URBAN DESIGN *International* (2008) **13**, 41–50
© 2008 Palgrave Macmillan Ltd. 1357-5317/08 $30.00
www.palgrave-journals.co.uk/udi

Multiple centrality assessment in Parma: a network analysis of paths and open spaces

Sergio Porta*[1], Paolo Crucitti[2] and Vito Latora[3]

[1]*Human Space Lab – Dipartimento di Architettura e Pianificazione, Polytechnic of Milan, via Bonardi 3, Milano 20133, Italy*
[2]*Scuola Superiore di Catania, viaS.N01105/i,95123, Catania, via S. Nullo 5/i, 95123, Catania, Italy*
[3]*Dipartimento di Fisica e Astronomia, Università di Catania and INFN Sezione di Catania, via S.Sofia 64, 95123, Catania, Italy*

One of the largest of Europe, the recently realized university campus 'Area of the Sciences' in Parma, northern Italy, has been planned for a comprehensive programme of renovation and revitalization with a special focus on vehicular accessibility and the quality of open spaces. As part of the problem setting phase, the authors, with Rivi Engineering, applied Multiple Centrality Assessment (MCA) – a process of network analysis based on primal graphs, a set of different centrality indices and the metric computation of distances – in order to understand why the existent system of open spaces and pedestrian paths is so scarcely experienced by students as well as faculty and staff members and why it appears so poorly supportive of social life and human exchange. In the problem-solving phase MCA was also applied, turning out to offer a relevant contribution to the comparative evaluation of two alternative proposed scenarios, leading to the identification of one final solution of urban design. In the present paper, the first professional application of MCA, an innovative approach to the network analysis of geographic complex systems, is presented and its relevance in the context of a problem of urban design illustrated.
URBAN DESIGN *International* (2008) **13,** 41–50. doi:10.1057/udi.2008.1

Keywords: multiple centrality assessment; network analysis; centrality; Space Syntax; public space; university campus

Introduction

The science of networks has been witnessing a rapid development in recent years since the seminal work of Watts and Strogatz on the so-called 'small worlds' in 1998 (Watts and Strogatz, 1998): the metaphor of the network has been applied to complex, self-organized systems as diverse as social, biological, technological and economic, leading to several unexpected results (Albert and Barabási, 2002). In particular, the issue of centrality in networks has remained pivotal, since its introduction in a part of the studies of humanities named structural sociology (Wasserman and Faust, 1994). The idea of centrality was first applied to human communication by Bavelas (1948, 1950) who was interested in the characterization of the communication in small groups of people and assumed a relation between structural centrality and influence/power in group processes. Since then, various indices of structural centrality have been proposed over the years to quantify the importance of an individual in a social network as well as that of an organization in an organizational network. Currently, centrality is a fundamental concept in network analysis though with a different purpose: while in the past the role and identity of central nodes was investigated, now the emphasis is more shifted to the distribution of centrality values through all nodes: centrality, as such, is treated like a shared resource of the network 'community' – like wealth in nations – rather than the unique property of the excellent.

In regional and urban planning centrality – though under different terms like 'accessibility', 'proximity', 'cost' or 'effort' – has entered the scene stressing the idea that some places (or streets) are more important than others because

*Correspondence: Tel: +39-333-4528646, Fax: +39-02-2399-5435, E-mail: s.porta@humanspacelab.com

they are more central (Wilson, 2000). A different wording ('integration' and 'connectivity') has accompanied a pioneering discussion of centrality for the specific purpose of urban designers, with a focus on public spaces, human exchange and liveability: that analysis of spatial systems has been successfully operated under the notion of 'Space Syntax' after Hillier and Hanson seminal work on cities since the mid-1980s (Hillier and Hanson, 1984). Space Syntax has been raising growing evidence of the correlation between the level of 'integration' of urban spaces – a 'closeness' centrality in all respects (Freeman, 1979) – and phenomena as diverse as crime rates, pedestrian and vehicular flows, retail commerce vitality and human wayfinding capacity (Hillier, 1996). However, the Space Syntax approach is profoundly different from most previous uses of networks in geographic space, that is, in transportation and land use planning or economic geography: in fact, while in those studies the urban pattern is subjected to a primal translation in a graph – where streets are turned into edges and intersections into nodes, Space Syntax conversely follows a dual representation – where streets are turned into nodes and intersections into edges. This dual character leads Space Syntax to the abandonment of metric distance (one street is represented with one point in the graph no matter its real length), which means the abandonment of the format that geographers as well as transportation and urban planners worldwide have always been basing their models on; in so doing, Space Syntax scientists actually reach the topologic world of non-geographic systems. Moreover, the Space Syntax analysis is mainly based on just one centrality index, called 'integration', which can be used only in association with a generalization model (in that case, the 'axial mapping' process) in order to minimize the so-called 'edge-effect', a typical distortion of the spatial distribution of centrality values that artificially groups the highest scores around the centre of the image no matter the actual configuration of the network (Salheen and Forsyth, 2001; Ratti, 2004).

In order to overcome such problems, we have recently proposed a new methodology for the network analysis of geographic systems named Multiple Centrality Assessment (MCA): we refer the readers back to that work for an extensive discussion of primal graph construction and MCA, in the context of both the new science of networks and Space Syntax (Crucitti *et al*, 2006; Porta *et al*, 2006a, b). In the next section, we just provide a short illustration of basic MCA's features and properties: the present paper, in fact, mainly focuses on a first application of MCA to a real case of urban design in Parma, northern Italy, which is covered later in this article.

Multiple centrality assessment

MCA is a structured process aimed at the evaluation of the spatial distribution of centrality over geographic systems like systems of roads and settlements at the regional scale, urban streets and junctions at the urban or metropolitan scale, areas of activity and their relationships at the scale of the square or the street, or internal spaces or functions and their relationships in complex buildings like office headquarters, airports, rail stations, hospitals or commercial malls. In this article, we will illustrate how MCA was applied over a network of paths and intersections and two networks of 'places' and their relationships of spatial proximity: all such networks were constructed to represent the system of open spaces of a large university campus in Parma, northern Italy.

The first step in operating MCA is the translation of the spatial system into a graph, that is, a mathematical entity defined by a set N of nodes and a set K of links, or edges, connecting pairs of nodes. In a network of paths and intersections a path (or street) pattern is translated into a primal graph so that intersections are turned into nodes and paths into edges. Networks of paths and intersections are graphed under a 'road-centre-line-between-nodes' rule: one edge is defined by just two end-nodes ('from_node' and 'to_node') and a variable number of vertices (points of linear discontinuity); edges follow the geographical footprint of real streets as they appear on the original map; connections between two edges are located at one of the two defining nodes (intersections); the distance between two nodes is calculated metrically along the edge, following real curves and angles. Thus, paths are identified directly on the original map, with no use of any generalization model. In the second application, the network of places and their relationships of proximity in Parma, places and connections were given a conventional definition: a place is an open space characterized by:

1. a convex internal shape;
2. visible borders (building facades, tree lines, hedges, pavement changes, paths and fencings…)

on at least three-quarters of the perimeter; and
3. a minor dimension <70 m.

Then, two places are connected when:

1. the minor distanced between their borders is <35 m; and
2. they are not separated by physical barriers (main trafficked streets, closed railings, buildings, floods, walls, high-level gaps,...etc.).

On such kind of graphs, MCA investigates how centrality 'flows' through edges over nodes. A key feature of MCA is that centrality is considered a multifold concept; in short, we have many centralities depending on what is our notion of 'being central'. Heavily drawing from the mentioned studies in structural sociology, we acknowledge four different families of 'being central', each described by a different centrality index:

1. 'being central as being close to others', closeness centrality (C^C);
2. 'being central as being between others', betweenness centrality (C^B);
3. 'being central as being straight to all others', straightness centrality (C^S);
4. 'being central as being critical for all others as a group', information centrality (C^I).

Again, we forward the readers to our previous work for a formal definition of such indices.

Finally, in MCA all distances are measured metrically; thus, the distance between nodes *i* and *k* is, say, 425.32. This metric/geographic concept of distance is used in MCA for all computations, including the identification of shortest paths, or 'geodesics', between pairs of nodes.

All that deeply differentiates MCA from Space Syntax, which conversely is based on dual graphs, the preliminary use of a generalization model (axial mapping), and just one main centrality index (closeness or 'integration' centrality). Moreover, like all the dual analysis, Space Syntax is necessarily anchored to a topologic concept of distance where the distance between nodes *i* and *k* is, say, 3 'steps'. With all the different meanings that have been assigned to the word 'step' in recent literature – as number of street intersections (Conroy-Dalton, 2003; Thomson, 2004; Porta *et al*, 2006a), directional change (Hillier, 1996), gradual directional change (Dalton *et al*, 2003), characteristic point (Jiang and Claramunt, 2002), street-name change (Jiang and Claramunt, 2004) – step-distance has to be recognized as a property of all dual approaches.

General advantages of MCA, compared to dual approaches like Space Syntax, are multifold:

1. MCA is not based on any generalization model, therefore it is more legible, feasible and objective;
2. it runs over the world standard geomapping graph format, which means that MCA can be applied directly over existing graphs like all traffic models of urban and metropolitan areas and most if not all national and regional geodatabases, like the huge TIGER/line developed by the US. Census Bureau: cutting the need to build the graph, to validate it and to keep it updated, MCA realizes a considerable gain in the cost of achieving source information as well as in data reliability; it is more realistic, in that it is grounded on metric rather than on step-distance measurements. This does not mean that step-distance is meaningless. There is a persistent debate whether topologic or geographic distance is more relevant in shaping collective behaviours in public space (Batty, 2004; Hillier and Shinichi, 2005; Joutsiniemi, 2005): while the former is more considered in cognitive and psycho-environmental studies, the latter is emphasized in geographic and geoeconomic sciences, traffic planning and classic regional and urban analysis. We believe that, when it comes to what people really do in cities, both types of distance are relevant: MCA computes distance metrically while, at the same time, retaining the topology of the system in that centrality indices are deeply affected by the architecture of the system's connectivity.
3. MCA gives a set of multifaceted pictures of reality, one for each centrality index, rather than just one: that leads to more argumentative, thus less assertive, indications for action.

The renovation of the open spaces of Parma university campus

A case's outline

The university campus 'Area of the Sciences' has been developed in the last two decades on 77 ha of land at the outskirt of the city of Parma, over a

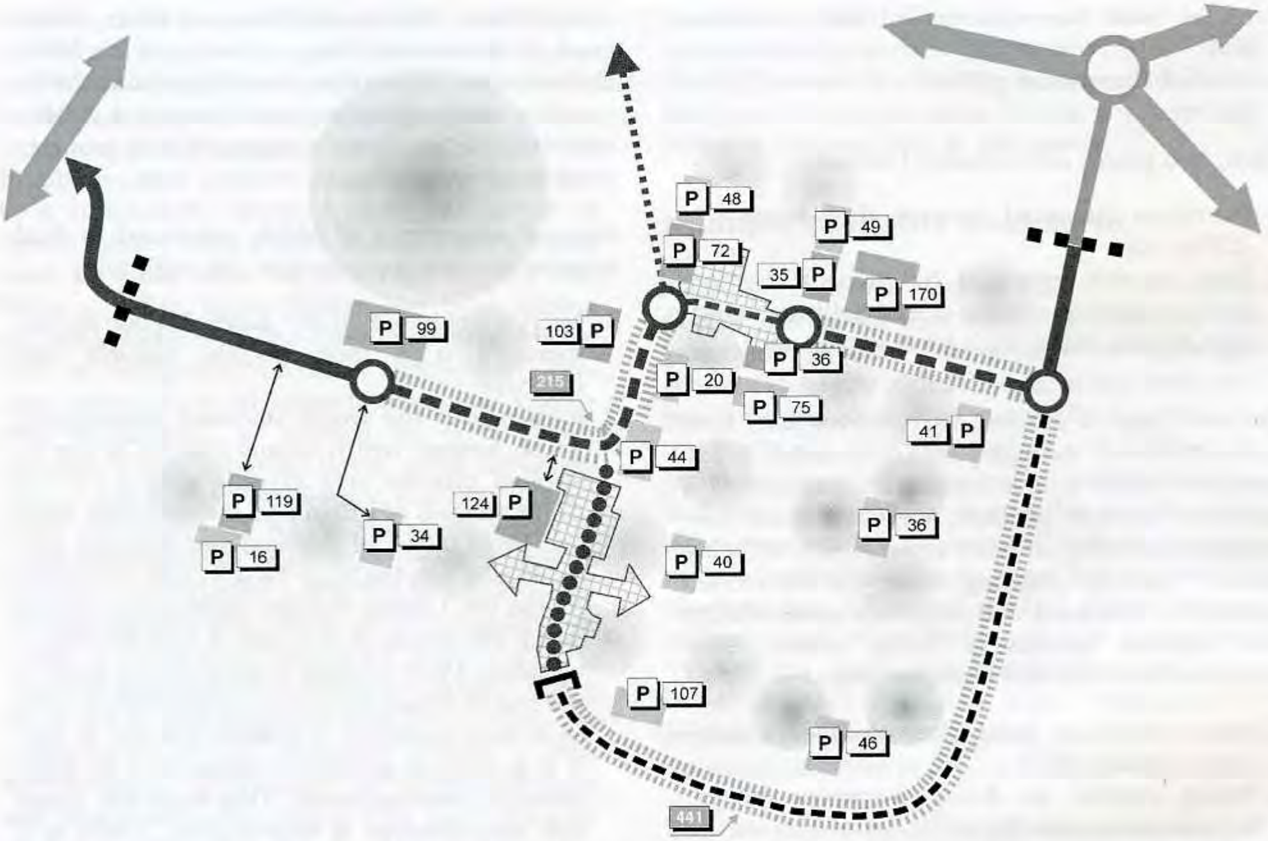


Figure 1. The conceptual plan of the envisioned development of accessibility facilities on campus: an organic whole replaces a collection of self-contained, inward-looking settlements while large parts of central areas are freed from in-lot parking, so made available for connecting landscaped environments. Project by Rivi Engineering and Human Space Lab.

plain area at the bottom of the first Appennini hills. The site development follows a general plan conceived with the aim of ensuring the largest possible autonomy to each department, resulting in an addition of self-containing sites, each served by its own parking and accessibility facilities dispersed in a large but poorly maintained and mainly uncontrolled 'green' open space. At the geometrical centre of the site a huge technologic plant is located, while services for food and leisure were decentralized to the southern and western fringe of the area. Sport facilities for football, tennis, rugby, golf and gym have been realized over the years in the north-western side.

Currently, the campus is used by some 8600 students and 980 staff or faculty members on a daily basis. After a period of intense development, a political impulse has been given for solving two growing problems that are perceived as main threats to the further attractiveness and functionality of campus:

1. *Accessibility*: vehicular traffic and parking has never been really ruled, resulting in aggressive behaviours against open spaces and non-motorized uses everywhere on campus;
2. *public paths and open spaces* that cover a large part of the area are nevertheless poorly used and maintained, often prone to abandonment or improper activities.

A project was requested to cope with such problems and suggest possible solutions. The project, worked out by Rivi Engineering and the Human Space Lab at the Polytechnic of Milan, Italy, envisions integrated actions for both a new model of accessibility and the revitalization of open spaces. In the following, we offer a short summary of the former and a more extensive illustration of the latter that was largely based on MCA.

Accessibility: a short summary

The rationale for the betterment of accessibility conditions on campus is the shift from an 'everyone

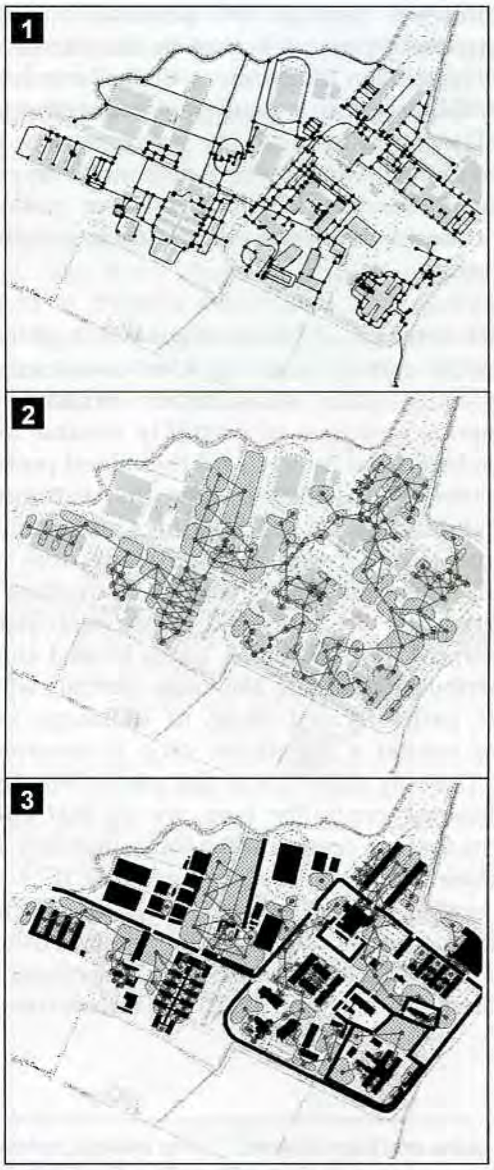


Figure 2. The three primal graphs constructed in the first step of MCA analysis: (1) *Paths*: the network of cycle/pedestrian paths and intersections; (2) *Potential places*: the network of places and connections in absence of barriers; (3) *Real places*: the network of places and connections after barriers (in thick black: main trafficked streets, buildings, fencings,...etc.) have been considered.

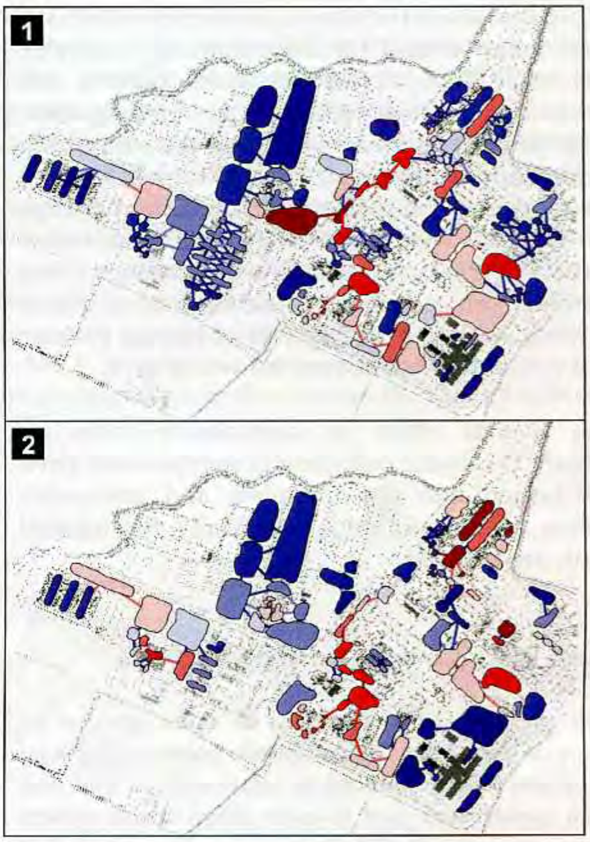


Figure 3. I^C distribution over the network of places and connections; (1) the 'potential' network, where physical barriers are not considered; (2) the 'real' network, where barriers are considered. The real network (2) is fragmented in four disconnected sub-networks, each one with its own focal spot; all these 'local centres' do not form any organic system. The potential network (1) is a single connected system with one emergent centrality located near the cultural centre and the sport facilities. In all cases, the structure of places and that of paths (see Figure 4, col. 1) are not consistent, in that – as a general rule – marginal paths serve central places and central paths serve marginal places.

everywhere' model to a 'selected users in selected places' one. That can be pursuit at the condition of a deep change in parking habits: a limited increase in parking offer is obtained after a large increase of short-time parking and a almost analogous decrease of long-time parking, where the former has been mostly located in central areas, adjacent to departments and the latter in outer areas. On-street parking largely replaces in-lot parking, especially along main streets: on-street parking, in fact, contributes to a broader policy of traffic calming on main streets, which have been found dangerous due to the over-limits speeds of significant shares of passing vehicles. In so doing , large open areas in central locations – former parking lots – that currently work as barriers are turned in new landscaped areas available for high-quality connecting facilities like cycle/pedestrian paths, areas for rest or play or visual corridors.

In two strokes of the main street pattern that have been found critical for the continuity of cycle/pedestrian paths across the whole campus, the streetscape has been radically converted topedestrian-oriented uses and vehicular uses have been particularly constrained. Policies for establishing the bicycle as the prime means for internal trips on campus have been suggested: university-owned bicycle facilities have been proposed along the outer vehicular routes of access and long-time parking, anchored to a system of bicycle parking and free-rental that covers the whole area.

The overall effect of accessibility measures (Figure 1) is that a collection of independent parts are turned into one organism and alternative means of transportation, especially for internal trips, are fostered.

Open space's liveability: applying MCA

The problem of the decay of open spaces on campus has been investigated posing a special attention to the topological relationships that link each constituent part to each other in the system by means of an MCA analysis on three different graphs (Figure 2):

1. the network of cycle/pedestrian paths;
2. the 'potential' network of places;
3. the 'real' network of places.

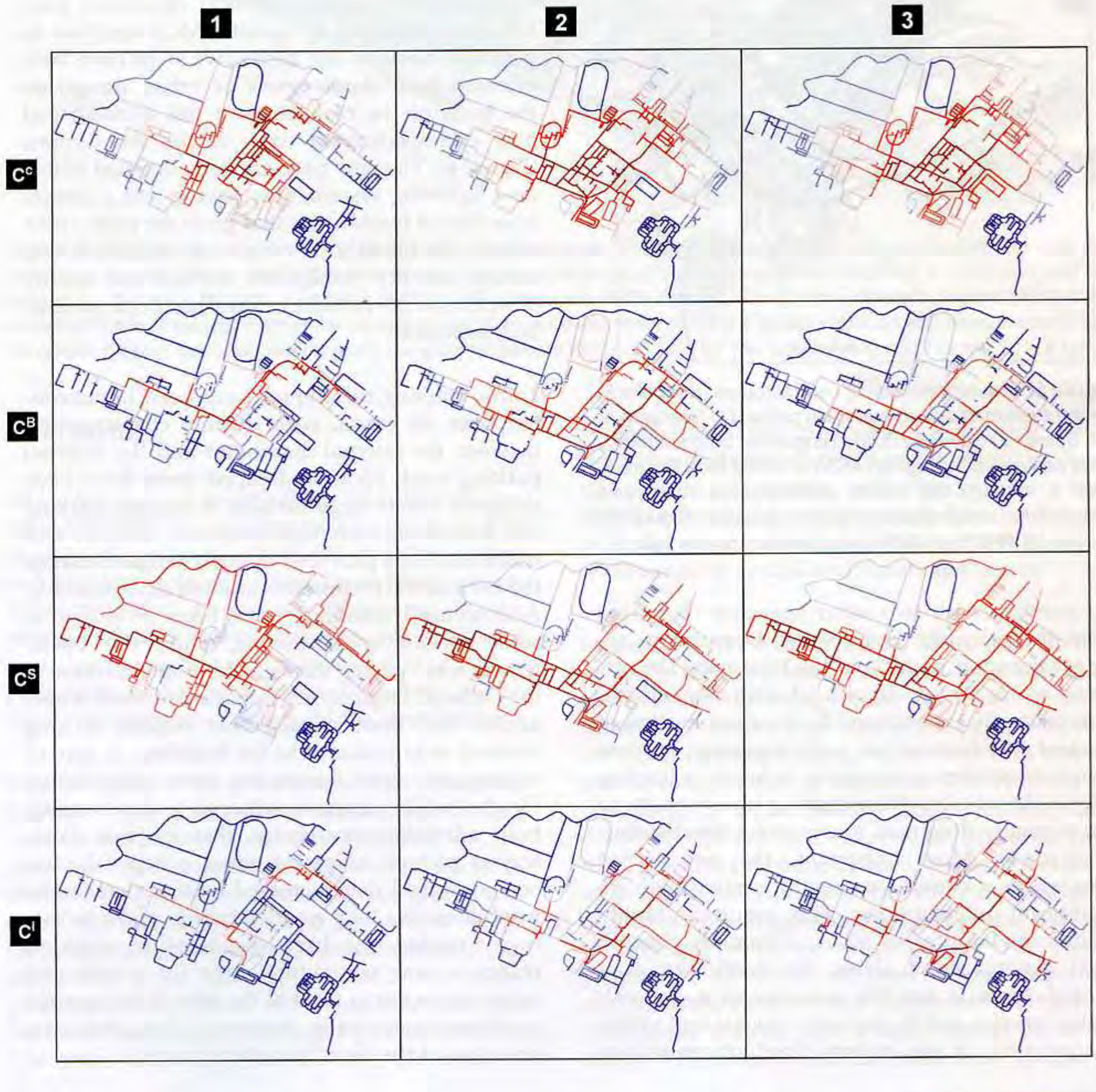
The difference between the potential and the real networks of places is that in the former all barriers have been removed, as if all places were 'freely' disposed on a plain and uninterrupted space. The introduction of the potential network is aimed at evaluating, by comparison, the impact of existent barriers like buildings or railings on the connectivity of spaces and their structure of centrality.

The real network of places (Figure 3, top) is a fragmented system made of four disconnected sub-networks; each sub-network exhibits an autonomous structure of centrality around four independent 'local centres'. All these local centres are located well detached from the distributor road, while close to the buildings of scientific departments or services. This structure does not find any correspondence with the structure of centralities on the network of existent paths (Figure 4, col. 1): in this case, paths located along the distributor road are the most central, while internal paths located close to buildings and facilities exhibit a significant drop in centrality values. The only exception to this pattern emerges with closeness centrality: here, we see that internal paths that are central in the sense that they are more close to all others in the network (C^C) are not so central in other senses, especially as being the intermediaries among other relationships (C^B) or as being critical for the connectivity of the system as a whole (I^C). The inconsistency

Figure 4. Centrality distributions over the network of cycle/pedestrian paths and intersections: (1) the existent network; (2) the proposed network, scenario A: the Spine; (3) the proposed network, scenario B: the Ring. The C^C distribution appears in all cases deeply affected by the 'edge effect', the distortion that typically groups higher C^C scores around the centre of the image rather than revealing any structural order of the network. In this case, however, the borders of the image do express a relevant territorial meaning, because the campus is really self-centred and isolated at the fringe of the urban settlement, a peripheral 'island' with just two points of connections with the larger urban system; so in this specific case the picture emerging from the analysis of C^C represents much more an inherent feature of the real network of the campus than an artificial outcome of the borders' cut. In the existent network (col. 1), a spine of higher centrality emerges along the distribution road, which is mostly vehicular channel that presents environmental conditions rather aggressive for pedestrians and cyclists; moreover, almost all buildings on campus are well detached from the road, significantly weakening its attractiveness for pedestrians and cyclists. The proposed realization of a continuous cycle/pedestrian path (col. 2, scenario A) that runs well beyond the distribution road and links together all activity centres and the systems of local spatial centres on campus is blessed by a great centrality potential for all indices. Most important, the new path is continuously central, with no significant local drops, weakening the previously dominant centrality system of the distribution road. In a way, the new path effectively 'drains' centrality flows from over the system, while at the same time resulting mostly consistent with the local structure of places' centrality (Figure 3, bottom). The alternative proposal (col. 3, scenario B) does not exhibit a comparable success. The idea of building a ring that includes part of the distribution roads lacks an acceptable level of centrality especially in the north-eastern side, with particular reference to C^B and C^I. The realization of such a ring would probably lead to a more confused system and a certain waste of financial and territorial resources.

between the structure of centrality over the two systems of places and paths emerged as a major obstacle to the efficiency of the open spaces on campus in terms of social use: raising and framing such an issue was a valuable contribution of MCA to the problem-setting phase of the project.

In a first pace of the successive problem-solving phase, the main strategy of the project was defined to create a new dorsal cycle/pedestrian path that intersects and links all 'local centres' running on an internal route. The new dorsal path should be connected to the external vehicular parking-roads in order to favour the car/bicycle exchange. After a detailed investigation of functions, place centralities and the conditions of existent paths to be reconnected, two alternative scenarios were envisioned and compared through a process of MCA. The two scenarios (Figure 5) especially differ in the eastern side of campus, where the first is spine-shaped and the second follows a more ring-shaped route. The results of the MCA analysis over these two alternative networks are presented in Figure 4, cols. 2 and 3. MCA reveals that the proposed scenario A, the spine-shaped route that crosses the eastern side of



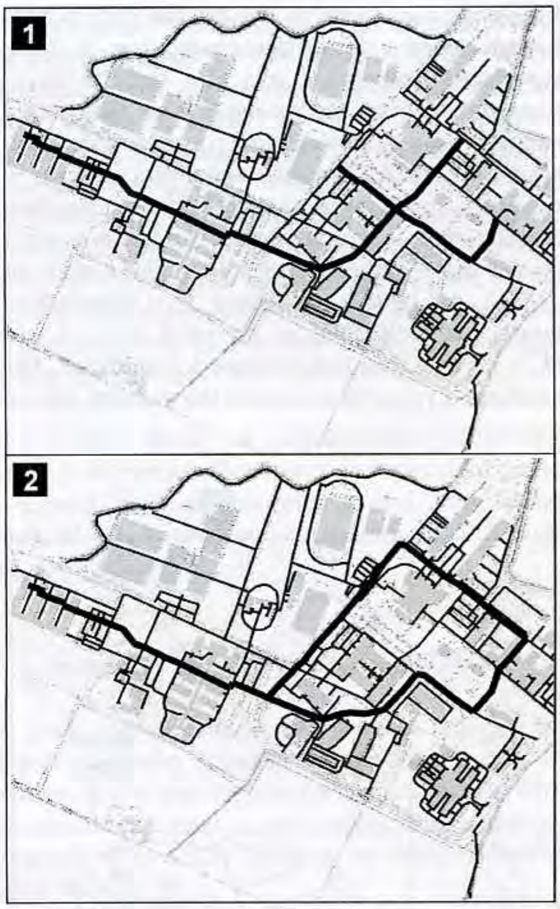


Figure 5. The proposed new central routes (thick black) for the system of cycle/pedestrian paths: (1) Scenario A: the Spine; (2) Scenario B: the Ring. After both scenarios were compared through an MCA analysis (see Figure 4, cols. 2 and 3), the former spine-shaped route was selected for shaping the proposed scheme (Figure 6). Project by Rivi Engineering and Human Space Lab.

the campus with two other branches departing from the Scientific Engineering Department towards the sport plants and the Pharmacy Department, scores very well with all centrality indices. This route, that is obtained by the reconnection of existent but fragmented path segments by new proposed strokes, consistently achieves a leading role in the whole system, leaving lower results to the currently dominant routes along the distribution roads. Most important, the new spine emerges as a continuous central system with no significant interruptions. This result is highly significant because in MCA, differently than in dual generalized analysis, the continuity of a central route is not the outcome of a generalization model and its distinct rationale, but rather the outcome of the 'natural flow' of centralities over each edge throughout the system's architecture and of the geographic location of spatial components in the system.

A rather worse performance is offered by the ring-shaped scenario B. Centralities describe a fragmented interrupted route that do not assume a univocal leading role in the system. The image that emerges, under this scenario, is that of a system that shows at least three routes at the same level, none of them really continuous, each with a certain level of contradiction between the four indices of centrality.

In-depth investigations of local conditions have been implemented by specific MCA analysis as well, but basically the successive steps have been oriented to a classic work of urban design on the basis of the realization of the spine-shaped new cycle-pedestrian route across the campus (Figure 6). The new path has been detailed with a new lightning system, new paving and a continuous line of blackthorns that gives the path – now called 'the blackthorns way' – a distinctive and unique identity; finally, the architectural quality of open spaces in local centres has been particularly enhanced.

Traffic calming techniques have been implemented over all roads, with distinct characteristics between the internal distributor and the external parking road. New landscaped areas have been designed where large surfaces of existing parking lots have been removed. A system of cycle free rental has been provided at interchanges between the car and the pedestrian-oriented environments. Architectural solutions have been proposed in some specific spots, that is, where the 'blackthorns way' passes through the main corridor of the Didactic Engineering Department: here, a new atrium has been created that realizes a long invoked new entrance to the building. A core of high-quality open spaces has been individuated for the whole campus adjacent to the recently built administrative centre, that involves landscaped as well as paved areas: a new lake has been designed that is crossed by the 'blackthorns way' through a long wooden bridge, and a former rugby facility has been displaced in order to realize a new community area for events and celebrations just in front of the lake. A landscaped park has been finally proposed along the side-branches of the new 'blackthorns way'.

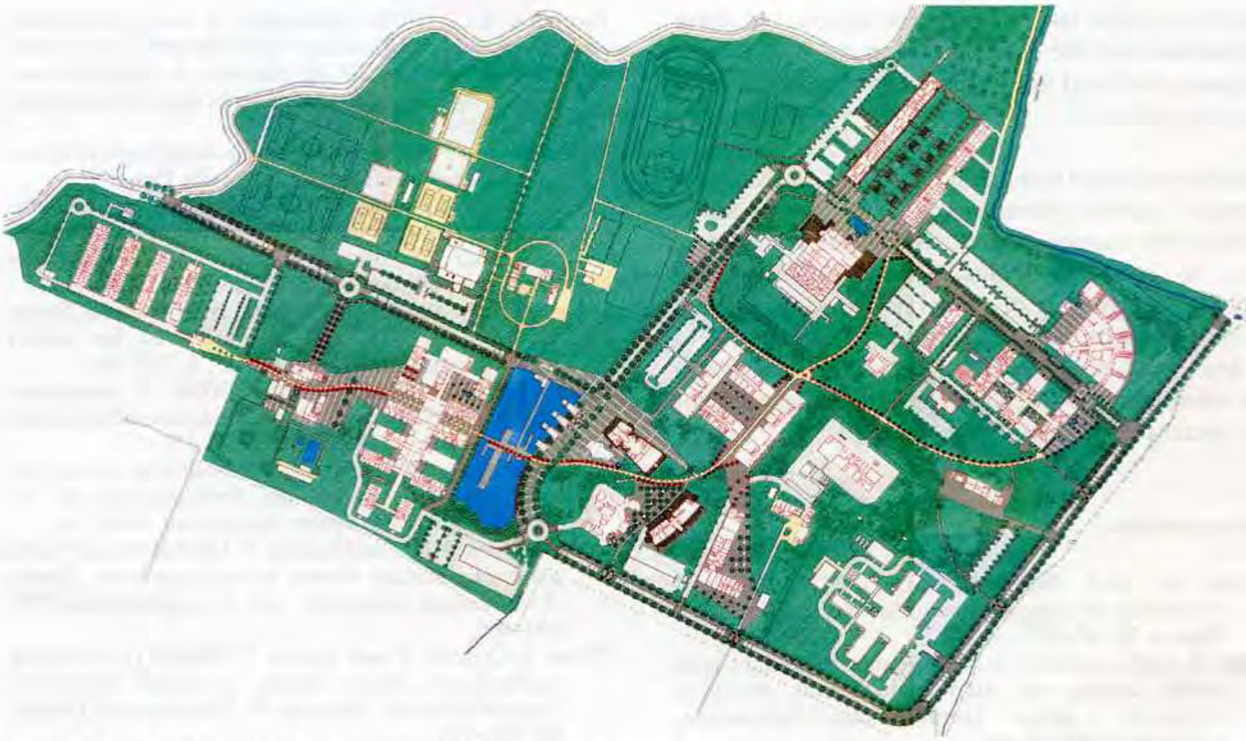


Figure 6. The final layout of the urban design plan for the campus. The proposed cycle/pedestrian spine that connects all local centralities is clearly visible; the core of the campus is landscaped with a new paved area and a small lake that is bridged by the spine through a wooden platform. All streets are traffic-clamed, though at a different degree taking into account the role of each of them in the general model of accessibility. In-lot parking is largely replaced with on-street parking. Long-term parking has been placed along the external service street. Project by Rivi Engineering and Human Space Lab.

Conclusions

MCA has helped in orienting an urban design project for the revitalization of a complex system of open spaces across both the problem-setting and problem- solving phases. In problem setting, MCA provided a new understanding of the reciprocal relationships between two different spatial systems, that of places and that of cycle/ pedestrian paths; both networks belong to the more comprehensive system of the open spaces.

The emerging of deep, structural inconsistencies between such components offered the project team a surprising new interpretation of the problem: that is, due to the different structures of the two systems that make the marginal paths serve the central places and the central paths serve the marginal places. A modification of the network of paths has been proposed then in the problem-solving phase: two alternative solutions have been tested again through a process of MCA. The more convincing of the two scenarios, a spine-shaped cycle/pedestrian route that connects the local central spaces and the main focuses of activities on campus, well detached from the distributor roads, has been detailed in the project of urban design that dealt with, on that basis, a wide range of spatial and functional issues.

In the context of this process, MCA provided a valuable contribution because of its distinctive characteristic of being based on a set of four different centrality indices, a primal graph representation of complex geographic networks and a metric computation of distances. The result is a multifaceted, argumentative understanding that does not offer any single, apodictic, universal key to all possible problems of open spaces, but rather an in-depth description of the different properties of the network in question, properties that belong to different ways of being central. All these properties, all these different ways of being central, are always at work together in a complex geographic system, with a deep impact on how people and human activities distribute spatially over the system itself. But the 'behaviour' of those properties and the level of reciprocal consistency depends on local conditions, topological as well as geographical.

Finally, we do not think that a network analysis of a complex spatial system can tell the whole story. Complexity cannot be reduced to one dimension, even to such an inclusive one like the geo-topological structure of spatial networks. MCA just offers a point of view. A highly informative one, to be true, but just one of the many that contribute to the astonishing, ever changing, surprising world of the social use of public open spaces.

References

Albert, R. and Barabási, A.L. (2002) Statistical mechanics of complex networks, *Review of Modern Physics*, **74**: 47–97.

Batty, M. (2004) *Distance in Space Syntax*. Working paper no.80, Center for Advanced Spatial Analysis, University College, London, http://www.casa.ucl.ac.uk/publications.

Bavelas, A. (1948) A mathematical model for group structures, *Human Organization*, **7**: 16–30.

Bavelas, A. (1950) Communication patterns in task-oriented groups, *Journal of the Acoustical Society of America*, **22**: 271–282.

Conroy-Dalton, R. (2003) The secret is to follow your nose: route path selection and angularity, *Environment and Behaviour*, **35**: 107–131.

Crucitti, P., Latora, V. and Porta, S. (2006) Centrality measures in spatial networks of urban streets, *Physical Review E, Journal of the American Physical Society*, **73**: 3.

Dalton, N., Peponis, J. and Dalton, R. (2003) To tame a tiger one has to know its nature: extending weighted angular integration analysis to the description of GIS road-centerline data for large scale urban analysis, *Proceedings 4th International Space Syntax Symposium*, Misc: London, UK.

Freeman, L.C. (1979) Centrality in social networks: conceptual clarification, *Social Networks*, **1**: 215–239.

Hillier, B. (1996) *Space is the Machine: A Configurational Theory of Architecture*. Cambridge: Cambridge University Press.

Hillier, B. and Hanson, J. (1984) *The Social Logic of Space*. Cambridge: Cambridge University Press.

Hillier, B. and Shinichi, I. (2005) Network and psychological effects in urban movement, Paper presented at *COSIT '05, Conference on Spatial Information Theory*, September 14–18, Ellicottville, New York.

Jiang, B. and Claramunt, C. (2002) Integration of Space Syntax into GIS: new perspectives for urban morphology, *Transactions in GIS*, **6**: 151–162.

Jiang, B. and Claramunt, C. (2004) A structural approach to the model generalization of an urban street network, *GeoInformatica*, **8**: 157–171.

Joutsiniemi, A. (2005) Generic accessibility challenges axial maps: case Helsinki, *Proceedings of the 5th International Space Syntax Symposium*, Delft, NL.

Porta, S., Crucitti, P. and Latora, V. (2006a) The network analysis of urban streets: a dual approach, *Physica A, Statistical mechanics and its applications*, **369**: 853–866.

Porta, S., Crucitti, P. and Latora, V. (2006b) The network analysis of urban streets: a primal approach, *Environment and Planning B: Planning and Design*, **33**: 705–725.

Ratti, C. (2004) Space Syntax: some inconsistencies, *Environment and Planning B: Planning and Design*, **31**: 513–516.

Salheen, M. and Forsyth, L. (2001) Addressing distance in the Space Syntax syntactical model, *Urban Design International*, **6**: 93–106.

Thomson, R.C. (2004) Bending the axial Line: smoothly continuous road centre-line segments as a basis for road network analysis, *Proceedings 4th International Space Syntax Symposium*, London, UK.

Wasserman, S. and Faust, K. (1994) *Social Networks Analysis*. Cambridge: Cambridge University Press.

Watts, D.J. and Strogatz, S.H. (1998) Collective dynamics of small-world networks, *Nature*, **393**: 440–442.

Wilson, G.A. (2000) *Complex Spatial Systems: The Modeling Foundations of Urban and Regional Analysis*. Upper Saddle River: Prentice-Hall.