Quantitative tools in urban morphology: combining space syntax, spacematrix and mixed-use index in a GIS framework

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Abstract. *A spatial modelling method is presented that utilizes a Geographical Information System (GIS) to combine the analyses of three constituent elements of urban form recognized by M. R. G. Conzen. The aim is to produce a spatial classification system for various types of urban areas, and reveal how they perform socio-economically. In the proposed method, space syntax, spacematrix, and mixed-use index (MXI) are used to assess street-network integration, building density, and land-use mixture. These elements are incorporated into a single framework. The validity of the method is initially tested through human behaviour records based on Global Positioning System (GPS) tracking. The method is then used in a comparison of the various spatial parameters of three new towns and one old town in the Netherlands. The results show that the old town has higher values of street-network integration, building density, and land-use mixture than the new towns. The method functions well as a diagnostic tool for suggesting ways of improving socio-economic performance in urban areas. For example a spatial diagnosis can be made for new towns suffering from a lack of vibrant street life. The method helps to reveal the interdependences of street-network integration, building density, and land-use mixture in urban transformation processes.*

Keywords: street-network integration, building density, land-use mixture, integrated approach, Netherlands

Advances in software over the past decade have provided new ways to describe, classify and represent various types of urban space through the visualization and analysis of the spatial and socio-economic properties of urban form (Conzen, 2010; Moudon, 1997; Stanilov, 2010). Methods proposed in recent years include those developed by Griffiths *et al*. (2010), Gil *et al*. (2012), Osmond (2010), and Oliveira (2013). Their main aim is to assess the morphological bases of urban areas. Improved computing capacity has contributed to great advances in existing methods, such as space syntax, spacematrix, and mixed-use index (MXI). Meanwhile, the use of Geographical Information Systems (GIS) as a tool for combining large amounts of place-specific socio-economic data is slowly entering urban research. Several researchers have identified the significance of applying GIS as a basic tool for integrating recently developed spatial analysis methods (Gil *et al*., 2012; Jiang *et al*., 2000; Marcus 2010; Pinho and Oliveira, 2009).

None of the various methods developed so far can individually provide a complete picture of the spatial properties of the built environment. For instance, while space syntax is a well-known method for measuring street-network integration (Hillier, 1996; Hillier, 1999; Hillier and Hanson, 1984; Turner, 2007), it does not consider other morphological aspects, such as built-mass density (Joosten and Nes, 2005; Ratti, 2004). Some other recently developed tools such as MXI (Hoek, 2009) and spacematrix (Berghauser Pont and Haupt, 2010; Rådberg, 1996) provide attractive possibilities for measuring the degree of land-use diversity and density of built-mass. Recently, Nes *et al*. (2012) separately converted space syntax, spacematrix, and MXI analyses into a grid-analysing GIS framework. The street-network integration values and plot-ratio data were combined to compare relative levels of social development in Rotterdam. The strong correlations between street-network integration and density in the Rotterdam case encouraged us to seek a better method for combining all the three analytical tools to represent more accurately the entire urban form. In this article, a quantitative classification system of various *types* of urban areas is presented based on analyses using our proposed spatial modelling method. Correlating this classification system with socio-economic performance contributes to an understanding of the interdependence of street-network integration, building density, and land-use mixture in the urban transformation process.

Combining street-network integration, built-mass density, and degree of land-use mixture

A useful starting point for a quantitative representation of urban form is M. R. G. Conzen's method of urban morphological investigation. Conzen's method combines town plan (that is, streets, plots, and the block-plans of buildings), patterns of building form, and patterns of land use (Conzen, 1960, 2004). Space syntax can be applied to measure various street-network integration values, or how any given street spatially relates to other streets. Measurements of building mass can be taken by using the spacematrix method to quantify building types and building density, and non-built space. Finally, the land-use pattern can be quantified by using the MXI tool to measure the degree of land-use diversity. Combining these three measurements makes it possible to quantitatively describe the spatial properties of urban form, thereby providing a new classification system for spatial types of urban areas in relation to their socio-economic performance. Viewed in this way, a high degree of accessibility, density and land-use diversity would generally mean a high degree of socio-economic performance, and *vice versa*. This hypothesis has been confirmed by many urban researchers since the 1960s, including Jacobs (1961), Alexander (1966), Gehl (1987) and Montgomery (1998).

Research design, methodology and verification

Research design

The method is applied here in a comparative study of the spatial properties of new and old towns. 'New towns' are defined as planned towns constructed over a short time span, often corresponding to a particular spatial structure and architectural style. However, the socio-economic outcome in these towns often turns out to be different from that expected: lack of street life, limited economic investment and monofunctional areas are evident. In contrast, 'old towns' developed over a longer time period often have centres with vibrant street life adjacent to well-functioning residential areas.

First, the space syntax, spacematrix, and MXI methods are explained separately. Then

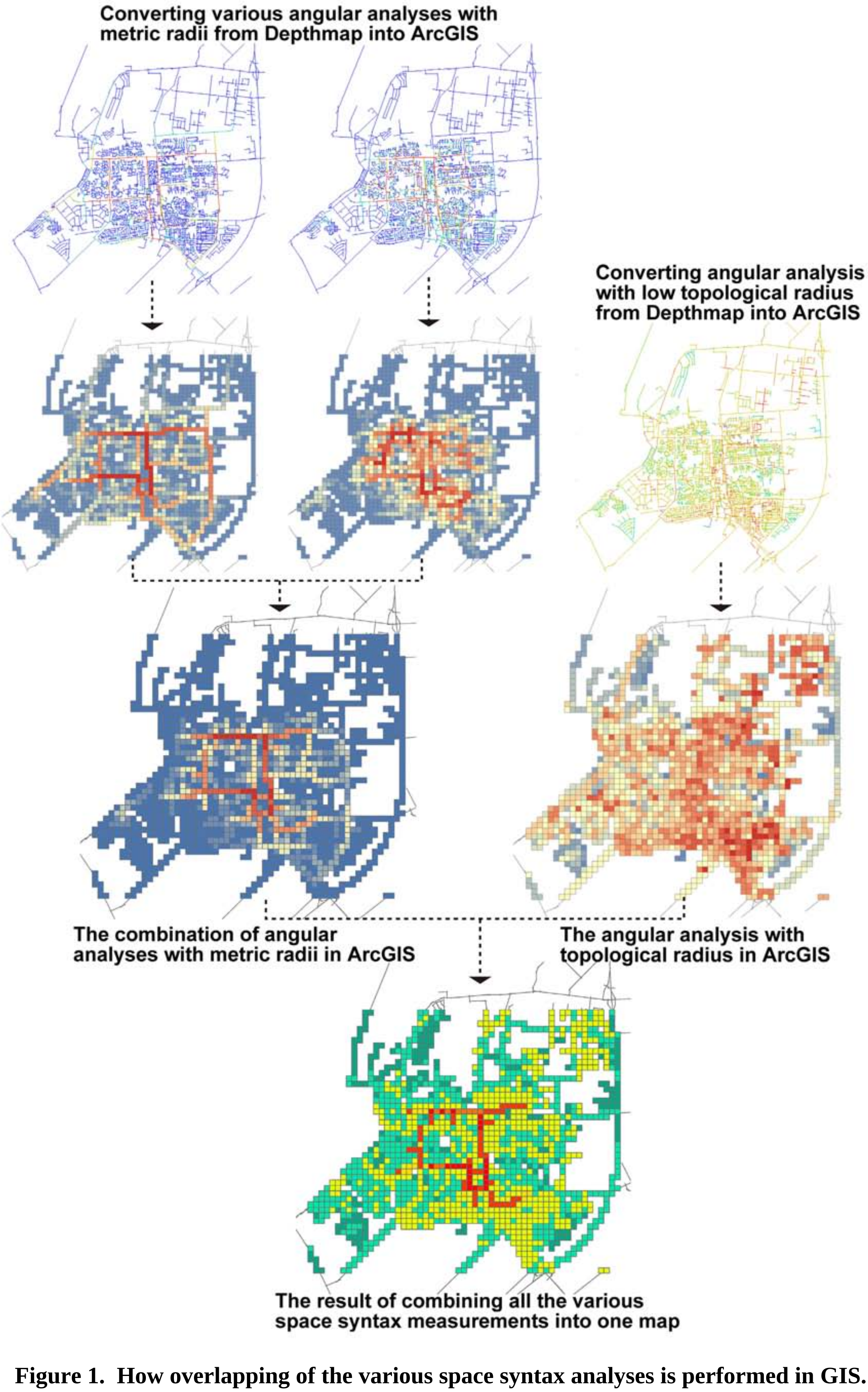

Figure 1. How overlapping of the various space syntax analyses is performed in GIS.

the method of integrating them is described. The results from the application of this new method are compared with human behaviour records to verify and test the socio-economic performance of urban areas. Finally, the method is applied to an old town and three new towns to show how various spatial types of urban areas perform socio-economically. It is shown to be feasible to create a classification system for different types of urban areas that provides the basis for proposing various intervention strategies.

Research method

The space syntax method has contributed to an explanation of how the spatial integration of street and road networks affects movement flows, the location of economic activities, and the amount of street life (Hillier *et al.*, 1993; Penn *et al.*, 1998). Computer programs such as *Depthmap* can be used to analyse the street network configuration according to metric distance (measuring shortest-length paths), topological distance (measuring fewest-turn paths), and geometric distance (measuring least-angular-change paths) (Hillier and Iida, 2005, pp. 557-8). Angular analyses with both topological and metric radii are undertaken. The main routes through and between urban areas are highlighted in an angular analysis with a high metric radius, whereas the various local centres are highlighted in an angular analysis with a low metric radius (Nes and Stolk, 2012). Angular analysis with a low topological radius is used here because a high radius analysis tends to overestimate street integration values, thereby blurring spatial integration data. Combining the various space syntax measurements into one map demonstrates simultaneously the spatial potential for local neighbourhood centres and the degree of vitality of the main routes (Figure 1).

The value of each grid cell is determined by the highest value of axial lines inside the grid. All measurements are separated into high, medium and low values using the ArcGIS natural break method. This minimizes the average deviation of each class from its own mean values while maximizing the deviation of each class from the mean values of other groups. The most integrated areas (shown in red in Figure 1) contain high values for both topological and metric radii. The blue-coloured cells represent low values for both integration values.

Building density and various building types can be represented simultaneously using the spacematrix method. In this way it is possible to quantify such variables as intensity, compactness, non-built space, and building height, and thereby differentiate urban form efficiently (Berghauser Pont and Haupt, 2007, p. 63; Rådberg, 1996). The floor space index (FSI) on the *y*-axis gives an indication of an area's built intensity or plot ratio. The ground space index (GSI) on the *x*-axis indicates the building coverage or ground-floor area. The spacematrix method divides building types into low-rise, mid-rise and high-rise, based on the number of floors. It also separates buildings into point type, strip type, and block type based on construction forms. Thereafter, the whole built environment can be divided into nine categories (Figure 2). Unlike the method of Nes *et al.* (2012), only FSI is used in the combination of space syntax and spacematrix. The classification of various building forms is based on the correlation between FSI and GSI, thereby more accurately reflecting the attributes of the built-mass.

The MXI quantifies the degree of land-use mixture (Hoek, 2009). It measures the functional mix, based on the percentages of gross floor area of dwellings, working places, and commercial amenities occupying all the floors of the urban blocks. 'Housing' encompasses various residential buildings, including apartments, condominiums and townhouses. 'Working places' includes offices, factories and laboratories. 'Amenities' includes commercial activities (such as retailing), educational activities (such as schools and universities) and leisure activities (such as stadiums, cinemas, and museums). Figure 3 shows the interrelationships of the three major land-use categories. Each corner of the triangle represents the complete dominance of one of the three major land-use categories. An area

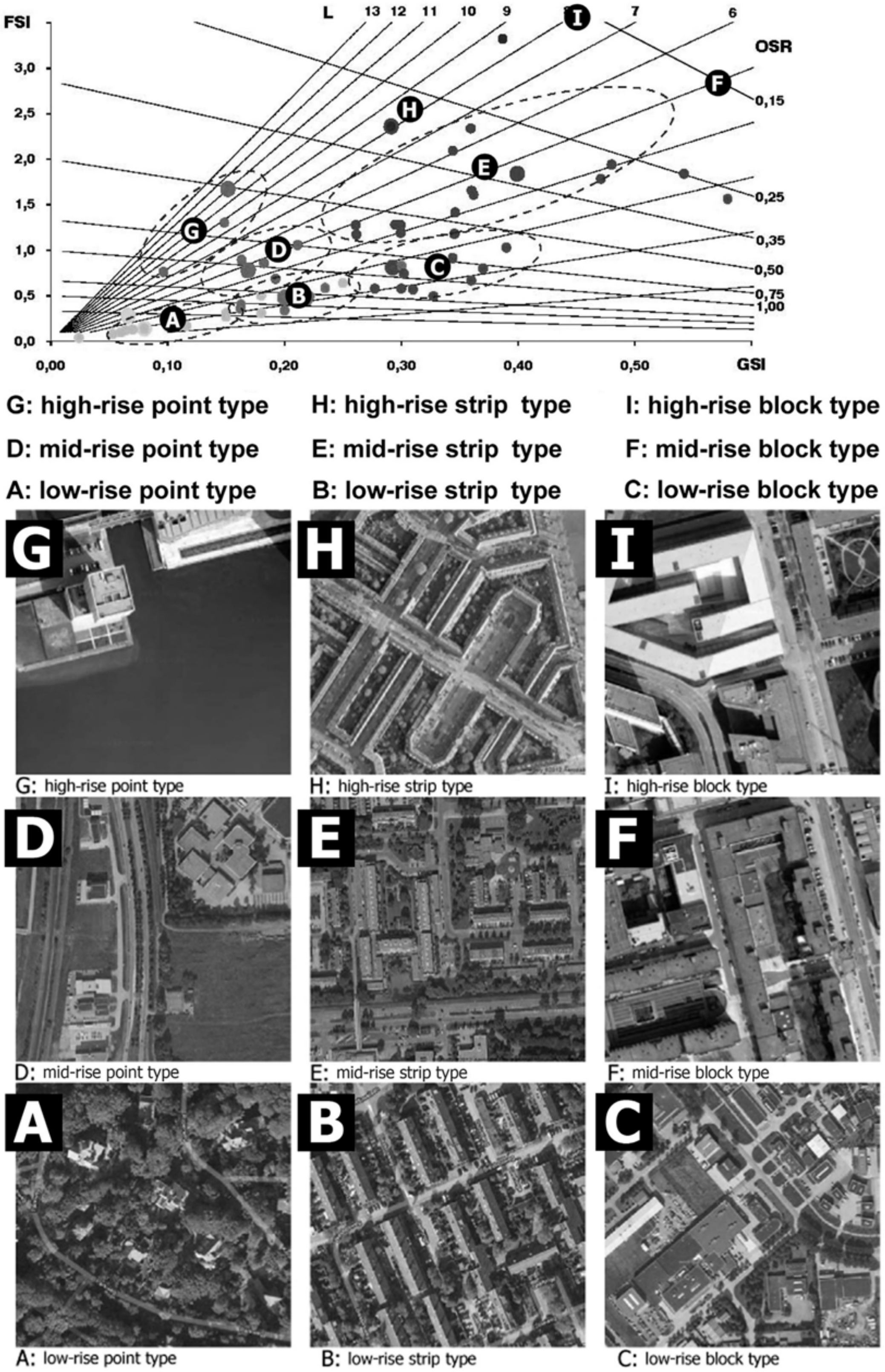

Figure 2. The FSI-GSI plane of spacematrix (top) and examples of various types identified through the spacematrix analyses (below).

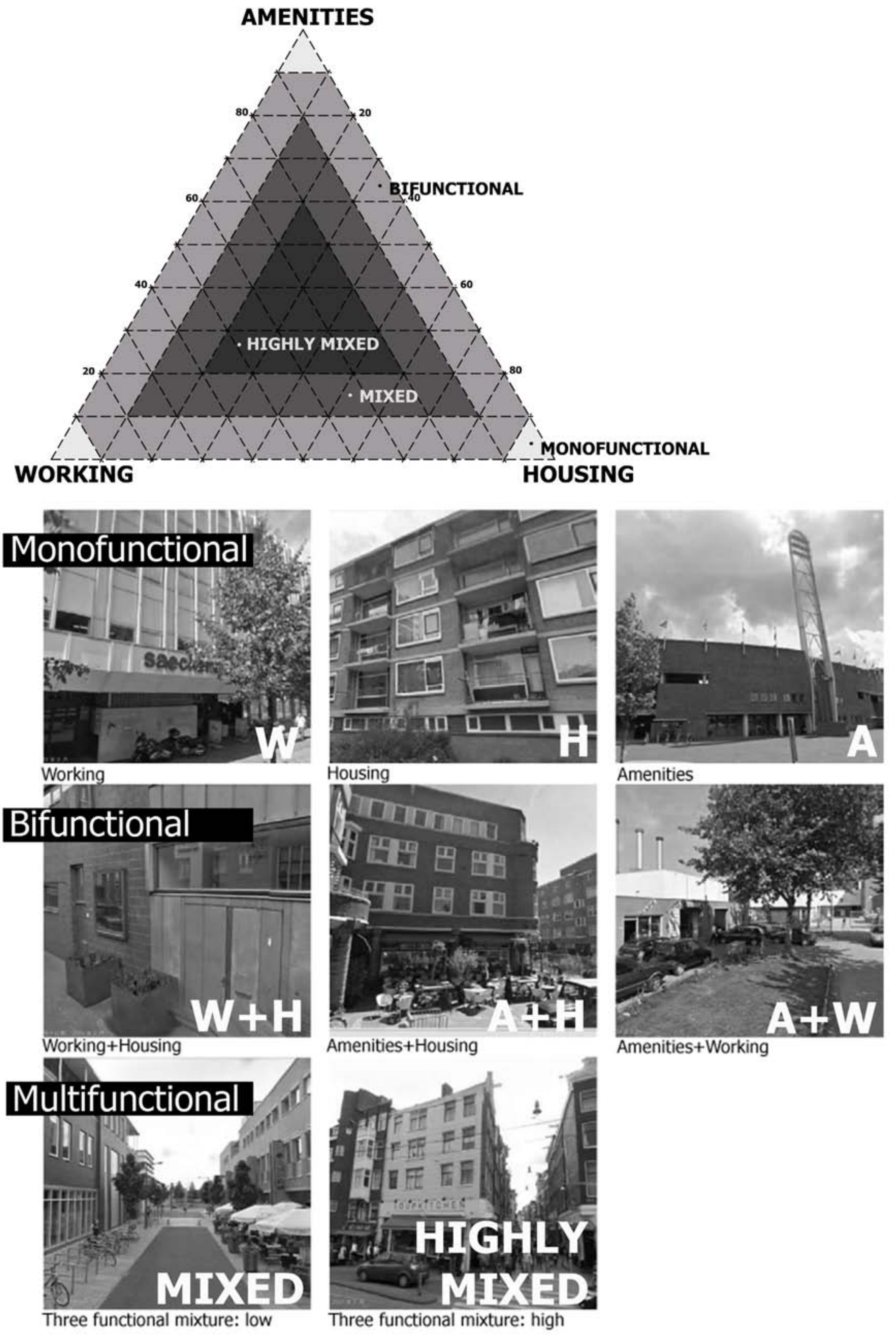

Figure 3. Ternary diagram of MXI (top) and examples of various categories of land-use mixture identified through MXI (below).

Table 1. The definition of high, medium and low values in space syntax, spacematrix and MXI

Space Syntax	**The content of this classification**
High value	High values in both metric and topological analyses; One analysis with high value and the other with medium value
Medium value	Medium values in both metric and topological analyses; One analysis with high value and the other with low value
Low value	Low values in both metric and topological analyses One analysis with medium value and the other with low value
Spacematrix	**The content of this classification**
High value	Mid-rise strip or block types; high-rise block types
Medium value	Low-rise block or mid-rise point; high-rise point or strip types
Low value	Low-rise point and low-rise strip types
MXI	**The content of this classification**
High value	Mixture of three functions
Medium value	Bifunctional areas
Low value	Monofunctional areas

consisting of all three land-use categories is considered as a multifunctional space. Where each land use occupies more than 10 per cent of the total floor space, but two of the three land uses occupy less than 20 per cent of the total floor space, the area is considered to be a mixed-use area. If each land use occupies at least 20 per cent of the floor space, it is considered to be a highly mixed-use area.

Combining the three different analytical methods into one requires converting the various measurements into one framework by using GIS. To correlate vector-based data with polygon-based data, the size of each grid must cover part of the street as well as a building adjacent to that street. The size of the raster-grid cell must not be so small that it separates building-block variables from street-network integration variables. Conversely, a very large raster-grid size is undesirable, since it will reduce the precision of the vector-based analysis. In this research, a raster size of 150 x 150 m for each cell is used. Figure 4 shows how spatial integration of the street and road network, degree of built-mass density, and relative multifunctionality can overlap with a GIS grid system in ArcGIS. To aggregate all of the data from the space syntax, spacematrix and MXI analyses into one framework, each measurement is divided into three levels: high, medium and low values (Table 1).

These values are assigned in the following way. Space syntax utilizes two types of spatial integration analyses, and whether the overall results can be classified as a high, medium or low depends on the combined outcome. For example, an overall high value in space syntax represents either two high values, or one high value and one medium value. The overall medium value represents either two medium values or one high value and one low value; and the overall low value represents either two low values or one medium value and one low value. In the spacematrix analyses, the mid-rise strip and high-rise block type have high values. The low-rise block and mid-rise or high-rise point and strip types have medium values, and the low-rise point and low-rise strip types have low values. The choice of these values is based on the research results from Berghauser Pont and Haupt (2010) and Nes *et al.* (2012). Plots with both high FSI and GSI are mostly located in vibrant urban centres. In the MXI analyses, monofunctional areas have low values, bifunctional areas have medium values, and multifunctional areas have high values.

Combining all the quantitative data from the space syntax, spacematrix and MXI analyses creates the opportunity to propose a new

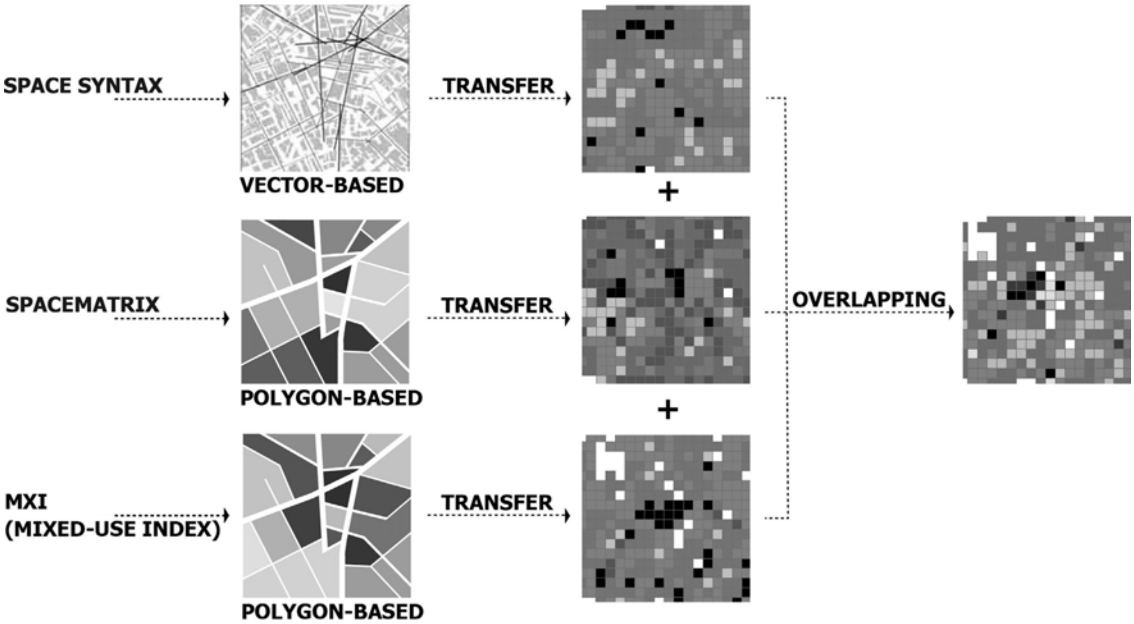

Figure 4. How overlapping of space syntax, spacematrix and MXI is performed in GIS.

Table 2. The definition of various categories in the final combination of space syntax, spacematrix and MXI

Types of urban areas	The values of Space Syntax, Spacematrix and MXI belonging to each type	Degree of Balance
1) Suburban	L/L/L, M/L/L, L/L/M, L/M/L	Balanced with low-values
2) Low-urban	L/M/M, M/L/M, M/M/L	
3) In-between (low)	H/L/L, L/H/L, L/L/H	Unbalanced with mixed-values
4) In-between (medium)	H/M/L, M/H/L, L/M/H, H/L/M, L/H/M, M/L/H	
5) In-between (high)	H/H/L, H/L/H, L/H/H	
6) Medium-urban	M/M/H, M/H/M, H/M/M, M/M/M	Balanced with high-values
7) Highly-urban	H/H/H, H/M/H, M/H/H, H/H/M	

L = Low value, M = Medium value, H = High value

classification system of various *types* of urban areas. Herein, the built environment is separated into the following three groups, namely 'balanced with low-values', 'unbalanced with mixed-values', and 'balanced with high-values.' 'Balanced' reflects similar values in the space syntax, spacematrix and MXI measurements (that is, similarly high or similarly low values), whereas 'unbalanced' reflects the existence of significant differences between the values of the three measurements. Based on this, seven categories are proposed, ranging from suburban to highly urban areas (Table 2).

The terms used in this classification matrix, for instance 'suburban' and 'urban', differ from their standard use in urban geography. Instead, this matrix reflects the spatial features of urban form as part of a continuous rural-to-urban gradient and also reveals the area's related socio-economic performance. For instance, 'suburban' areas belong to the 'balanced with low-values' group because they have either three low values, or two low values and one medium value in all spatial measurements, which suggests a low degree of socio-economic performance (for example, silent, mono-functional urban areas). Con-

Figure 5. A comparative analysis of human behaviour records using GPS tracking and a final combination analysis integrating three measurements.

versely, 'highly-urban' areas belong to the 'balanced with high-values' group because they have either three high values, or two high values and one medium value in all measurements, which suggests a high degree of socio-economic performance. 'In-between areas' (with high values) belong to the 'unbalanced with mixed-values' group because these areas have a mixture of high and low values in the space syntax, spacematrix and MXI analyses. These areas are defined as 'in-between' areas since their spatial parameters tend to support a higher degree of socio-economic performance than the 'suburban' areas but a lower performance than the 'highly-urban' areas. Moreover, such 'unbalanced' areas contain one or two relatively low values in the three spatial measurements, which also indicates their potential to transform.

Testing the hypothesis

Whether this proposed spatial classification methodology could express various degrees of socio-economic performance of urban areas requires investigation of independent variables. Human behaviour records can be regarded as a good representation of an area's socio-economic activities (Schaick and Spek, 2008). GPS tracking-records of people's movements in the Dutch city of Delft (Spek, 2010, pp. 81-3) are compared with our proposed urban morphological taxonomy in

Figure 6. Results of the spatial integration analyses of Lelystad, Almere, Zoetermeer and Haarlem.

Figure 5. Figures 5A and 5B display non-local visitors' activities in Delft's city centre over a sample day: local move-ments of people have been excluded to avoid the effects of population density. The GPS tracking record begins in two car parks near Delft's city centre. Colours represent various densities of movements of people, ranging from green (low) to red (high). A high correlation is found between recorded movement density and the type of urban area identified from the spatial analyses. The densest movement flows occur in areas with high values. Movement flows are also relatively high in unbalanced zones with areas of high development potential, but little movement is observed in generally low-value areas (that is, suburban and low-urban types). These results suggest that our proposed spatial modelling method is capable of providing an indication of varying degrees of socio-economic performance.

Application of the method

Towns that have kept detailed records of street networks, building types and building uses over several decades would be ideal for testing this method. However, such detailed record-keeping does not exist. An alternative is to conduct comparative research into sets of new and old towns at different stages of development. Several new towns were planned and built near major Dutch cities in the 1960s and 1970s. A comparison of these new towns with one another and with an example of an old town can shed light on the spatial properties of Dutch new town development over the past half-century. Lelystad, Almere and Zoetermeer are examples of new towns. They were built within the same period and are of similar size. Haarlem, in contrast, has existed for many centuries. It is close to Amsterdam and of comparable size to Lelystad, Almere and Zoetermeer.

Several indicators are used to assess these towns from a socio-economic perspective, including population density, population structure, amount of office space, percentage of the workforce in creative employment (for example, designers, architects, artists), availability of facilities, and immigration rates (Reijndorp, 2009). According to Reijndorp's socio-economic ranking, Haarlem has the highest values, followed by Zoetermeer, Almere and Lelystad (Ye and Nes, 2013).

To what extent are these towns' socio-economic characteristics correlated with their built environments? First, street network integration values correlate with socio-economic rankings. The space syntax analysis (Figure 6) shows that main roads generally have high integration values. In all three new towns, the red cells, with the highest integration values, tend to encircle a segregated hole (with green and blue cells) in the middle where the shopping centres are located. In other words, the integrated main routes are located outside the main centres in the three new towns. Lelystad scores the lowest on spatial integration, followed by Almere and Zoetermeer. Haarlem has highly integrated main routes running through its town centre. Degree of spatial integration correlates with the ranking of socio-economic characteristics in all four towns.

A similar correlation exists between building density and socio-economic characteristics (Figure 7). The high-rise strip and block-type buildings occupy greater percentages of the built-up area in Haarlem than in Zoetermeer, Almere and Lelystad. The percentage importance of these categories is 1.7 per cent of total built-up area in Lelystad, 4.3 per cent in Almere, 8.4 per cent in Zoetermeer, and 12.2 per cent in Haarlem.

In the MXI analysis in Figure 8, blue cells represent offices and industrial areas, pink cells represent amenities, and yellow cells represent housing areas. Red areas have a mix of housing and amenities. Darker shades of grey are used to represent higher degrees of land-use mixture. The percentage of blocks containing roughly equal amounts of all three functions – housing, working and amenities – is only 0.6 per cent in Lelystad, 1.1 per cent in Almere and 4.1 per cent in Zoetermer, but 9.0 per cent in Haarlem. Bi-functional areas have their lowest extent in Lelystad (11.4 per cent) and their highest in Haarlem (21.2 per cent).

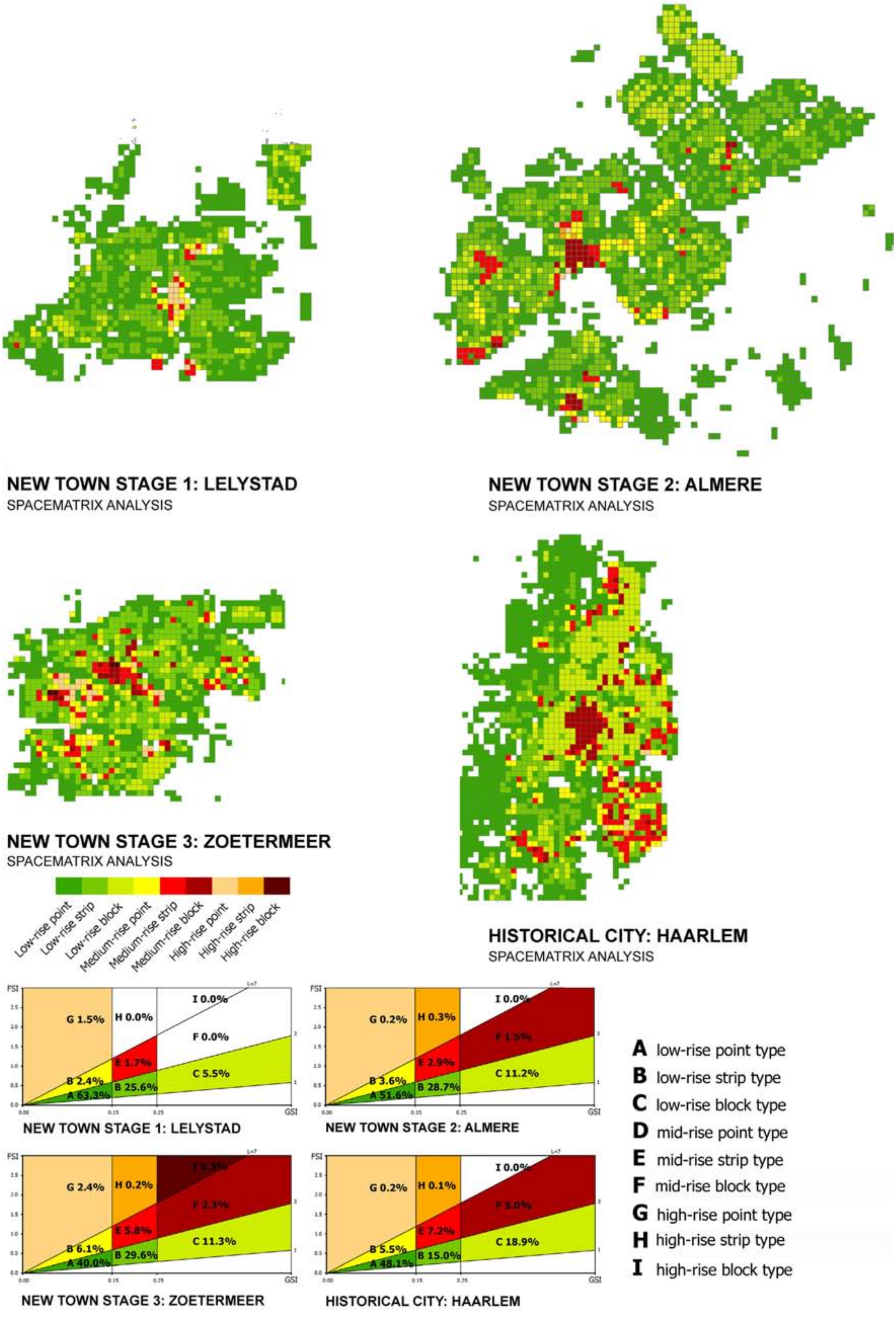

Figure 7. Results of the density and building type analyses in Lelystad, Almere, Zoetermeer and Haarlem.

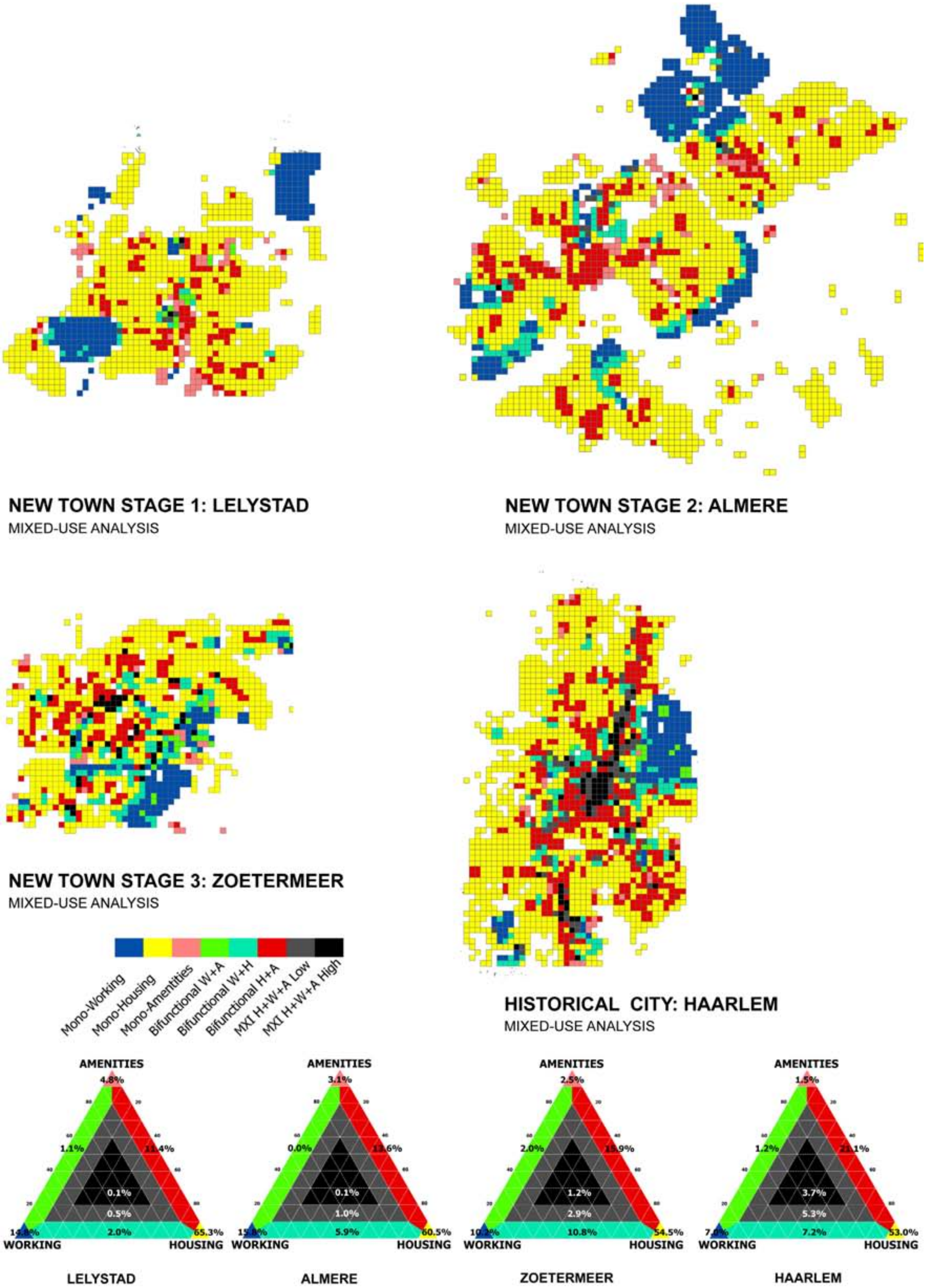

Figure 8. Results of the land-use mixture analyses in Lelystad, Almere, Zoetermeer and Haarlem.

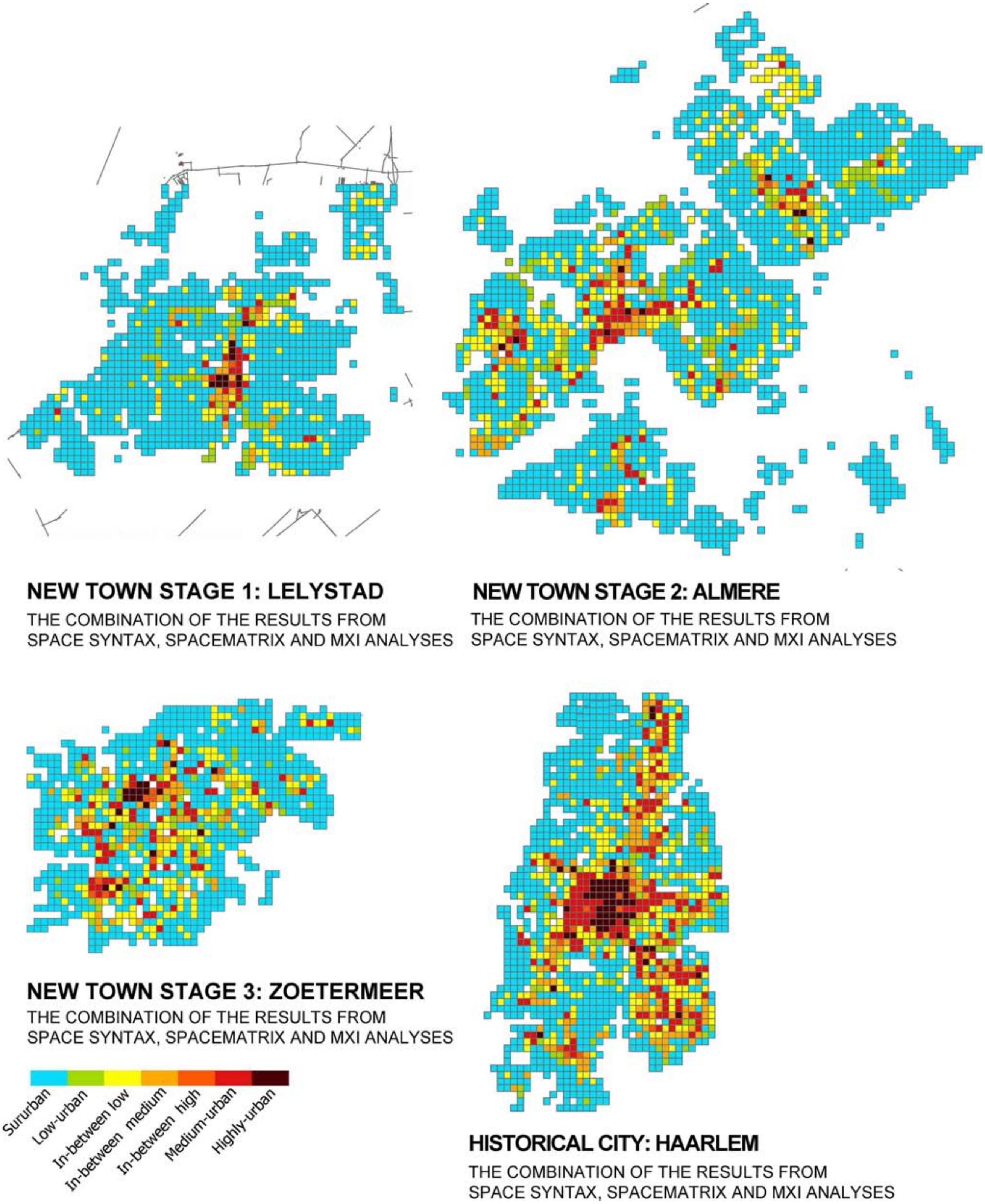

Figure 9. Results of the combination of space syntax, spacematrix and MXI analyses in Lelystad, Almere, Zoetermeer and Haarlem (reproduced from Ye and van Nes, 2013, p. 28).

The higher the density of the built-mass, the higher the degree of multi-functionality within buildings.

Finally, the spatial integration, building density, and functional mix values can be combined into one matrix to visualize the various types of urban areas from a spatial perspective (Figure 9 and Table 2). The results indicate that the lower a town's socio-economic ranking, the higher the number of areas with low spatial values, and vice versa. Lelystad, for example, has a small number of areas belonging to the 'balanced with high-values' group and a high number of suburban, mono-functional areas belonging to the 'balanced with low-values' group. In this combined spatial analysis, Almere's city centre and some local sub-centres score relatively highly, because they have a large number of unbalanced areas and balanced areas with high values. Furthermore, a considerable number of Almere's areas belong to the category of unbalanced urban areas. Zoetermeer already has a relatively highly-urbanized centre with a relatively high number of balanced areas with high values. Haarlem's town centre, however, has a spatial structure with very high values in all the analyses. In short, an urban transformation towards spatial features supporting high socio-economic performance probably occurs when new towns transform over a long time span. Thus one may ask whether it is possible to accelerate this transformation process, and what kinds of spatial improvements are necessary to promote higher degrees of socio-economic performance in poorly functioning urban areas.

The identification of development potential in unbalanced areas

It is evident that the combination of space syntax, spacematrix and MXI methods through GIS can represent spatial differences between new and old towns. Figure 10 shows the percentages of various types of urban areas in the four towns. Here the 'percentage' is calculated as the number of grids belonging to certain types divided by the total number of grids in this town. Lelystad – the new town ranking lowest in both spatial and socio-economic respects – has the highest percentage of 'balanced with low-values' areas (Table 2). Haarlem, in contrast, has the highest percentage of 'balanced with high-values' areas and the lowest percentage of 'balanced with low-values' areas. Most of Haarlem's 'balanced with low-values' areas are located in the post-war or recently developed neighbourhoods. Almere and Zoetermeer have a high percentage of 'unbalanced with mixed-values' areas. The percentage of 'balanced with high-values' areas is 3.4 per cent in Lelystad, 4.9 per cent in Almere and 6.8 per cent in Zoetermeer, compared with 15.9 per cent in Haarlem. Conversely, the percentage of 'balanced with low-value' areas is 89.4 per cent in Lelystad, 84.6 per cent in Almere, 78.5 per cent in Zoetermeer, but only 67.9 per cent in Haarlem. Seemingly, a town's socio-economic performance depends on the provision of 'balanced with high-values' areas in its centre. Unbalanced urban areas seem to be undergoing substantial transformation processes. There is scope for transforming unbalanced areas into balanced areas with high-values. However, it depends on which spatial parameters are scoring low or high in these types of areas, and note should be taken of the interrelationship between street-network integration, building density and degree of land-use diversity.

The data from this inquiry indicate that a hierarchical relationship exists between street-network integration, building density and land use. This accords with the long life of roads in comparison with buildings and the frequently changing functions within buildings (Nes, 2002). The spatial integration of street networks may well have the strongest effect on transformation processes, followed by building density, and then the degree of functional mix. The observations made in the four cases analysed accord with this inference. Lelystad performs poorly in terms of density and functional mix. Almere has a high built-mass density compared with Lelystad, but lacks land-use diversity. Zoetermeer and Haarlem have high land-use diversity in their centres.

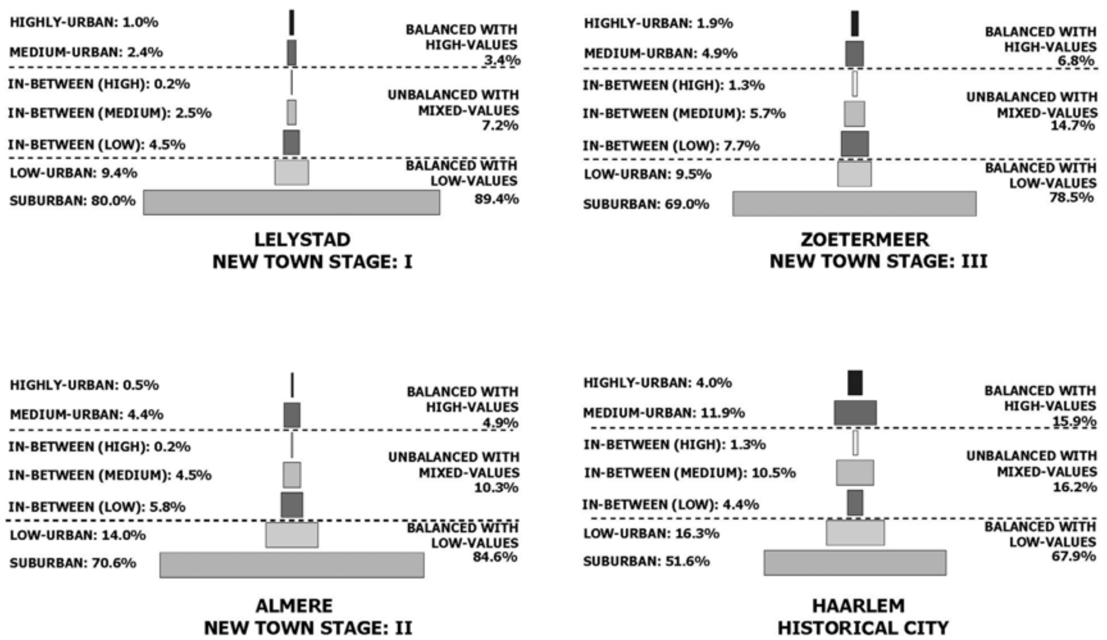

Figure 10. The percentages of various types of urban areas in Lelystad, Almere, Zoetermeer and Haarlem.

It seems that building density is associated with spatial integration of street-networks, and high degrees of functional mix tend to be associated with high building densities.

A classification system based on this hierarchical relationship can be used to identify the spatial elements with low values in unbalanced areas and to indicate where and what kinds of improvements are needed. Specific strategies can thereby be proposed to transform unattractive areas into balanced areas with socio-economic characteristics appropriate to their spatial settings. Table 3 contains a matrix that can be used to identify five different development strategies based on space syntax, spacematrix and MXI values. For instance, the spatial integration of the street network is high in areas belonging to category A where spacematrix values are low – in other words imbalances exist between FSI, GSI and spatial integration. These areas show the potential for further increases in density or morphological improvements of the built-mass. For the area belonging to category B, the building density is high, but the street-network integration is low. These kinds of areas need to improve their street-network integration if the intention is to create lively urban areas. Policies encouraging better land-use mixture are needed in category C areas, which score high in both the space syntax and spacematrix analyses, but low in the MXI analysis. In several cases, a lack of land-use diversity in category C areas is related to lack of active frontages between buildings and streets. The qualitative relationship between active frontages and functional mix has been discussed by Jacobs (1961) and Gehl (1987), and quantitatively tested by Joosten and Nes (2005) and Nes and Lòpez (2010).

Figure 11 shows the distribution of the five different improvement strategies for the four towns. The map shows that there are several potential areas for increasing density along integrated roads in the new towns and post-war areas. There is also the potential for improving areas of poor street-network integration – for example, improving the links of culs-de-sac to the street network.

The accuracy of this diagnostic method has been explored by using 'street view' in Google Earth. Figure 12 shows examples of each type

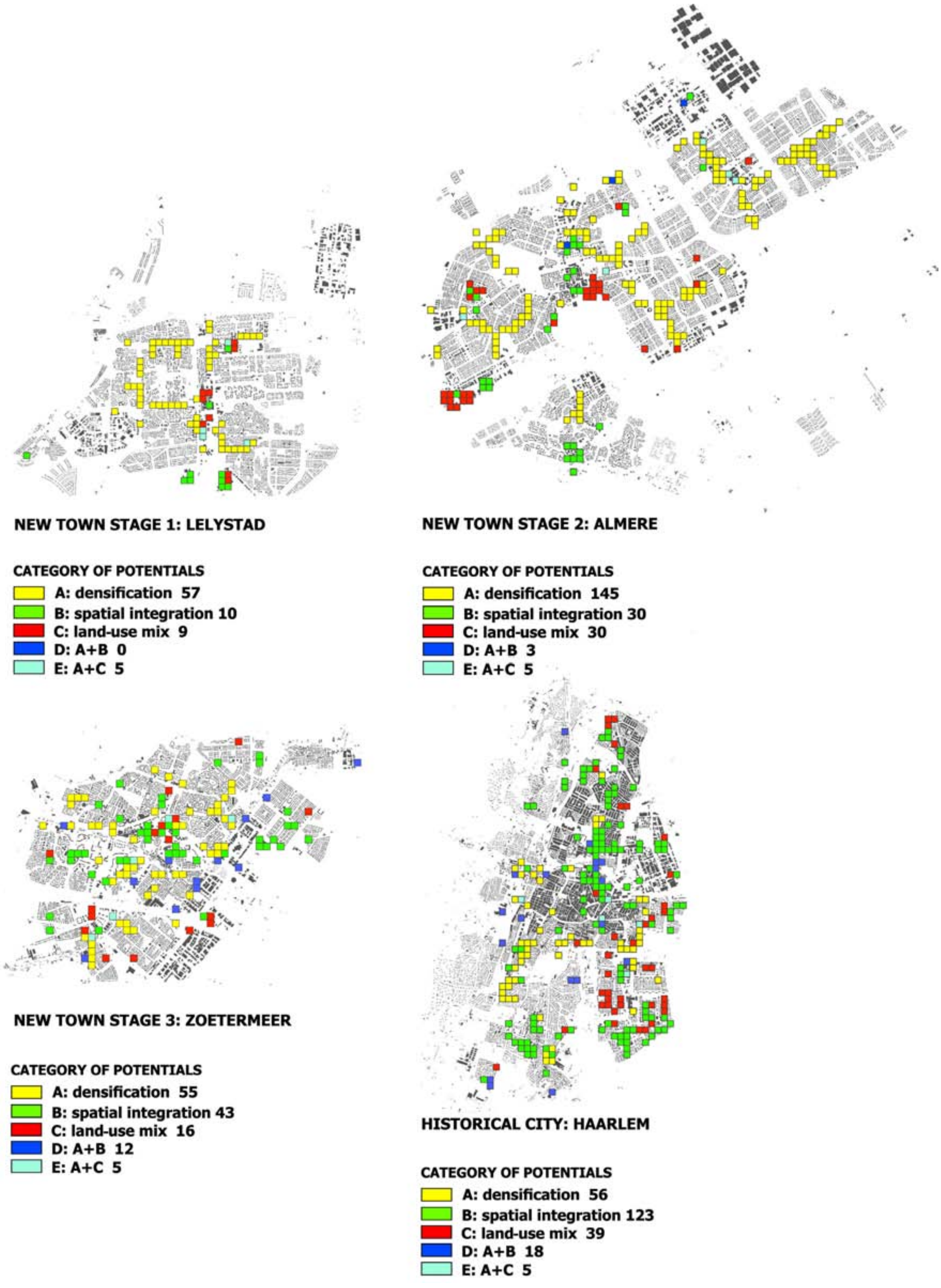

Figure 11. Various strategies for developments in Lelystad, Almere, Zoetermeer and Haarlem.

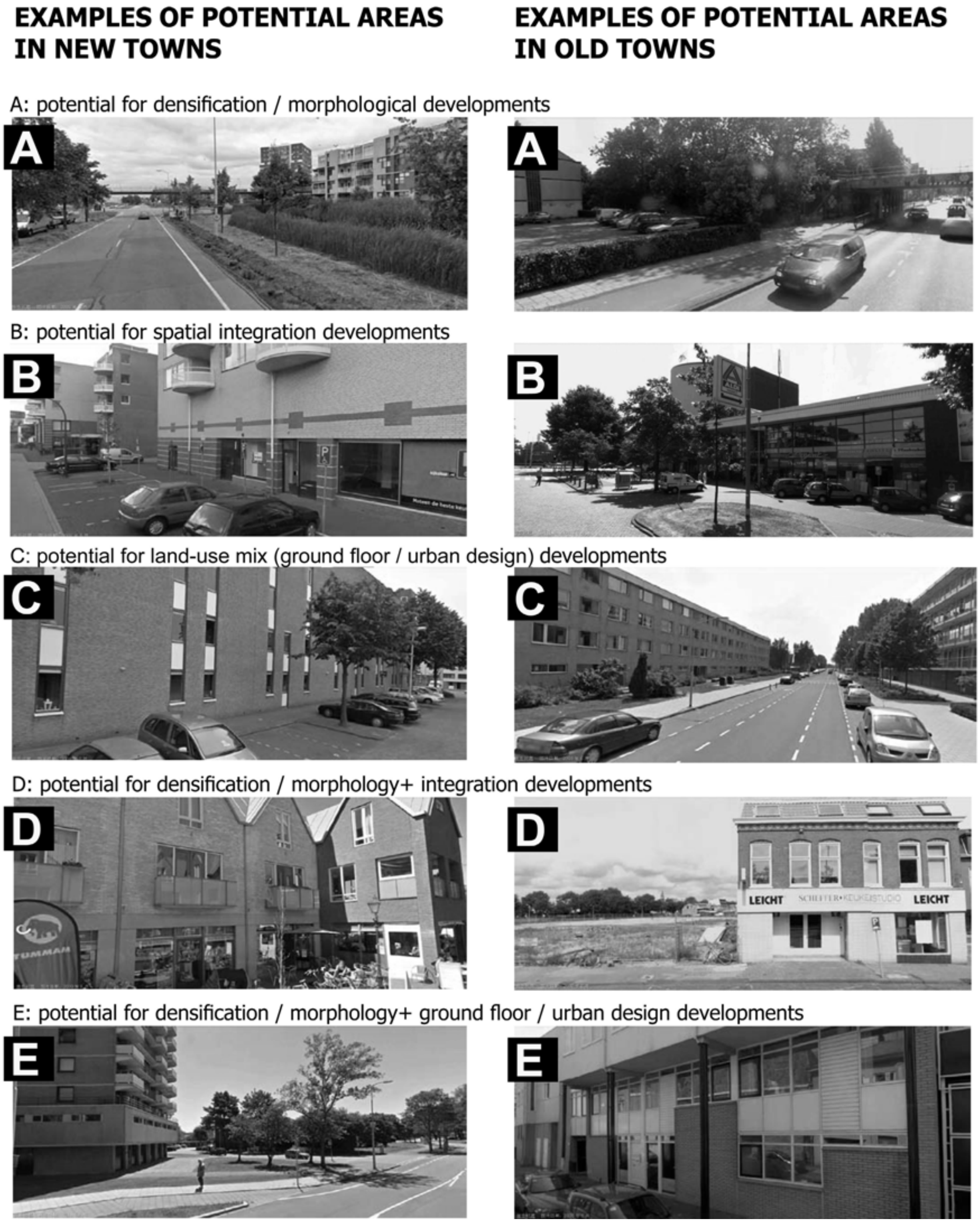

Figure 12. Examples of potential areas for development in new and old towns.

of potential development area. Areas with the potential for increasing density are mainly along integrated main routes. Areas with potential for improving the street network are mainly in segregated areas with high building density. Nevertheless, some areas having a well-integrated street network as well as high built-mass density, yet remain mono-functional. The explanation for this mono-functionality is zoning policies. An effect of these policies is the construction of buildings with limited interaction with streets, leaving

Table 3. The classification of various types of potentials in unbalanced areas

In-between (low): High, Low, Low			
Potentials	A	B	D=A+B
MXI	Low	Low	High
Spacematrix	Low	High	Low
Space Syntax	High	Low	Low

In-between (medium): High, Medium, Low						
Potentials	E=A+C	A	C	A	B	B
MXI	Low	Medium	Low	High	High	Medium
Spacematrix	Medium	Low	High	Low	Medium	High
Space Syntax	High	High	Medium	Medium	Low	Low

In-between (high): High, High, Low			
Potentials	C	B	A
MXI	Low	High	High
Spacematrix	High	High	Low
Space Syntax	High	Low	High

A: Potential for densification / morphological developments
B: Potential for spatial integration developments
C: Potential for land-use mix developments
D: Containing both potentials as described under point A and B
E: Containing both potentials as described under point A and C

few possibilities for micro-economic diversity and social interaction.

Conclusion

This inquiry is a first step to describe quantitatively the essential elements according to the Conzenian research tradition of urban form and to reveal how these spatial parameters affect an urban area's socio-economic performance. Applying this method to four Dutch cases has indicated how street-network integration, building density, and degree of land-use mixture are interacting with one another. The underlying spatial parameter – street-network integration – tends to influence other spatial and socio-economic parameters. It can be regarded as steering the spatial transformation processes in urban areas. This research contributes to exploration of the internal, spatial, evolving 'logic' of urban form, and 'the rules of transformation over time…laws that urban morphology tries to identify' (Levy, 1999, p. 79).

Our proposed method introduces a new classification system of urban areas based on urban spaces and building form genotypes (in other words, revealing the underlying spatial structures of urban areas), as well as phenotypes (that is, how building form, land-use mixture and street-network patterns appear to us). An urban area's genotype is revealed by the way the space syntax method shows the hidden spatial logic of the street structure. The spacematrix method shows how the relationship between FSI and GSI yields a classification of the density of the built mass. The MXI method shows degrees of land-use diversity. An area's phenotype can be observed by the degree of street life, and by describing various building volumes through the use of spacematrix. The significance of this new classification method is that these spatial genotypes and phenotypes of urban areas can be quantitatively and independently analysed in relation to socio-economic data. As the results show, strong correlations are found between various spatial types and their socio-economic characteristics.

Reflections on the proposed method

This research has shown that the combination of street-network integration, building density, and functional mix provides an indication of the location of particular spatial weaknesses, what they consist of, and what needs to be done to improve an area's socio-economic performance. It has direct relevance to the upgrading of existing European new town developments. In addition, bearing in mind the rapid construction of new towns, particularly in Asia, the method described can also be used to assess plans for new areas by identifying spatial flaws before the plans are implemented.

The comparison of four Dutch towns is just the first step in identifying the spatial differences between new and old towns. The robustness of this urban diagnosis tool needs to be further tested by investigating cases from other countries. This is an obvious prerequisite in considering the incorporation of the method in urban planning and design practice.

A further requirement is to add quantitative measurements of the relationship between private and public space – for example, incorporating the degree of permeability of buildings in relation to streets. Nes and Lòpez's micro-scale tools help to reveal urban areas scoring high on all spatial variables in our proposed method yet lacking street life. Quantifying the spatial characteristics and combining them with socio-economic and cultural elements needs further exploration.

Contributions to theory building on built environments

Finally, in what way does our proposed method contribute to the general understanding and theory of the spatial and socio-economic processes of built environments? Hillier's research using space syntax has contributed to the *theory of the natural movement economic process*. He claims that the spatial configuration of the street network influences movement flow and the location of economic activities (Hillier *et al.*, 1993; Penn *et al.*, 1998). The results of our research suggest that we may be assembling some constituents of a *theory of the natural urban transformation process*. Not only does the spatial structure of the street and road network influence building density and types, and degree of land-use diversity, but the degree of land-use diversity is also affected by building density and types. This proto-theory mainly works for a built environment that is not restricted by a rigid planning system, regulation plans, trusts connected to plots, religious aspects, collective memories, historical artefacts and urban areas protected by law. More cases are needed to validate and fine-tune the research described here as we work towards a theory of the natural urban transformation process.

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