure areas could possibly be developed in the future, and therefore clear criteria for their exclusion from analysis would be helpful. Furthermore, even the seemingly non-developable areas (such as open water or green space) excluded from the analysis might be considered for development at some point to exploit their proximity to transit. Therefore, the effects of undevelopable areas should be examined, for example by comparing the share and distribution of built-up area within station areas. Non-developable areas next to stations should also be considered in transit network design as potential barriers for transit access and as increasing distance between activities and transit. Second, more precise activity data would increase accuracy. Ideally, activities per building should be used as input data to avoid the potentially distorting activity

disaggregation to addresses. Furthermore, visitor data for locations such as sports venues or shopping malls would be beneficial – currently, some of these show as areas of low density in Figure 3, which is not adequate. Third, experimentation with different bandwidths and cell sizes for kernel density estimation could shed light on the effect of extreme density concentration (single addresses with a very high number of activities) on indicator results.

In future research it would be interesting to use the proposed indicator combined with an intensity indicator in a direct transit demand model and compare its predictive power for transit demand with other indicators for co-location.

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Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: C.M. Marti, L. Bertolini, U. Weidmann; data collection: C.M. Marti; analysis and interpretation of results: C.M. Marti; draft manuscript preparation: C.M. Marti, L. Bertolini, U. Weidmann. All authors reviewed the results and approved the final version of the manuscript.

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