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Walkable Urban Environments: An Ergonomic Approach of Evaluation

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Abstract: Background. The *salutogenicity* of urban environments is significantly affected by their *ergonomics*, i.e., by the quality of the interactions between citizens and the elements of the built environment. Measuring and modelling urban ergonomics is thus a key issue to provide urban policy makers with planning solutions to increase the well-being, usability and safety of the urban environment. However, this is a difficult task due to the complexity of the interrelations between the urban environment and human activities. The paper contributes to the definition of a generalized model of *urban ergonomics* and *salutogenicity*, focusing on *walkability*, by discussing the relevant parameters from the large and variegated sets proposed in the literature, by discussing the emerging model structure from a data mining process, by considering the background of the relevant functional dependency already established in the literature, and by providing evidence of the solutions' effectiveness. The methodology is developed for a case study in central Italy, with a focus on the mobility issue, which is a catalyst to generate more salutogenic and sustainable behaviors.

Keywords: salutogenic cities; walkable environments; urban health; physical activity; healthy urban planning; bayesian networks; sustainable mobility

1. Introduction

The quality of urban life depends on the ability to combine the natural environment, the built environment and mobility, so that social and functional needs of the inhabitants are fully satisfied, and the long-term negative impact of health risk factors is minimized. One of the main objectives of the Global Action Plan on Physical Activity (GAPPA) 2018–2030 of the World Health Organization (WHO), is to create urban environments that promote and safeguard the rights of all people, of all ages, to have equitable access to safe places and spaces to perform regular physical activity, according to their needs [1,2]. *Salutogenicity* is a concept that captures in a word this complex statement [3]. The WHO has identified a set of affordable and cost effective interventions to achieve good levels of *salutogenicity*, providing the greatest possible impact on health by reducing illness, disability and premature death from non-communicable diseases (NCDs) [4]. In particular, increasing all forms of physical activity could provide considerable benefits on different diseases, like type-2 diabetes, dementia, cerebrovascular diseases, breast cancer, colorectal cancer, depression, ischemic heart disease. Jarrett et al. [5] estimates that, in the UK context, a widespread physical activity, such as walking 1.6 km or cycling 3.4 km, would save approximately 17 billion GBP/year in 20 years (1% of the National Health Fund).

By emphasizing the conditioning aspects that the urban structure has on the behaviour of its inhabitants, the WHO objectives establish a direct relationship between *salutogenicity* and urban ergonomics. In particular, the literature largely supports the WHO perspective, by emphasizing the relevant relations occurring between mobility (i.e., walkable urban environments) and health [6–13]. Sallis et al. [14] observe a direct relationship between physical activity and residential density, density of the intersections, density of public transport, number of parks and green spaces within a radius of one km from the house. Similar results have been observed in other studies concerning the relationship between urban spaces and physical activity [15], between the built environment and physical activity [16–23], and between the built environment and several chronic diseases [24–27], highlighting some of the main risk factors [28–30]. Other consistent evidence concerns the relationship between environmental exposures (e.g., air pollution, noise, etc.), cardiovascular disease and mortality [24,25]. Only few studies, mainly qualitative, correlate the built environment with inhabitants' perceptions of the outdoor environment (e.g., chromatic and olfactory features) [31]. The wide range of health benefits for all age groups caused by the presence of green elements, which complements the improvement of the ecological–climatic conditions of the cities, is investigated in [32]. In general, the proximity to the parks and recreational environments is associated with reduction in stress, improvement of mental health, stimulated social cohesion, increased physical activity, reduced cardiovascular diseases and diabetes, reduced exposure to air pollution, reduced exposure to excessive noise, and improved comfort [9,33–36]. However, more studies are required to qualify to a better degree the influences of the size, the distance and of other features of green areas, on the level of physical activity achieved by the population [36]. Even within the transportation and mobility governance domains, the role of walking and cycling is no longer considered just ancillary to motorized modes, with several examples in literature and practice acknowledging physical activity as crucial for sustainable transportation planning [37–39]. Moreover, research on innovation for transit facilities strongly relies on ergonomics as an element of strength to increase the attractiveness of public transport and create new urban landmarks [40,41].

Modelling urban ergonomics is a complex issue since it involves a number of different domains, from the citizens' behaviour to urban planning and building technology. The main problem in modelling systems with a high degree of complexity concerns the achievement of a sufficient level of generality in the representation, so that reliable predictions can be formulated. In the urban ergonomics case, for example, the unsystematic components of citizens' behaviour, affected by hardly quantifiable socio-cultural aspects, can cause significant variations, from case to case, both in the model's structure and in the relevance of its parameters. In such situations, a combined probabilistic and case-based reasoning approach can be effective [42]. Case-Based Reasoning (CBR) [43] is a form of exemplar-based analogical reasoning, which provides support to problem solving whenever general domain theories are missing. In CBR, past solutions are reused to solve problems in similar contexts. The practical problem of CBR is that reusing past solutions in new contexts usually requires a portion of general knowledge that is usually not available in the CBR systems. On the other side, probabilistic reasoning, and more specifically Bayesian Networks (BNets), can be used to derive general models that are shared by the elements of a training case set [44]. For example, in transport planning BNets are long used to develop activity-based models, with further applications and case studies on a vast array of fields (from environmental safeguarding, to road safety, to policy decisions, etc.), involving all modes. However, one of the problems arising in using BNets in modelling complex domains is that a general statistic can be hard to achieve because the training set is usually not homogenous within the boundaries of the knowledge modelling set. For example, in urban ergonomics, similar neighbourhoods may have totally different influence degrees of green areas on the general performance parameters. This often happens because the relevant elements fall outside the knowledge boundary of the modelling effort, and, consequently, are not represented. On the other hand, the knowledge modelling effort is always constrained by a number of practical limits, not least, the manageability of the parameter set.

Two main issues emerge at this point of the discussion as the main focus of this paper. The first concerns the identification and qualification of a distinctive set of measurable indicators that reliably captures the influence of the urban ergonomics on the *salutogenicity* degree of an urban context.

The sets of core indicators proposed in the literature [16,29,45–54] are scarcely integrated, sometimes unmanageable (i.e., the number of indicators is too high) and sometimes inconsistently shaped (i.e., unbalanced in specific arguments). An in-depth analysis of the indicators proposed in the literature has already been accomplished by the authors [55,56] showing flaws, including data completeness, the difficulty and the cost of accessing the database and the lack of standardization (there is no common standardized method of measurement or cataloguing). Hence, a careful selection of available indicators and their arrangement in a sound, complete and effective set must be developed. The second point concerns the modelling approach. A modelling strategy that is able to overcome the limits of CBR and BNet, by highlighting contextual regularities that would have been otherwise hidden by the domain complexity, must be developed.

The paper structure is as follows. In Section 2, the urban ergonomics indicators that have been used to investigate the *salutogenicity* of the downtown of the Rieti city, a midsized Italian town close to Rome, are introduced. In Section 3, the paper details the modelling approach and structure of the Bayesian Network model. Analytical results are presented and elaborated in Section 4, and some areas for further improvements are elaborated in Section 5; eventually, concluding remarks are provided in Section 6.

2. The Human–Environment Interface to Link Ergonomics and Sustainability

The urban space's *salutogenicity*, as defined above, can be read in terms of ergonomics. More specifically, ergonomics can be defined as: "scientific discipline concerned with the understanding of the interactions among human and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimize human well-being and overall system performance" [57]. Consistently, ergonomics is multidisciplinary as it focuses on the Human–Environment Interface (HEI) and searches for a concrete and rational answer to such a complex relationship [58,59]. As such, ergonomics is applicable to systems of urban areas. In fact, urban spaces shape the system that structures a city by linking people, places and functions. The vision of the city as a complex system was pioneered by Christopher Alexander in 1965, and epitomized by his statement: "the city is not a tree" [60]. The HEI was central in this approach although, nowadays, a revision placing major emphasis on the sustainability issues is needed. Since the urban environment is, above all, a human environment, the HEI represents the whole set of interactions between the complex systems of urban spaces and the people (or users) who inhabit them and walk within. Quality HEI can be claimed when an urban space's performance fully meets people's requirements, starting from *Safety* and *Well-being* as primary needs. The meeting of *Safety* and *Well-being* requirements implies that the urban environment is designed and structured as a set of spaces where people experience and perceive freedom from whatever sort of risks, danger or losses. In turn, *Sustainability* can be interpreted as the ability of the users to maintain such status with no (or minimal) long-term negative effects on the environment they experience and perceive. All of the above is complemented by an additional requirement: *Usability*, i.e., the possibility to perform appropriate functions, complying with *Safety* and *Well-being* requirements, within a sustainable approach.

2.1. An Approach to Urban Ergonomics Indicators

Within this vision, ergonomics by managing HEI, can be applied to any phases of planning, design, implementation, evaluation, regeneration, maintenance and improvement of the system of urban areas/spaces, to generate an effective requirement/performance equilibrium. In Italy, the requirement/performance approach was initially developed by UNI (Ente Nazionale Italiano di Unificazione, i.e the national board for standardisation) and applied to standardize a wide range of products, components, services, operations and functions, hence its full transferability to this study, as well.

Measuring or assessing a performance, as the efficiency with which each urban space component fulfils its intended purpose, is the main task within walkability tools. The quality of the performance assessment relies on the accuracy in the investigation and surveys of places, their constitutive elements and the activities they generate. Coherently with the HEI approach, the results from such investigation can be further developed in two ways:

- *The conventional walkability exercise:* a walkability list is designed to assess a set of performances according to the perception of the urban spaces walked by the exercise participants (surveyors, interviewees); each item in the list is weighted and scored, so as to identify a rank of performance which may enable/hinder people walk the surveyed areas (typically a very specific origin/destination path, e.g., home-to-school) and decide whether they are walkable, and to what extent. To progress beyond this practice, walkability lists can be associated with weighted indicators, for which a range of performance targets are set. Performance targets, in turn, are reported according to threshold and optimal values. Surveyors can score the listed indicators and success can be claimed only when the performance targets are achieved.
- *The study of walkability variables:* after the detailed survey and the creation of the walkability list, the indicators are interpreted in terms of variables describing the dynamic relationships between the characteristics of the surveyed areas and the behaviour of their inhabitants. The variables can be disassembled and classified in terms of requirement/performance analysis within a BNets process. This gives rise to a structured system of variables classified in terms of needs, requirements and performance.

Each way complements the other, with scientific literature abounding for the former. For the latter, a classification system focused on the *Usability, Well-being* and *Safety* requirements, as defined by the UNI standards [61], has been developed and applied to the case study described in Section 4, to highlight the role of each within the ergonomics of urban spaces/areas. More specifically, each *Usability, Well-being* and *Safety* need gives rise to several requirements that the urban areas' performance is designed to meet [62]. The reference for the definition of these needs and the related requirements was based on previous studies [63,64] and synthesized in Table 1.

It must be noted that *Usability* includes the concept of *Accessibility*, according to its broader definition as the "the ease with which exchange opportunities can be accessed" [65]. Consequently, within HEI, *Accessibility* is considered as a prerequisite that all the requirements already comply with.

The BNet approach might provide an effective response and a reliable solution to the research question about the complexity in the management of urban phenomena, as it discloses all the interrelations among the HEI components.

According to Table 1, to each need several requirements correspond, and the urban space performance is designed to meet all of them [56].

Table 1. Main needs and requirements within the Human–Environment Interface.

Needs	Well-Being	Safety	Usability
Requirements	*Sunshine exposure*	*Conflicts with motorized users*	*Architectural barriers' removal*
	Winter exposure (>8 h)	Sidewalk on one side of the street	No grades to access buildings
	Summer exposure (<10 h)	Sidewalk on both sides of the street	Crossing equipped with ramp+grade
	Ventilation	*Non-slippery surfaces*	Rest facilities/equipment on hilly links
	Canyon effect	Signaled crossings	No grade between driveways and sidewalks
	Temperature	Unsignaled crossings	Accessible bus stops
	Vegetation, tree-lined link	*Obstacles*	Tactile-plantar route for visually impaired users
	Brick/stone surfaces	Dumpsters	Natural directions for visually impaired users
	Impervious surfaces for road and sidewalks	Ads markers	Rumble strips
	HVAC units along the street	*Surfaces' evenness*	Equipment for hearing impaired
	Relative humidity	Avoidance of chinks and potholes	*Maintenance*
	Availability of natural surfaces (vegetation, bodies of water, etc.)	Avoidance of distresses	Distress density < 50% of the surface
	Noise	*Slippery factors*	*Cleanness and Sanitation*
	Traffic noise	Leaves	Availability of dumpster and bins
	Noise from working activities	Water	Road cleaning
	Public lighting	Ice	Graffiti removal
	Light poles only		*Adaptability to events*
	Neon lights		Availability of route for emergency rescue
	Glare		Possibility to enforce car-free areas
	Reflecting surfaces		Possibility to remove urban furniture
	Level of service (LoS)		
	Suitability of (LoS) for sidewalks		
	Suitability of urban furniture		
	Sidewalk evenness		
	Availability of universal design furniture		

To quantify the performance levels, a set of 29 measurable performance domains has been defined, according to 5 categories: *Natural elements, Built environment, Mobility, Urban furniture* and *Perceived environment*. Each set of performance includes a variable amount of indicators for a total of 67, each of them described according to the measurement unit, threshold and optimal values (with reference to presently existing regulations on this matter), achievable score and weight (Tables 2–5). Some of these indicators have been selected from other sets already in use in the literature [56,63,64].

Weights for evaluation categories and indicators were developed by a multidisciplinary panel of 10 experts. The preliminary literature review analysis on neighborhood environmental factors affecting walking and, therefore, ergonomics was the basis to define the above-mentioned indicators, evaluation categories and criteria for scores and weights, which were presented to the experts, from different fields: public health, urban planning, transportation and urban policy makers. They were asked to assess the overall set of urban ergonomics indicators and define weights for each indicator. After this first round, the panel of experts, representing the involved fields of study, agreed to participate in a discussion to finalize the weights. The weights reported in Tables 2–5 are the shared result of this discussion [63].

The performance's value (e.g., A1. Vegetation, etc.) is obtained by adding the scores of the indicators (e.g., A1.1, A1.2, A1.3, etc.), weighted by their relative weight (e.g., wA1.1, wA1.2, wA1.3, etc.), normalized in the interval 0–10, according to the following Equation (1):

$$Pp = [(a^*w1) + (b^*w2) + (c^*w3) + \ldots \ldots ..]/10 \quad (1)$$

where

Pp = performance score (e.g., A1);
a,b,c = scores of the individual indicators calculated by the surveyors (e.g., A1.1, A1.2, A1.3);
w1, w2, w3 = weights attributed to each indicator (e.g., wA1.1, wA1.2, wA1.3).

Table 2. Performance Indicators within the Human–Environment Interface, *Natural elements*.

Category	Performance	Indicators	Measure Unit	Limit Value	Optimal Value	Score Max/Min	Weight
A–Natural elements	A1. Vegetation	A1.1—Green area/inhabitant	m^2/inhabitant	9	20	0/10	60
		A1.2—Proximity to green area	m	≤300	≤300		20
		A1.3—Quality of green area	bad/poor/mediocre/ sufficient/good/excellent	sufficient	excellent		20
	A2. Bodies of water	A2.1—Proximity of elements	m	≤300	≤300	0/10	60
		A2.2—Quality of elements	bad/poor/mediocre/ sufficient/good/excellent	sufficient	excellent		40
	A3. Protection of biodiversity	A3.1—Proximity to green area	m	≤300	≤300	0/10	40
		A3.2—Percentage of permeable surfaces	%	≥30	≥30		40
		A3.3—Proximity to green corridor	m	1000 > A3.3 ≥ 750	A3.3 < 600		20

Table 3. Performance Indicators within the Human–Environment Interface, *Built environment*.

Category	Performance	Indicators	Measure Unit	Limit Value	Optimal Value	Score Max/Min	Weight
B—Built environment	B1—Functional mix	B1.1—Land use mix	B1.1—Entropy equation	≥0.5	1	0/10	40
		B1.2—Proximity to business	m	≤300	≤300		30
		B1.3—Quality of elements	bad/poor/mediocre/ sufficient/good/excellent	sufficient	excellent		30
	B2—Hierarchy	B2.1—Hierarchical relationship	Yes/no	Yes	Yes	0/10	40
		B2.2—Dimensional relationship	Yes/no	Yes	Yes		30
		B2.3—Formal relationship	Yes/no	Yes	Yes		30
	B3—Landmarks	B3.1—Cultural and natural landmarks	Yes/no	≥1 in the reference area	1 everywhere	0/10	60
		B3.2—Quality of landmarks	Bad/poor/mediocre/ sufficient/good/excellent	sufficient	excellent		40
	B4—Margins	B4.1—Strong margins	% compared to the edge length	≥70	≥70	0/10	50
		B4.2—Dimensional relationship H/W	m/m	0.5 ≤ B4.2 < 1	1		10
		B4.3—Percentage of sky view	% of sky view	≥70	≥70		30
		B4.4—Quality of margins	bad/poor/mediocre/ sufficient/good/excellent	sufficient	excellent		10
	B5—Nodes	B5.1—Density of intersections	n/Km2	50 < B5.1 ≤ 70	≥130	0/10	100
	B6—Surfaces	B6.1—Percentage of permeable surfaces	%	≥30	≥30	0/10	20
		B6.2—Reflective power	Albedo	>0.3 at least 50% of the surface	>0.3 at least 50% of the surface		10
		B6.3—Technical adequacy	Yes/no	Yes	Yes		30
		B6.4—Quality of surfaces	bad/poor/mediocre/ sufficient/good/excellent	sufficient	excellent		40
	B7—Temporary uses	B7.1—Amount of time dedicated to temporary functions	[Hours spent for temporary uses/day] *100	≤10%	≤10%	0/100	100

Table 4. Performance Indicators within the Human–Environment Interface, *Mobility*.

Category	Performance	Indicators	Measure Unit	Limit Value	Optimal Value	Score Max/Min	Weight
C—Mobility	C1—Sidewalks	C1.1—Length of sidewalk	% of the total viability	≥50	≥75	0/100	40
		C1.2—Width of sidewalk	m	≥1.50	3.00 ≤ C1.2≤ 5.00		20
		C1.3—Quality of sidewalk	bad/poor/mediocre/ sufficient/good/excellent	sufficient	excellent		40
	C2- Parking	C2.1—Proximity to parking area	m	≤300	≤300	0/100	60
		C2.2—Quality of parking area	bad/poor/mediocre/ sufficient/good/excellent	sufficient	excellent		40
	C3—Transit supply	C3.1—Frequency and flow of public transportation	n/h	≥ 4	≥ 6	0/100	60
		C3.2—Quality of public transportation	bad/poor/mediocre/ sufficient/good/excellent	sufficient	excellent		40
	C4—Transit stops	C4.1—Proximity to stops	m	≤300	≤300	0/100	60
		C4.2—Quality of stops	bad/poor/mediocre/ sufficient/good/excellent	sufficient	excellent		40
	C5—Pedestrian crossings	C5.1—Presence of crossings	Yes/no –No every 100 m	1	>1	0/100	50
		C5.2—Width of crossings	m	≥2.50	≥4.00		50
	C6—Road (vehicle) traffic	C6.1—Traffic flow	n/h	600 ≥ C6.1 > 300	≤300	0/100	100
	C7—Bicycle paths (intermodality)	C7.1—Percentage of bicycle paths	% of the total road network	≥50	≥50	0/100	30
		C7.2—Proximity to paths	m	≤300	≤300		50
		C7.3—Quality of bicycle paths	bad/poor/mediocre/ sufficient/good/excellent	sufficient	excellent		20
	C8—Pedestrianization (intermodality)	C8.1—Percentage of pedestrian zones	% of the surface urban spaces	≥50	≥50	0/100	30
		C8.2—Proximity to pedestrian zones	m	≤300	≤300		50
		C8.3—Quality of pedestrian zones	bad/poor/mediocre/ sufficient/good/excellent	sufficient	excellent		20
	C9—Limited traffic zones—LTZ	C9.1—Percentage of limited traffic zones	% of the surface urban spaces	≥40	≥40		50
		C9.2—Proximity to limited traffic zones	m	≤300	≤300		30
		C9.3—Quality of limited traffic zones	bad/poor/mediocre/ sufficient/good/excellent	sufficient	excellent		20
	C10—Public Roads	C10.1—Percentage of arterial roads	% of the surface urban spaces	≤10	≤10	0/100	60
		C10.2—Quality of road network	bad/poor/mediocre/ sufficient/good/excellent	sufficient	excellent		40

Table 5. Performance Indicators within the Human–Environment Interface, *Urban furniture* and *Perceived environment*.

Category	Performance	Indicators	Measure Unit	Limit Value	Optimal Value	Score Max/Min	Weight
D–Urban furniture	D1—Seats	D1.1–Length of seating	m/m^2 every 3 m^2 of space	0.15 < D1.1 < 0.30	≥0.30	0/100	60
		D1.2–Quality of the seating	bad/poor/mediocre/ sufficient/good/excellent	sufficient	excellent		40
	D2—Public Lighting	D2.1–Light flow	Lux	15 < D2.1 ≤ 18	15 < D2.1 ≤ 18	0/100	60
		D2.2–Quality of the light fixtures	bad/poor/mediocre/ sufficient/good/excellent	sufficient	excellent		40
	D3–Signs	D3.1–Minimum distance from danger sign	m	≥50	≥50	0/100	20
		D3.2–Presence of information signs	No for each intersection	≥1	≥1		40
		D3.3–Quality of signs	bad/poor/mediocre/ sufficient/good/excellent	sufficient	excellent		40
	D4–Waste dump	D4.1–Distance between dumpsters	m	≤ 150	≤ 150	0/100	60
		D4.2–Quality of waste containers	bad/poor/mediocre/ sufficient/good/excellent	sufficient	excellent		40
	D5–Shadows	D5.1–Percentage of shaded areas	% compared to open space	>30	>50	0/100	50
		D5.2–Transmission coefficient	%	25 ≥ D5.2 > 15 at least 50% of surface	15 ≥ D5.2 ≥ 0 at least 90% of surface		15
		D5.3–Albedo	Albedo	>0.3	>0.3		15
		D5.4–Quality of sun protection elements	bad/poor/mediocre/ sufficient/good/excellent	sufficient	excellent		20
E–Perceived environment	E1–Chromatic feature–colors	E1.1–Chromatic harmony	bad//mediocre/ good/excellent	good	excellent	0/100	100
	E2–Olfactory feature–smells	E2.1–Presence of olfactory source	Yes/no–m	>300		0/100	100
	E3–External environment noise	E3.1–Daytime noise level	dB(A)	≤57		0/100	50
		E3.2–Night-time noise level	dB(A)	≤47			50
	E4–Neatness	E4.1–Frequency of road cleaning	n/week	2 < E4.1 ≤ 4	>7	0/100	60
		E4.2–Frequency of waste collection	n/day	≥3	≥3		40

The *Natural elements* category in Table 2 includes both man-made components that translate into green public areas, tree lined streets, fountains and waterworks, and the availability of bodies of water, whose effects on the behaviors and habits of the inhabitants are largely recognized in the scientific literature, due to their capacity to mitigate temperature and sun exposure [33,36,66].

The *Built environment* category (Table 3) relies on indicators applicable to describe the major features of the urban structure, from morphology, to configuration, density, texture and quality and its functions. All highlight crucial features for evaluating the ergonomics of the urban spaces [16,29,63,67–72].

In the *Mobility* category (Table 4), ten indicators specifically describe the infrastructure specifically associated with the capability to increase and facilitate active and sustainable mobility [73–77] as "part of the daily life of all the inhabitants, by means of transportation, free time and workplace activities ... " [78]. The *Natural elements* and *Built environment* categories describe the urban fabric features where walkability takes place, whereas *Mobility* assesses the quality of connections to generate walkable conditions. Together, they describe the walkability of the public realm.

The *Urban furniture* category (Table 5) relies on five indicators to assess comfort and perceived safety. They describe the characteristics of a given urban space needed to increase social interactions and support walking [66,71,79]. To conclude, *Perceived environment* (Table 5) includes four indicators related to the users' perception of neatness of the urban space [50,54,73,80]. Both categories represent added values to the walkability of the public realm.

2.1.1. The Performance–Requirement Matrix

The selection of indicators is often a challenging task in planning and evaluation practice. Indicators should be SMART—Specific, Measurable, Attainable, Realistic and Tangible [81] and, possibly, comparable. Issues of uncertainty and difficulties in the measurements are commonly addressed. For example, accessibility is a broad concept (as synthesized in [82]), measurable in different ways and with different indicators. A control tool is then required to check whether a specific requirement is actually met by a given performance. This could be a control matrix, like the one presented in Table 6, where the requirements from Table 1 are matched with the performance listed in Tables 2–5.

Table 6. The Requirement–Performance Control Matrix.

HEI Human—Environment Interface																															
Human			Environment																												
			Performance																												
			Conditions and functions to meet users' need																												
			Walkability of the public realm																												
			Urban fabric										Connectivity										Added values								
			Natural element			Built environment							Mobility										Urban Furniture					Perception			
Need	Requirement		A1	A2	A3	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	D1	D2	D3	D4	D5	E1	E2	E3	E4
Conditions to be maintained or a desired state to be achieved in the field of:	To make explicit users' need, specifically for:		Vegetation	Water	Biodiversity	Functional mix	Hierarchy	Landmarks	Margins	Nodes	Surfaces	Temporary Uses	Sidewalks	Parking	Transit supply	Transit Stops	Pedestrian crossings	Road (vehicle) traffic	Bicycle paths	Pedestrianization	LTZ	Public Roads	Seats	Public Lighting	Signs	Waste dump	Shadows	Coloros	Smells	Noise	Neatness
Well-being	Hygienic-environmental management	Sunshine/ sunlight	A.11 A13						B42 B43																		A.11 A13 D51 D52 D53				
		Air quality	A.11	A.21														C61		C71C81 C82 C83	C71C91 C92 C93										
		Ventilation		A.21					B42																						
	Hygrometric control	Temperature	A.11		A32				B42		A32																D51 D52 D53				
		Relative humidity		A.21																											
	Visual suitability	Lighting																						D21 D22				D21 D22			
		No glare			A32 B62																			D21 D22			D51 D52 D53				
	Auditory suitability	Noise level				B12			B42									C61				C101 C102								C61 E31 E32	
	Ease	Levels of Service					B21 B22 C22					B51	C11	C21 C22	C31 C41 C42	B22 B51 C32	C52		C72 C72	B51	B51		D11 D12								
Safety	Risk prevention	Avoidance of conflicts with motorized users											C12		C31	C31 C32	C51 C52		A33 C71 C72 C73	C81 C82 C83	C91 C92 C93			D21 D22	D31						
		Obstacle/barrier-free sidewalks											C11 C12 C13										D11 D12								
		Even sidewalk											C13																		
		No-slippery sidewalk											C13																		
Usability	Maintenance	Cleanness and sanitation									B64		C13	C22	C22	C22 C32										D41 D42		E11	B12 C61 D41 D42 E11 E12 E21	B12 C61	C61 D41 D42 E11 E12 E21 E 41 E42
	Flexibility	Adaptation to events		A.12 A.13 A.31 A.33		A12 A21 B11 B12	C12	A12 A22 B13		B51		A12 A22 A13 B32	C12		C31 C32					C81 C82 C83	C91 C92 C93	C101 C102	D11 D12								
	Relationships	Privacy					B23						C13																		
		Communication	A12			A12	A12			B51			C12		C31								D11 D12		D31 D32 D33						D12

This control matrix makes it possible to check that each performance of the environment is meeting at least one requirement, from the users' side. Each single indicator may be used for more than one requirement/performance relationship, which creates a multiscope assessment of the walkability features.

2.2. The Case Study

The set of walkability indicators was tested on a case study where a previous analysis focused on the walkability of the urban areas around the historic center of Rieti, a middle-size province town, 80-km far from Rome, in Central Italy, with just less than 50,000 inhabitants. The former analysis was designed to test and validate a composite indicator, the Walking Suitability Index of the Territory—T-WSI [63]. Unlike other walkability tools, T-WSI was not designed to assess the walking-friendliness of given origin-destination's paths or trips, but of the whole walking environment of an area, in this case 9 out of 15 neighbourhoods in Rieti. T-WSI can be thus considered the "prequel" of the current HEI approach which, in turn, includes a larger array of indicators (those in Tables 2–5) and covers a vaster area (approximately 60% of the built area of the city as in Figure 1).

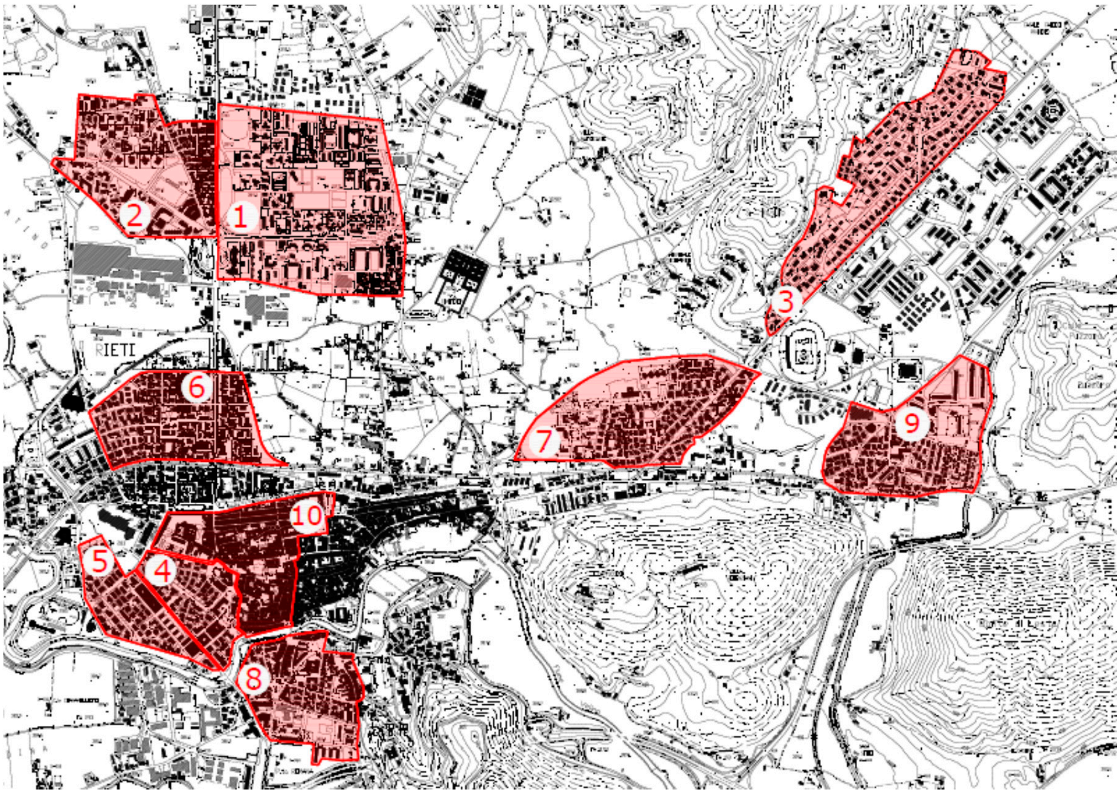


Figure 1. The case study areas in Rieti, central Italy.

Increasing the number of indicators obviously improves the accuracy of the study and great attention was attached to their SMART characteristics. Within the HEI approach, however, one more advance is represented by the quality of the analysed districts. Areas 1 to 9 in Figure 1 and Table 7 were developed between the 1920s and 1990s, under different planning criteria and visions of the city, but under the same need to provide the 1900s' expanding population with housing and basic services (schools, churches, etc.). Much different is the city center (Area 10 in Figure 1 and Table 7), which has always been a pedestrian area since it was developed in 1149 as a papal seat. The quality of the built environment is high with narrow alleys, squares and landmarks such as the medieval walls and cultural heritage buildings (with an enforced Limited Traffic Zone—LTZ helping to preserve all of that). Usually, historic centers are not included in the walkability analysis since, by definition, they are fully walkable.

In this case, contemplating the city center in the HEI analysis makes it possible to introduce an unusual but significant term of comparison (a reference) among the more modern districts. Moreover, it introduces the research question about the assumed attractiveness of historic areas as a catalyst to attract pedestrians.

Table 7. Characteristics of the districts in the study area.

FEATURES	DISTRICT		SURFACE (m^2)	POPULATION (unit)	POPULATION DENSITY (Inhabitants/km^2)
1100s–1920s original settlement of the city with mixed land use including several landmarks	10	Historic center	259,341	1771	6828.8
1920s–1990s residential, working class area, mix of building types: one- or two-family houses, two or three-storey apartment buildings (some within social housing projects)	9	Villa Reatina	282,320	2303	8157.4
	2	Fassini	307,985	2437	7912.7
1950s–1980s residential middle-class areas, mix of detached and terraced houses, little villas, low-rise apartment blocks	4	Fiume dei Nobili	119,400	824	6901.2
	5	Città Giardino	124,408	1375	11,052.3
	8	Borgo	210,383	1849	8788.7
	6	Regina Pacis	175,874	2390	13,589.3
1960s–1990s suburban residential areas, mix of prevalently low-rise apartment blocks and terraced houses	1	Micioccoli	571,395	3562	6233.9
	7	Piazza Tevere	273,879	1765	6444.5
1970s–2000s mainly residential upper middle class area, consisting of single-family villas, little villas, terraced houses, small apartment blocks.	3	Zona Residenziale	355,811	865	2431.1
Total			*2,680,796*	*19,141*	

To describe the differences between these districts, an abacus of photographs associating local environments with HEI categories is provided in Table 8.

2.3. The Data Collection

The first step in the analysis was the data collection to "feed" the indicators. A trained researcher was in charge of collecting data for every link of the road network at each considered district. This required surveys, calculations and/or measurements according to the type of indicator to develop. A spreadsheet was specifically designed to collect data for each indicator's category. Once data were entered, a further data assessment was carried out by a different trained researcher, who performed quality control on a random sample of records, independently re-collecting the same data under the same experimental conditions. Finally, the validated set of entered data was processed and results are presented in Section 3.

Table 8. Local environments and HEI.

HEI CATEGORIES NEIGHBORHOODS	NATURAL ELEMENTS	BUILT ENVIRONMENT	MOBILITY	URBAN FURNITURE	PERCEIVED ENVIRONMENT
10 Centro Storico					
	body of water, vegetation	landmarks availability, strong margins, paving quality	pedestrianized areas	quality seating, availability of lighting,	chromatic harmony
9 Villa Reatina					
	modest vegetation	poor presence of strong margins, low quality of margins	low availability of pedestrian crossing, lack of pedestrian areas, bicycle paths and LTZ	low availability of urban furniture	
4 Fiume dei Nobili					
	modest vegetation	lack of strong margins, good quality of margins	low availability of pedestrian crossing, low availability of sidewalk, lack of pedestrian areas, bicycle paths	low availability of urban furniture	chromatic harmony
1—Micciocccoli					
		no strong margins, no landmarks	low availability of pedestrian areas and bicycle paths	low availability of urban furniture	
2 Fassini					
		no strong margins, no landmarks	low availability of pedestrian crossing, lack of pedestrian areas, bicycle paths and LTZ	low availability of urban furniture	
7 Piazza Tevere					
	modest vegetation	no landmarks	lack of pedestrian areas, bicycle paths and LTZ	modest availability of urban furniture	
8 Borgo					
	vegetation	functional mix, landmarks, strong margins	low availability of pedestrian crossings	low availability of urban furniture	
6 Regina Pacis					

Table 8. *Cont.*

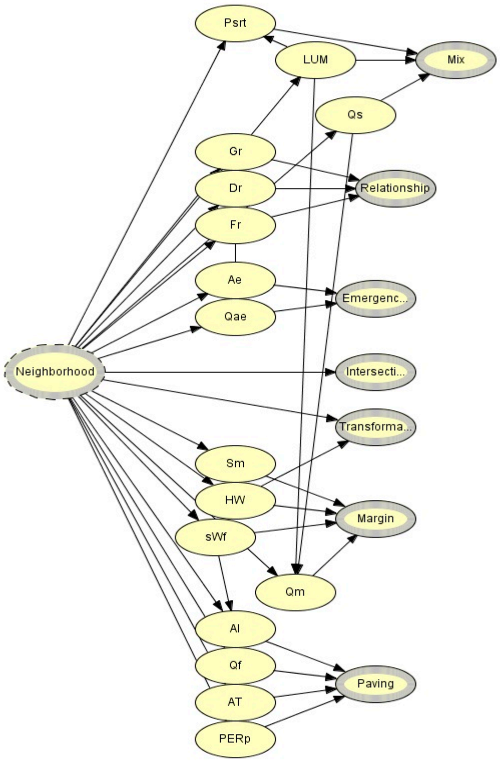
HEI CATEGORIES NEIGHBORHOODS	NATURAL ELEMENTS	BUILT ENVIRONMENT	MOBILITY	URBAN FURNITURE	PERCEIVED ENVIRONMENT
		low availability of functional mix, no landmarks	poor quality of sidewalk, low availability of pedestrian areas and bicycle paths	low availability of seating	noise level (daytime)
3 Zona Residenziale;					
	availability of vegetation	no functional mix	low availability of pedestrian crossings; lack of pedestrian areas, bicycle paths and LTZ	low availability of urban furniture	chromatic harmony
5 Città Giardino					
		no landmarks	low availability and poor quality of sidewalk; low availability of bicycle paths	availability of lighting for pedestrian low availability of seating	noise level (daytime)

3. The Bayesian Network Model

A BNet probabilistic model has been built to seek out and analyse the complex relationships occurring among the different performances, which become "variables" in the BNet model. The BNet model was built in two phases:

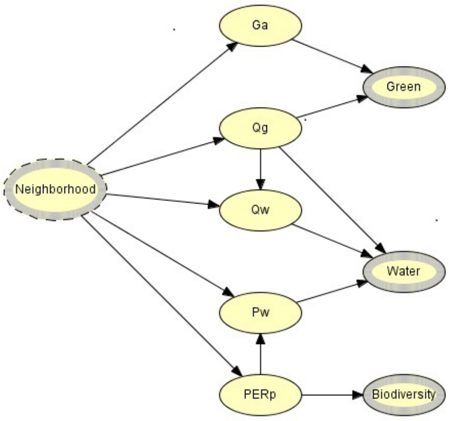
1. *Structural modelling*: consisting of the definition of the model structure, which was carried out by determining the conditional independency among the variables;
2. *Dependency modelling*: by calculating of the strength of conditional dependency among the variables.

Both phases were based either on data, through machine learning algorithms (i.e., structural learning and EM-learning), or on first principles implemented by manual coding physical laws, well established rules, or expert knowledge depending on their availability (as further reported). The final model was composed of seven elementary networks arranged in three levels. The first level includes five elementary networks (Figures 2–6) that represent the basic parameters used to quantify the main features of the urban space ergonomics. Manual coding has been mainly used in first-level networks, since there is a clear functional dependency among the measured parameters and the ergonomic features. Just a small number of inter-parameter dependencies have been derived by data only when a well-grounded explanation could have been formulated.



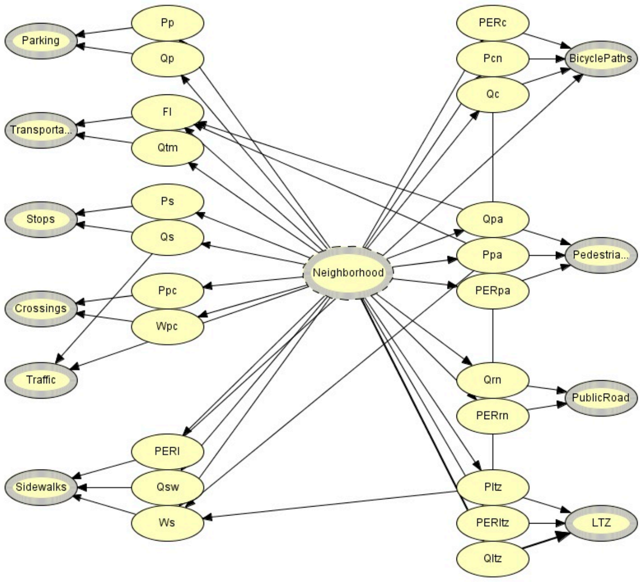
Psrt: proximity of neighborhood services, recreational and tertiary activities;
LUM: land use mix;
Qs: quality of services offered;
Gr: geometric relationships;
Dr: dimensional relationships;
Fr: formal relations;
Ae: presence of landmarks;
Qae: quality of landmarks;
Sm: strong margin;
H/w: dimensional relationships between height of building and their distance;
SWf: sky view factor;
Qm: quality of the margins;
Al: albedo;
Qf: quality of surfaces;
AT: technical adequacy of the materials used;
PERp: permeable surface percentage.

Figure 2. I level: Bayesian elementary network, *Built Environment.*



Ga: green area/inhabitant;
Qg: quality of green areas;
Qw: quality of the water elements;
Pw: proximity of the water elements;
PERp: permeable surface percentage.

Figure 3. I level: Bayesian elementary network, *Natural Elements.*



Pp: proximity to parking lots;

Qp: quality of parking areas;

Fl: transit flows;

Qtm: quality of transport modes;

Ps: proximity to stops;

Qs: quality of the stops;

Ppc: presence of pedestrian crossings;

Wpc: weight of pedestrian crossings;

PERl: sidewalks length in percentage;

Qsw: sidewalks quality;

Ws: width of sidewalks;

PERc: availability of cycle paths in percentage;

Pcn: proximity to the cycle network;

Qc: quality of the cycle paths;

Qpa: quality pedestrian areas;

Ppa: proximity to pedestrian areas;

PERpa: availability of pedestrian areas in percentage;

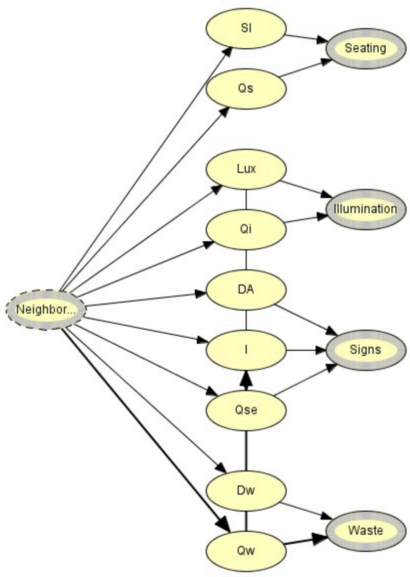
Qrn: quality road network;

PERrn: availability of road network in percentage; Pltz: proximity to limited traffic zones;

PERltz: availability of limited traffic zones in percentage;

Qltz: quality of limited traffic zones.

Figure 4. I level: Bayesian elementary network, *Mobility*.



Sl: seat length;

Qs: quality seating elements;

Lux: light intensity;

Qi: quality lighting elements;

DΔ: minimum distance warning signs;

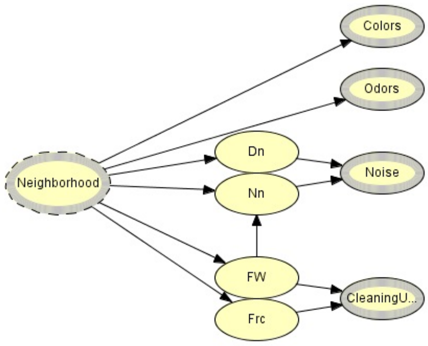
I: presence of signs of indications;

Qse: quality signage elements;

Dw: distance from dumpsters;

Qw: quality of dumpsters.

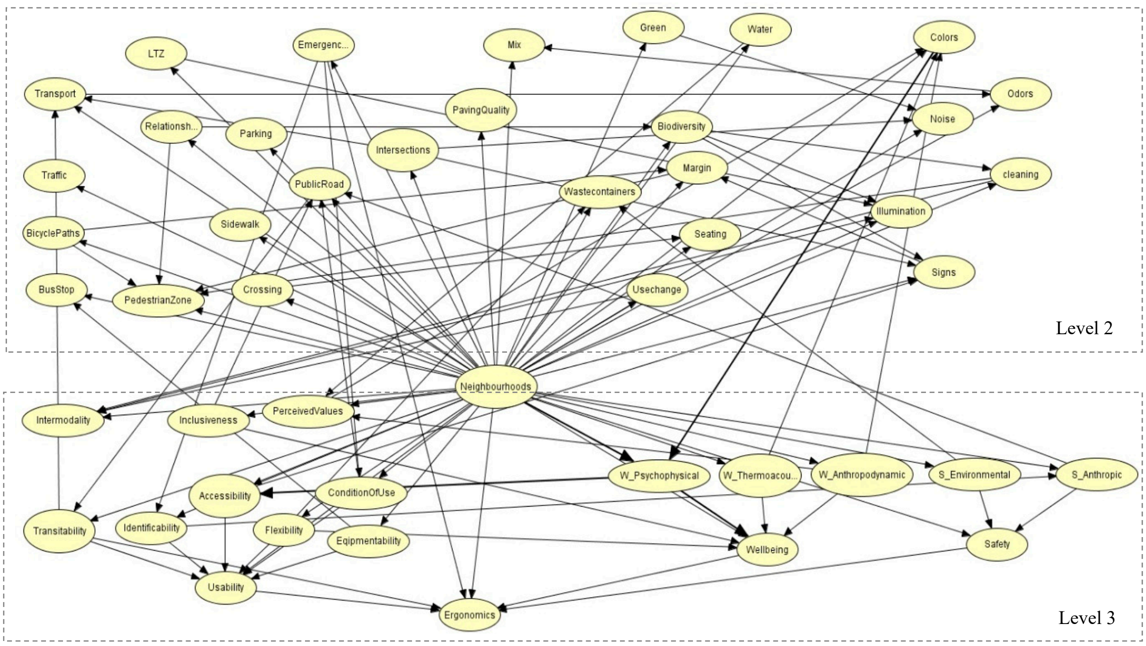
Figure 5. I level: Bayesian elementary network, *Urban Furniture*.



Nn: night noise level;
Dn: daytime noise level;
Fw: frequency of sanitation (emptying dumpsters);
Frc: road cleaning frequency.

Figure 6. I level: Bayesian elementary network—Perceived Environment.

The 29 output variables of these networks are the input nodes of the second level network. The second level is made of a single network (Figure 7—top) that arranges the 29 urban ergonomic indicators calculated by the level 1 networks by establishing the conditional dependencies occurring among them. This network has been derived essentially from data, but a careful and systematic analysis of each derived relation has been carried out, to assess the statistical analysis on a semantic basis.



(W_Psycophysical: Wellbeing Psycophysical; W_Thermoacoustic: Wellbeing Thermoacoustic; W_ Anthropodynamic: Wellbeing; S_Environmental: Safety Environmental; S_Anthropic: Safety Anthropic)

Figure 7. The final BNet model representing the ergonomics of urban spaces.

The third level is made of a single network as well, and it is aimed at eliciting and coding experts' assessment about the performance level of the different neighbourhoods. As for the weights, a group of 10 urban planners and designers, both from professional and academic fields, was involved to assess the quality of the outdoor spaces of each neighbourhood. To this end, the experts have been provided with a specific assessment template where the general performance parameters were detailed (for example, usability is itemized in terms of easiness to equip, transitability, flexibility, accessibility, identifiability and conditions of use). The experts' assessment outcome has been finally integrated in the overall model using standard BNet learning algorithms. In this way, statistical dependencies have been calculated among the 29 observable neighbourhoods' ergonomic features and the expert assessments (Figure 7).

Finally, all the variables in the three networks have been connected to the *Neighbourhood* node, containing just the neighbourhood identifiers, so as to have a *case-based reasoning* (CBR) support to urban design. By observing or providing evidence to one or more neighbourhood identifiers in the *Neighbourhood* node, the network shows the statistics of a single case or a combination of cases, respectively. In fact, this inference resembles the case selection in CBR. Through this simple expedient, the network gives the possibilities to compare the models of different neighbourhoods' cases, pointing out similarities and differences. Furthermore, the neighbourhood identifier can be used as a key to access unstructured information sources (e.g., drawings, photos, tabled data, etc.) stored in complementary data environments, so that the analysis can be easily extended beyond the representation boundary of the statistical model. On the other hand, by selecting a single feature or performance node, the network points out the cases (i.e., the neighbourhoods) that share the selected value and the statistics of the other performance and feature nodes. Hence, by combining observations in the different network levels, a number of interesting inferences can be implemented. In general, the BNet model provides support to preliminary urban design through what-if analysis, by means of forward propagation of the observations of level 1 nodes, as well as support to urban regeneration policies through diagnostic reasoning, by means of backward propagation of observations of level 2 or level 3 nodes. The following section details the networks' levels.

3.1. Level 1 Networks

Five level 1 networks have been defined according to as many domain analyses: *Built Environment*, *Natural Elements*, *Mobility*, *Urban Furniture* and *Perceived Environment*. Direct dependencies among input and output nodes have been manually coded, the output (thick boundary nodes) being weighted sums of the inputs. Occasionally, parallel data analysis showed some strong dependencies between input nodes. These dependencies were included only when they were understood in terms of general theories, hence preserving the highest possible generality degree of the model.

Figure 2 shows the network concerning the *Built Environment* domain analysis. Data analysis pointed out some dependency relations among features: the sky view factor (sWf) affects the albedo (Al), as it is geometrically explainable, while the quality of the margins (Qm) is affected by the mix of land use (LUM), by the quality of services (Qs) and by the sky view factor (sWf), which can be figured out as well.

Figure 3 describes the network related to the *Natural Elements* domain analysis of the *Water*, *Green* and *Biodiversity* nodes. Some inter-parameter links occur in this domain as well. The quality of green areas (Qg) affects the quality of the water elements (Qw), and the percentage of permeable surfaces (PERp) affects the proximity of the water elements (Pw). In both cases, this evidence is explicable on a clear conceptual basis, hence, they have been included in the model.

The *Mobility* domain analysis is represented in Figure 4 where the features of the urban space that enhance sustainable and active mobility are highlighted.

A number of dependencies among urban features, having a plausible ground in theory, have been strongly suggested by the recorded data, and therefore added to this network. These include, the relation between the length of the sidewalks (PERl) and the presence of cycling paths (PERc), the relation between the proximity of the pedestrian areas (Ppa) and the width of sidewalks (Ws), the relation between the proximity of the LTZ (P and the proximity to parking lots (Pp), the relations among the proximity (Ppa) and the quality (Qpa) of the pedestrian areas with the flow of public transport means (Fl).

Figure 5 represents the network of the *Urban Furniture* domain analysis. Dependency relations among features concern the luminous flux (Lux) and therefore the brightness of an urban space, which influences the quality and affects, therefore, the readability of information signs (Qse). In fact, the quality of these elements is measured by analysing their visibility and maintenance status.

Finally, in the network representing the *Perceived Environment* domain analysis (Figure 6), the road cleaning (Frc) and emptying waste containers (FW) conceivably influence night noise levels (Nn).

3.2. Level 2 and 3 Networks

Figure 7 shows the final BNet model resulting from the integration of the output nodes of the seven networks (Level 2—top) with the network generated by experts (Level 3—bottom). The relations occurring among nodes at level 2 have been derived from data by selecting the ones that provided strong semantic evidence. In fact, the BNet machine learning algorithms supplied more than one model for the given data set. Among them, the ones that were the most plausible on a semantic basis were selected, excluding ordinary or counterfactual correlations, and correlations that appeared to be scarcely generalizable. The results show the relevant complexity of the real situation, deriving from the high degree of interconnectedness of the urban performance parameters. Each of these links is semantically dense, thus calling for additional multidisciplinary interpretations, to be addressed in forthcoming studies.

The level 3 network captures the general knowledge about urban ergonomics. Our approach, to include directly a significant number of expert assessments, is an attempt to capture and quantify the different perspectives on a statistical basis. The noteworthy point is that level 3 coding has been carried out by experts on a general set of parameters (e.g., *intermodality*, *inclusiveness*, *accessibility*, etc.), which was not directly connected with the performance variables part of level 2.

A final issue concerns the relationships occurring among level 2 and level 3 nodes. In this research, the case-based approach implemented by the *Neighborhood* node provided an initial solution to the problem, acting in principle as a sort of naïve Bayesian classifier. Then, a number of direct relations have been implemented, as in the previous levels, when the data provided strong insights about semantically well-grounded correlations.

4. Results Analysis

Following the layered model structure, the analysis is arranged by levels. According to the HEI approach, level 1 network analysis provides an overview of the general urban ergonomic indicators for each neighborhood and a quantitative assessment of the indicators' scores to highlight drivers and barriers for walkability. Level 2 and 3 network analysis provides an integrated and more systemic evaluation of ergonomics according to the emerged Bayesian Network structure.

4.1. General Urban Ergonomic Indicators—Level 1 Network Analysis

The availability of a large test area, which amounts to 10 neighbourhoods, ensures a good soundness of results and the emergence of performance gaps and critical factors affecting walkability in real built environments.

Table 9 shows the scores of each indicator and the average scores per performance obtained in the investigated neighborhoods. The table also shows, for each indicator, the percentage of neighborhoods with unsatisfactory scores and, for each district, the percentage of indicators with unsatisfactory scores. In this preliminary study, the values ≥6/10 have been arbitrarily considered satisfactory.

Table 9. Scores of each indicator for each neighbourhood in the case study.

	Neighbourhoods	**1.Micioccoli**	**2.Fassini**	**3.Zona Residential**	**4.Fiume Dei Nobili**	**5.Città Giardino**	**6.Regina Pacis**	**7.Piazza Tevere**	**8.Borgo**	**9.Villa Reatina**	**10.Centro Storico**	***Average Scores Per Performance***	**Insufficient Score < 6 (%) ***
Natural Elements	Vegetation	5.6	6.2	6	3	6.3	6	6	6.2	4	4.6	5.4	*40*
	Water	3.2	5.2	0.3	4.8	3.6	4.4	4.3	6.4	4	6.4	4.3	*80*
	Protection of biodiversity	10	10	10	8	8	8	10	8	8	8	8.8	*0*
Built Environment	Functional mix	7	5.6	2.4	8	8.1	5.7	8.6	8.1	5.5	7.8	6.7	*40*
	Hierarchy	4	4	4	7	7	7	4	10	0	10	5.7	*50*
	Landmarks	0	0	0	0	0	0	0	6.8	6	9.2	2.2	*70*
	Margin	4.2	4.3	4.7	8.3	6.2	5.9	3.9	6.1	3.8	8.3	5.6	*50*
	Nodes	3	3	3	10	3	3	3	3	3	8	4.2	*80*
	Paving quality	7	7.3	7	6.5	6.3	6.3	7.2	6	7	6.1	6.7	*0*
	Change of use	2.5	7.5	0	7.5	2.5	0	2.5	6.3	0	5.6	3.4	*70*
Mobility	Availability of Parking	9.1	6.9	6.8	7.7	7.7	7.2	6.4	7.4	7.1	7	7.3	*0*
	Public transportation	3.4	2.2	2.4	3.3	2.5	2.3	2.6	2.7	2.5	3.3	2.7	*100*
	Public transportation stops	6,8	4,2	6,1	6,5	6,9	6,5	6,5	6,6	7,1	6,5	6.4	*10*
	Pedestrian crossings	6.2	3.1	0.4	5.5	3.2	4.2	4.4	3.3	1.8	3.3	3.5	*90*
	Road (vehicle) traffic	6.6	8.8	8.9	4.3	7.5	6.9	7.1	5.9	7.1	7.7	7.1	*20*
	Sidewalks	7.1	4.2	1.8	4.5	4.5	4	2.4	6.4	2	3.6	4.0	*80*
	Availability of bicycle paths	0.1	2.9	0	3.2	4.5	2.7	0.3	5.5	0	3.5	2.3	*100*
	Availability of pedestrian zones	5.5	2	5.4	6.9	6.2	2	5.5	7.9	3.8	8	5.3	*60*
	Availability of LTZ	0	0	0	3	1.5	2.9	0.8	7.6	0	8.9	2.5	*80*
	Pres. public roads	2	2.1	2.3	2.2	2.4	2.1	2.2	2.1	1.7	8.1	2.7	*90*
Urban furniture	Availability of Seating	3.2	3	2.4	2.7	3.4	3	2.7	3.1	2.7	3.1	2.9	*100*
	Availability of lighting	6.5	6.3	7.2	5.8	6.5	5.6	6.5	6.5	5.5	5.7	6.2	*40*
	Availability of Sign	4.9	4.8	4.8	5.2	5.4	4.4	4.6	4.5	4.1	5.4	4.8	*100*
	Availability of dumpsters	6.1	6.2	3.6	7.1	7.6	7.3	6.5	8	7.5	6.9	6.7	*10*
	Pres. Protection	0	0	0	0	0	0	0	0	0	0	0:0	*100*
Perceived environment	Colors	4.4	5.1	6.8	5.3	6.8	4.5	4	5.3	4.5	6.4	5.3	*70*
	Odors	10	6	6	10	6	6	6	6	6	10	7.2	*0*
	Noise	6.4	7.1	7.8	5.3	8	7.1	7.1	7.2	8	7.4	7.1	*10*
	Neatness	3.2	2.9	2.8	4.6	3.6	3.4	3.6	4.3	4.2	4.7	3.7	*100*
	Insufficient score < 6 (%)	*58.6*	*65.5*	*65.5*	*58.6*	*48.3*	*65.5*	*62.1*	*37.9*	*65.5*	*37.9*		

*:% of neighborhoods with indicator score <6; % of indicators with a score <6 for each neighborhood.

The analysis on the neighbourhoods stresses how the city centre is the most walkable, as expected. Likewise, the second and third ranked districts (Borgo and Fiume Dei Nobili) supply a walkable environment due to low-rise building stock, pedestrian-oriented management of local mobility, and clear hierarchy and functional mix, with residence as the prevailing use. According to the scores associated with the different performance levels, the perception of safety seems rather critical (for example, in 90% of the neighbourhoods, crossings signs and markings are not adequate; in 80% of the areas, the sidewalks are not present or are inadequate). The unsuitability of some environmental factors (especially vegetation and waters, density of intersections, density of public transport, the presence of cycling and pedestrian paths, sidewalks, etc.) is clearly detrimental to the *salutogenicity* of the neighbourhoods [3]; these, along with the poor enforcement of LTZs (missing in 80% of the areas), and pedestrianized areas (unavailable for 60%), no cycle paths or seats (everywhere in the case study), are additional barriers to support behavioural changes in favour of more physical activity levels and more active environments [56,66].

A focus on the *Mobility* performance might help to explain some of the barriers mentioned above. This is the bulkiest category, which describes the quality of connections and, in turn, is strongly affected by the urban fabric. It is not surprising, then, that *Mobility* highlights contrasting results. On the one hand, areas such as the city centre (District n. 10) are fully preserved by traffic phenomena by the enforcement of LTZ (although vehicular flows are not negligible, as surveyed in [63]), supplied with parking areas to avoid on-street parking, and pedestrianized to recreate the pristine HEI and enhance the cultural heritage. On the other, in areas where monofunctional land use (residence) is associated with modest or poor building quality, the *Mobility* features are consistently similar, with no walking-enhancing solutions: no LTZ and pedestrianization, basic transit supply, on-street parking, double lines and spill over. The paucity of *Urban furniture* and *Natural elements* are contributing factors in both cases, although with different outcomes. In the city centre, seating, public lighting, signs and marking are designed to highlight the premium built environment, which is so significant per se that natural elements are reduced to waterworks and sparse vegetation. In the contemporary districts, urban furniture is mostly reduced public lighting and road signs, mostly to prevent unsafe events. Vegetation, although richer, relies on small public parks and gardens, tree-lined streets and private areas, which help to increase the quality of the urban environment but not enough to trigger *salutogenic* behaviours.

4.2. The Overall Systemic Assessment—Levels 2 and 3 Analysis

The average value of ergonomics of Rieti obtained through the Bayesian model, expressed in percentage, is 44.2%, and Table 9 illustrates the score obtained by each neighbourhood. About 80% of the neighbourhoods have a low ergonomic level, which, therefore represent a widespread situation in the city of Rieti. Through a backward analysis (i.e., by observing the lower value on the *Ergonomics* node—see Figure 7), it is possible to identify the causes of the overall poor performance for the Rieti town. The analysis of the individual indicators (Table 8) highlights significant deficiencies, especially in terms of public transport, cycle paths and street furniture; the presence of green areas and the cleanliness of the urban space are also lacking. All these factors can be easily improved through a review of local land use planning policies [83,84]. At present, however, the lack of the aforementioned environmental factors determines the critical issues in terms of indicators related to the ability to walk and more generally to physical activity [3,63].

A further analysis can be conducted, selectively observing different values of the *neighbourhood* node. In that way, it is possible to compare the statistics of the different neighbourhoods, to highlight specific deficiencies and to identify possible improvements. As we have already pointed out, the explanations of complex states of affairs can affect the representation of boundaries of the probabilistic model.

For example, on one side, the *Centro Storico* shows the highest value of the ergonomics score (57.1%—Table 10). This can be explained in terms of several interventions already realized by the public administration in that area to increase its ability to attract people and to improve the economy.

On the other side, however, the same neighbourhood shows poor performance in some inner nodes that can be explained only through the topology of the network. In fact, the lack of public transport shows, in the *Centro Storico* case, a strong correlation to the olfactory perception nodes and to the presence of traffic (Figure 7), providing a clear hint of the unpleasant smells generated by unbalanced traffic patterns.

Table 10. Neighbourhoods' ergonomics obtained using a discrete Bayesian network and level of ergonomics of each component in the investigated neighborhoods.

Neighbourhoods	Ergonomics Value (%)	Usability (%)	Well-Being (%)	Safety (%)
1.Micioccoli	42.0	45.1	42.2	40.1
2.Fassini	40.9	42.8	42.4	38.3
3.Zona Residenziale	45.9	46.0	49.3	44.9
4.Fiume dei Nobili	45.8	49.0	47.7	42.9
5.Città Giardino	48.6	50.4	51.6	46.8
6.Regina Pacis	39.7	42.3	41.0	35.9
7.Piazza Tevere	40.4	43.1	40.7	38.0
8.Borgo	45.1	47.3	47.3	43.1
9.Villa Reatina	36.6	38.5	38.4	32.0
10.Centro Storico	57.1	61.8	59	54.9

A second noteworthy example is the *Villa Reatina* neighbourhood, where the worst situation is observed (36.6%—Table 9). *Villa Reatina* is considered a working-class neighbourhood whose first urbanization dates back to the fascist period and expanded in the following years. It is mainly a residential area, consisting of one or two-family buildings (built from 1920 to 1940) and multi-family buildings (built from 1960 to 1990), most of which fall within economic and popular building projects [54.6%]. It is a neighbourhood where social inequalities are particularly evident due to both the origin of the neighbourhood and its urban conformation. The Bayesian Network model shows that the low level of ergonomics is determined by equally scarce values of usability, well-being and safety (worst value). Proceeding backwardly on the BNet model, it is possible to identify the causes that are the prime factors determining such a low level of ergonomics. In the neighbourhood, at present, there are several shortcomings, mainly related to the urban structure that compromise the aesthetic quality of the neighbourhood and its liveability (lack of identity and recognizability). They include lack of hierarchical relations among spaces, both formal and dimensional, poorly defined urban margin and connectivity between the various parts of the neighbourhood, etc. As for the historic centre, shortcomings are identified in public transport, in cycling networks, in pedestrian crossings and, more generally, in the design of urban space dedicated to pedestrians (lack of seats, lighting, etc.).

4.3. General Trends

Finally, it is worth annotating some general trends concerning *salutogenicity* that can be identified from this level of analysis.

4.3.1. Environmental Factors

Environments with poor environmental and aesthetic quality could greatly influence the lifestyle of the population and be perceived as unsafe. The lack of environmental factors that support physical activity pushes *Villa Reatina* to the worst ergonomics rank and to the fifth to last in walkable neighbourhood among those studied. In fact, urban and indoor environments represent one of the major health determinants, and a clear and updated regulatory system is a key factor to ensure not only Public Health safeguarding [84], but also more sustainable mobility patterns.

4.3.2. The Safety Issues

Table 9 shows the ergonomics scores, stratified by their principal components (*Usability*, *Well-Being* and *Safety*). According to previous studies [12,24], *Safety* obtains the lowest scores in all the neighbourhoods. Results achieved for *Safety*, as "the set of conditions related to the safety of users, as well as to the defence and prevention of damage caused by accidental factors, in the operation of the urban outdoor space system" [85], highlight once more the relevance of *Mobility* in promoting sustainable travel habits. In particular, the factors determining the low safety score are mainly related (Figure 7) to the lack of public transport and cycle paths (both with insufficient scores in 100% of the districts), crossings (insufficient in 90% of districts), pedestrian areas and limited traffic areas (both insufficient in 80% of districts). These aspects, addressed within local general mobility policies [86,87], should be taken into account and solved into the Urban Traffic Plans (UTPs) and Sustainable Urban Mobility Plans (SUMPs), by means of specific actions, like those recently recommended by the WHO [2,88,89], as further discussed in Section 5.

The *Safety* issue introduces one more element to consider: the relevance of maintenance of paths and urban furniture to ensure proper and favourable walking conditions and to avoid accidents and falls. Several studies on areas similar to those in the case study [64,90,91] stressed how maintenance, if neglected, generates inappropriate walking behaviours among the pedestrians, thus reducing the overall walkability of an area. This means that walkability needs an integrated management (land use policies, mobility regulations, maintenance plans), which the BNet applications might help to foster by highlighting the several interrelations between the HEI other variables.

The use of the BNets provides a complete framework of the current situation in the neighborhoods, highlighting the causes that determine the above-mentioned ergonomic results in the various areas.

4.3.3. The Well-Being Issue

The factors involved in the definition of the districts' wellbeing also obtained insufficient scores. *Well-being*, as defined by the WHO ("*a state of total physical, mental and social well-being*" and not simply "*absence of disease or infirmity*" [87]), in the study was intended primarily as "*the set of conditions relating to states of the open urban spaces system adequate to life, health and the performance of the inhabitants' activities*" [40].

The conditions of well-being, as stated in the norm [88], refer to the positive sensory perception of the environment by the user, to health and hygiene situations, to the absence of pathogenic conditions and to the safety of users. If the user's satisfaction represents the level of comfort that is perceived in the performance of daily activities in an open space, the concept of well-being can be conditioned, since it is connected (Figure 7) to the factors that define the use and safety of the spaces in carrying out the activities. Several variables negatively affect the *Well-being* scores; some of them still due to *Mobility* issues (the lack of public transport, of bicycle paths, limited traffic areas, crossing). In addition, the inadequate management and maintenance of public roads (with insufficient scores in 90% of the districts), cleaning of outdoor spaces (insufficient in 100% of the districts), as well as approximate street furniture (lack of seats and suitable signs in 100% of the districts) are equally lacking.

4.3.4. Mobility

Mobility has a central role in generating *salutogenic* cities according to the HEI approach. Both the results from the indicators and the BNet analyses evidence how unbalanced traffic patterns in favour of private traffic are detrimental to *Safety* in general and in some specific areas within *Well-being* and *Usability.* Hence, an appropriate *Mobility* governance should be adopted, starting from the enforcement of its sustainability-oriented regulatory tools. The usual regulatory tools are those to manage traffic flows and to develop sustainable mobility patterns (fully described in the literature [89] and largely enforced across Europe).

As shown by scores achieved in the city centre and in the other neighbourhoods in the case study, pedestrianization, LTZs and Zone 30s can be considered unavoidable interventions to safeguard and rehabilitate premium value environments in central historic areas and, in general, to enhance walking even in areas where the built environment may lack distinct qualities.

5. Discussing Possible Advances

The methodology described in Section 2 relies on the reported array of measurable indicators to assess the salutogenicity of a given urban context. However, cities are complex, each with different local features and living conditions. Such specificities introduce three issues to address as possible areas of advancement in the proposed methodology: i) once more, the relevance of selecting SMART indicators, but also the possibility of creating flexible tools, adaptable to the most different of urban contexts by adding more parameters; and ii) the possibility of enlarging the analysis by contemplating non-physical aspects like the human or social environments, and iii) the need to include different categories of surveyors in the analysis.

For what concerns the first issue, the HEI approach makes it possible to freely add to, or remove from, the selected categories more indicators than those used for this case study, if need be, thus tailoring the assessment and further fine-tuning the overall analysis to any case in hand. The evaluation of land use as an element affecting the walkability of a given urban environment is a case in point. In the literature, the assessment of land use is often assumed in terms of dominant functions, thus replicating the approach usually applied in urban planning. Consequently, an area can be assessed in terms of land use mix, by measuring the availability of its main uses: residential, commercial, etc. This is certainly a major determinant, as, in the literature, it has been long-acknowledged that monofunctional uses are detrimental to livability, based on specific indicators like, for example, land use entropy [92]. However, these types of indicators. although accurate, call for extensive data process [82,92], are area-based and do not consider local effects at the ground level generated by bustling storefronts, street activities, and outdoors-based behaviors [67,79]. These contribute to *urbanity*, i.e., those specific characteristics of urban life, and placing an emphasis on indicators measuring the vibrancy of the city life at the ground level results in an added-value to the walkability assessment. Some urbanity indicators describing the sidewalks' levels of service (width, types of equipment) to accommodate the street activities were already developed for this case study and fully described in [61], but, in the literature, more can be found associated, for example, with: Trip-Generating Clusters (i.e., the capacity of given urban activities and facilities to generate the displacement of pedestrians); buildings' variety of formal features as elements to support walking (mostly space syntax-based, such as: Mean Convex Space; Mean Number of Entrances per Convex Space; Percentage of Blind Convex Spaces, etc.) [93]; landscape and environmental metrics (based on the quality of vegetation and pollutants' concentrations) [94]; participation in public life (as revealed preferences) [95].

The relevance of participation introduces the second issue, i.e., the possibility of highlighting how the human and social environments affect this type of study. Additionally, in this case, more indicators can be easily introduced than those used for the case in hand, which were derived by the local situation: Rieti is a typical middle-size European provincial town, with modest crime rates, no social conflicts, poor-quality but still livable outskirts, and welfare problems rarely experienced. Thus, the difference in this matter between the city center and the surrounding districts relies mostly on the former's higher quality of built environment over the latter's, and its natural vocation as a walking environment is also preserved by the enforcement of the local LTZ. Here, a consolidated land use based mostly on a mix of commercial facilities at the ground level and residential use on the upper stories, which attracts locals and visitors from the surrounding cities for most of the day, also helps to keep the area alive and avoid decadence. On the contrary, in urban areas with marked social inequalities among the city center and the other neighbourhoods (the former being either too exclusive with high-value properties and tourism-gentrified, or too dilapidated due to subpar building stock, security and safety problems, and inhabited by less and less affluent residents and businesses), more indicators and additional analyses are certainly needed. Again, in the literature, indicators to assess the role of the social environment that are consistent with the HEI approach abound and can cover all the contemplated categories. For example, indicators assessing social costs of transport, public perception and awareness, and safety levels [96,97] are appropriate to highlight the relationships between social inclusion and mobility. The approach in [98] seems to be particularly germane to assess how inequalities can be generated by natural and built environment features (by considering indicators assessing vegetation planting, access to green and recreational areas, on the one hand, and the effect of foreclosure, homeownership or vacancy rates on the other). Eventually, surveys based on Revealed and Stated Preferences can give rise to accurate assessment of how citizens perceive the environments they inhabit and the quality of the supplied services and equipment.

As described in Section 2.1.1, both the survey and the data process for the case study were carried out by researchers, so to achieve an expert assessment as a research goal. However, consistently with the HEI approach and the easiness of scoring the performance via the lists presented in Tables 1–5, the assessment can be extended to the real users, i.e., the neighborhoods' inhabitants. This opportunity, currently under study, calls for the voluntary involvement of different users' categories (according to age, gender, special needs). Perceptions vary not only with physical status but with familiarity with the urban context, trip purposes, weather conditions. All of the above will be considered to design accurate survey conditions and ensure comparability of the prospective results with those already available. Involving citizens represents a two-fold added-value as it complements the expert assessment and provides specific insights according to the actual abilities of the participants.

6. Concluding Remarks

This paper has discussed the *salutogenicity* issue of urban environments and its relationship with urban ergonomics, focusing on mobility and walkability. The paper has proposed a methodology to define generalized statistical models of urban ergonomics and *salutogenicity*, has introduced and discussed the relevant parameters derived from the large sets proposed in the literature, has discussed the emerging structure of a multi-level Bayesian network model, and has provided evidence of the solution's effectiveness through an in depth discussion of the modelling result. The methodology has been applied to the city of Rieti, a middle-sized town in central Italy.

Although the model has been able to provide consistent snapshots of the actual state of affairs of the case study, and has supported interpretations and diagnoses of the emerging performance gaps, further work is still necessary to extend this methodology to provide a more generalised approach and consider the possible advances highlighted in Section 5. Moreover, a preliminary first principle modelling approach, developed exclusively using equations and parameters derived from the literature, shown, in our case study, scarce correlations among the various parameters, making the resulting model relatively unusable. On the other side, a second, purely data-driven approach gave a perfect image of the state of the matter, which, possibly due to overfitting, was hardly generalizable to other cases. The mixed data-driven plus first principle approach presented in this paper provided the best trade-off between accuracy and generality. However, further studies are still necessary to consolidate the methodology and the possibility of including more indicators, as stressed in Section 5, will contribute to mitigating the elements of uncertainty.

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