Urban Form and Sustainability: Modelling Evidences From the Empirical Case Study of Rome

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URBAN FORM AND SUSTAINABILITY: MODELLING EVIDENCES FROM THE EMPIRICAL CASE STUDY OF ROME

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1. INTRODUCTION

It is widely accepted that a connection exists between the shape, size and density of an urban area and its sustainability. However, consensus is lacking about the extent and characteristics of this relationship. Certain urban forms appear to be more sustainable in some respects, for example in reducing travel, but unfavourable in other aspects, as the environmental quality or social inequalities; furthermore, some forms may be sustainable locally, but not at the city wide scale (Burton et al. 2013). A number of empirical studies dealing with the influence of urban form on sustainability has not been conclusive and comes out with mixed outcomes.

In order to provide empirical insights to this debate, this study investigates the relation between urban form and sustainability in terms of economic, social and environmental characteristics of the transport-land use integrated system, by comparing three different urban forms: compact, TOD and sprawl. The main research question is: does urban form, in terms of density and distribution of activities, impact the sustainability levels of urban areas?

To give an answer to this question, the paper proposes a methodology for assessing urban forms, based on a system of Land-Use and Transport Interactions (LUTI) models. This has been designed and applied able to simulate the behaviour of both dwellers and transport users and how they react to changing conditions. A system of indicators has been then set up to systematically test and compare three urban scenarios, which differ in terms of density and distribution of activities and to assess to what extent different urban structures achieve or not sustainability in terms of economic, environmental and social impacts. More details are provided in the methodological section.

This study presents some innovations points with regard to the existing literature. First, while already existing studies mainly focus of the assessment on a single urban form (with the exception of some more recent studies, Echenique et al., 2012), in this study we compare three urban structures.

An additional difference with present literature is that most studies focus on small scale and local factors influencing travel behaviour and its consequence on sustainability level, while in this research we analyse the interaction between urban form and sustainable travel behaviour at the city wide scale.

Finally, another novelty regards a specific application of utility based models, which are usually used for simulate the LUT system performance in terms of transport network speed or congestion. In this study we instead integrate them in a scenario analysis and in particular addressing sustainability and equity issues as managing the side effects of growth such as sprawl, congestion, housing affordability, pollution, energy consumption and loss of open spaces. In this way, we do not examine the effect of urban form only by parameter of travel (distance, time, frequency), but we propose a more complete sustainability assessments. Nevertheless, it is important to stress that in this study we do not take into account health and well-being aspects of sustainability, putting this focus off at future steps of the research.

The paper is organized as follows. In Section 2 we refer to the existing literature and to the debate on the relations between urban form and sustainability. Section 3 describes the research design and in particular the system of models and the assessment indicators system. In Section 4 we discuss the results of the application to the empirical case study of Rome. Conclusions are drawn in Section 5.

2. LITERATURE REVIEW: COMPACT, TOD AND SPRAWL URBAN FORMS AND SUSTAINABILITY

A substantial body of literature exists on sustainable urban form aimed at defining if and to what extent certain urban forms contribute more than others to sustainability (Breheny 1992; Jenks at al., 1996; Williams et al., 2000; Jabareen, 2006; Banister, 2008). However, the debate whether a particular shape, a density threshold or an activities distribution can have an impact on the mobility behaviour and on cities sustainability is still undergoing (Jenks and Jones, 2010; Echenique et al., 2012). In fact, a number of studies dealing with such issues have not been conclusive in identifying determinants for a more sustainable urban form of cities.

The big interest on this topic is related on one side on the fast growth of world cities, and their changing spatial structure from a more compact towards polycentric or fragmented shapes; on the other side urban and transport planners have been trying to understand if different urban forms can and to which extent have impact on city sustainability levels in order to define how a measure of sustainability can be achieved.

Within this context, three specific urban structures have been assessed and studied in literature: the compact, the TOD and the sprawl urban forms.

The compact city model has received much emphasis in these debates, in which it has been discussed that urban intensification, high-density development, and mixed-use development strategies to support travel behaviour changes by enabling people to live near their workplaces and amenities and thus reducing travel distances. In the EU Green Paper of the Urban Environment, this model was advocated as the most sustainable for urban development (Commission of the European Communities, 1990) and according to several researches (Newman and Kenworthy, 1999; Næss, 2013), compact cities can promote sustainability by limiting the losses of surrounding natural and agricultural areas; reducing the amount of travel, car dependency and energy use for transport; reducing energy use; limiting the consumption of building materials for infrastructure; and maintaining the diversity and possibilities for choice among workplaces, service facilities and social contacts. Other studies state, on the other hand, that compact developments can cause severe congestion in transport network, increase land and dwelling prices and create social exclusion (Breheny, 1997; de Roo and Miller 2000; Neuman, 2005). In fact, while compactness may result in shorter distances to be travelled, quality of life could decline to a significant degree due to the intensification of traffic and emissions (Barter 2000), also with direct negative health impacts. In addition, it has been discussed that reinforcing compactness may result in a reduction in affordable housing, thus causing higher housing costs and creating a less sustainable city in social terms (Boschmann and Kwan 2008).

Another urban form that has been studied in literature is the Transit Oriented Development (TOD), based on corridor developments along transit lines and on concentration of higher densities in stations areas, which are characterized by higher accessibility by public transport. This model which can enable highcapacity and high-quality public transport service along a linear form or ‘‘polynucleated urban forms’’ (Jenks and Burgess 2000; Williams et al. 2000; Givoni and Banister, 2010; Bertolini et al., 2012; Knowles, 2012;). Some authors assert that TOD is the most able to reduce car use and travel distances and conserving land (see review in Cervero et al., 2002; Lund et al. 2006; Arrington and Cervero, 2008; Houston et al., 2014), to reduce commuting distances and times and to stimulate non-motorized travel (Curtis and Olaru, 2010). On the other hand, other factors as housing type and tenure, local and sub-regional density, bus service level, and particularly parking availability, have been claimed by some to play a much more important role on car use than proximity to transit (Chatman, 2013). Furthermore, yet others argue that TOD impacts on travel behaviour are also, if not mainly dependent on personal characteristics such as travel-related attitudes (De Vos et al., 2014). Furthermore TOD strategies have some commonalities with the compact city model since they also propose density and diversity in development as the main elements of the built environment, and in this way could have its same disadvantages: increase of housing costs and consequent public welfare trade-off.

As regard sprawl urban structure, most studies agree that this urban form induces auto-oriented lifestyles and higher urban management costs (e.g. energy distribution, waste collection, etc.) loss of green space, high cost of infrastructure and energy, increased social segregation, and is accompanied by intensive travel movements and associated environmental effects (Camagni et al. 2002; Westerink et al. 2013). In other words, the “sprawl costs” literature mentions many negative impacts of sprawl (Frank et al., 2000): the more clear ones are related to green land and farmland lost, while most controversial impacts of sprawl are those linked with transport (Travisi et al. 2010). However, some arguments can be defined in favour also of the sprawl: the reduced impact on people of emissions which grows with density (the canyon effect), reduced congestions, reduced housing prices because of less building constraints, and also the possibility of large retail stores lowers prices. In fact, as stated in the most comprehensive review of urban sprawl literature (Burchell et al. 1998), most of the 475 studies analysed concluded that sprawl could have both positive and negative effects

3. THE PROPOSED METHODOLOGY

The methodology used in this research follows three steps (Figure 1:

1. Scenarios design. In this phase development scenarios in terms of density and distribution of new built areas development, are defined for the study area, by means of evolution hypothesis, based on the three urban form models definition: compacts, TOD and sprawl;

2. Forecasting. In this phase, the scenarios are simulated by means of a system of LUTI models, that have been previously calibrated, in order to forecast the three different options ;

3. Assessing. In this phase the scenarios are evaluated across three assessment domains: economic, environmental and social.

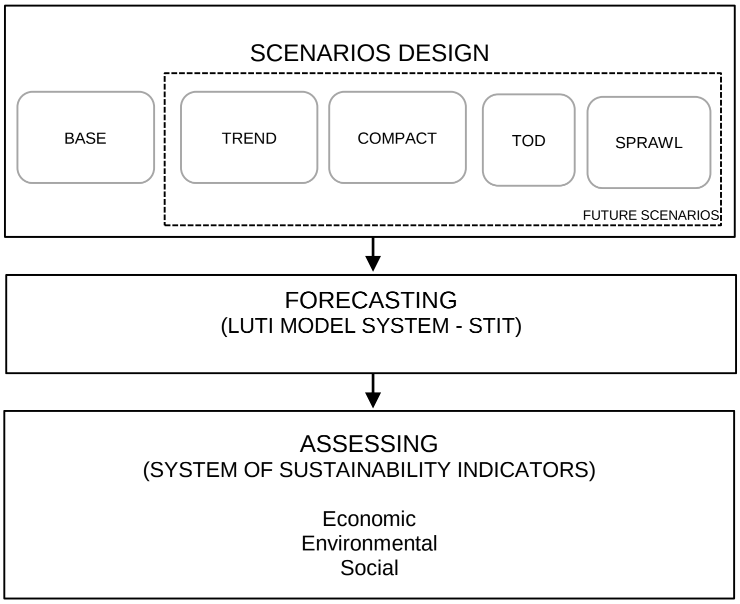


Figure 1. The three steps approach of the research methodology

3.1 Scenarios design

In this phase the study area is first divided into traffic analysis zone (TAZs), to which geo dataset are linked. The scenario setting phase consists in the database design for different hypothetic development scenarios for each TAZ, according to a different distribution of new built up areas, but maintaining the same city-region-wide totals. In the same way the transport network is designed for each different evolution scenario, defining the road system, new locations of stations and the design of the new infrastructures and services of the regional, suburban, metro, tram lines.

Scenarios are based on the three different urban patterns that are also the most debated urban morphologies in literature (see par. 2):

- “Compact” scenario, characterized by a clustering of high density areas in the most central location of the city;
- “TOD Transit Oriented Development” scenario, characterized by activities clustering around the rail-based public transport system;
- “Sprawl” scenario, characterized by a market-led dispersal of activities in peripheral areas.

Two more scenarios were developed to be used as benchmarks in the assessment phase:

- “Base” scenario (BS) referred to the current situation;
- “Trend” scenario, that corresponds to the evolution of the current situation, according to the plans for land use and transport by the city government.

3.2 Forecasting

The second phase is the scenarios forecasting, developed by means on a LUTI models system (Figure 2) that simulate the behaviour of dwellers and transport users and how they react to changing conditions.

The LUTI model STIT (Coppola and Nuzzolo, 2011) is here used for the simulation of the interactions between Transport and Land Use systems: the location choices of residents, of private and commercial businesses through random utility theory, and their interactions with the transport system.

The models allow forecasting the impacts that new built areas and new transport supply have on the spatial distribution of economic activities (such as services and retail) and on the population, as well as on real-estate property values. At the same time, it simulates the future transport demand flows and transport networks performance, which are consequent to future distribution of activities.

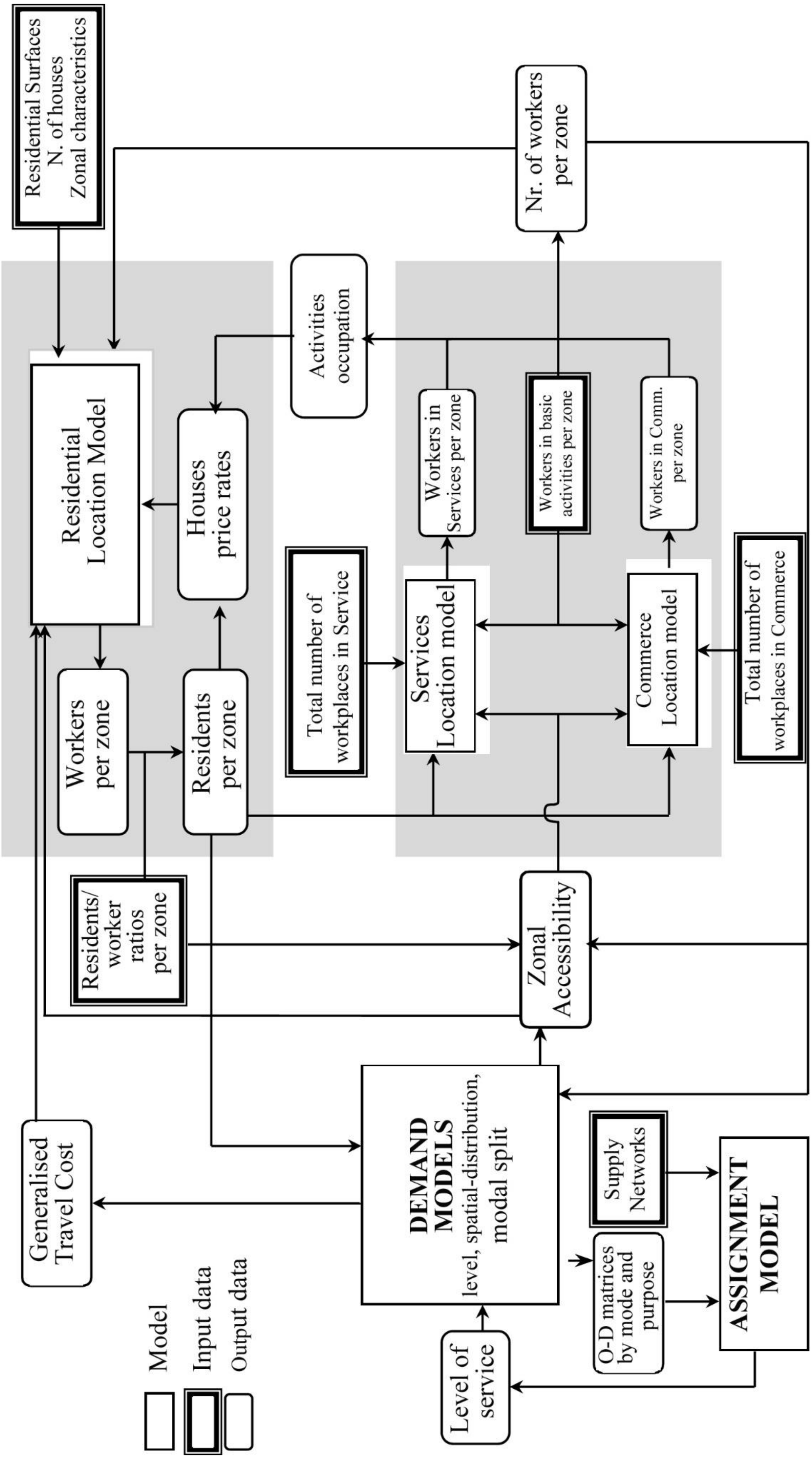


Figure 2. Schematic representation of the LUTI models system (Coppola and Nuzzolo, 2011)

In more details STIT consists of the following models:

- Supply models, for the estimation of the level-of-service attributes of both private and public transport modes;
- Demand models, for the estimation of the Origin-Destination (OD) trip matrices by mode and trip purpose;
- Assignment models, that estimate the flow on multimodal transport network;
- Residential location models, that allows to estimate the spatial distribution of resident in the study area and the variation of housing prices by zones, by simulating the residential location choice of the population;
- Service and commerce location model, that allows to estimate the spatial distribution of service and commercial activities in the zones of the study area, simulation the location choices of the firms.

The input of the models, for each scenario and each TAZ are: the total number of jobs in commerce and in service; the number of jobs for services in public sectors for each TAZ (whose locations doesn't change in the different scenarios); the resident/jobs ratio per TAZ; the surface of housing, the number of houses and zonal characteristics (i.e. house prices) per TAZ.

The outputs of the models for each scenario and each TAZ are: the number of ingoing and outgoing trips by mode and purpose, the accessibility level, the ingoing and outgoing generalized travel costs, the number of inhabitants, the number of jobs in commerce and private services.

3.3 Assessing

The third phase consists in the assessment of the model outputs, across three main evaluation domains: economic, social, environmental.

The economic domain is measured by three indicators measuring the performance of the transport network and in particular:

- Travel time by car (weighted by travel demand);
- Travel time by public transport (weighted by travel demand);
- Construction costs for new infrastructures and houses, beingthe latter estimated by distinguishing between housing typology costs, and taking into account the different values of the areas, and the urbanization costs for suburban areas.

The environmental component is measured by five indicators:

- Land development, in terms of new built up areas and infrastructures, taking into account different typologies of housing (single house, four, eight and ten floors building);
- Inhabitants and jobs density in the city centre;
- Commuting trips by car and motorbike
- Commuting trips by public transport;
- CO2 emissions and energy consumption deriving from car use.

The social domain is measured by means of four indicators:

- Accessibility to job by car, using a gravity based measure to jobs (Hansen, 1959) as a proxy for the ease of reaching jobs opportunities located in the traffic zones of the study area by car;
- Accessibility to job by public transport, using a gravity based accessibility measure to jobs, by public transport;
- Accessibility inequality by public transport, being measured as the Gini coefficient for accessibility to job by public transport: the closer the indicator is to 1, the more unequal is the accessibility distribution.
- Housing property values in the city centre, as a proxy of social inequality deriving from increase of property values in the most lively and dense-of-activities part of the city.

4. APPLICATION TO THE METROPOLITAN AREA OF ROME

The designed methodology was applied to the urban area of Rome, with the aim of testing the developed methodology and of contributing to the ongoing debate on the future development of the city, compared to what is planned by the City Master Plan (CMP).

The study area here analysed reaches 2.8 million inhabitants over 1,285.3 km^2 and 1.1 millions of jobs, contributing to about 552,000 commuting trips in the morning peak hour. The structure of the city is strongly mono-centric and it can be split into circular rings with increasing densities approaching the city centre.

A circular freeway of approximately 68 km of length delimits the densest and populated area of the test area that reaches an average density of population of about 70 inhabitants per hectare and an average job density of about 75 jobs per hectare. Within the GRA, population and activities are mainly located along radial roads to and from the city centre that correspond to the old access roads of the ancient roman town. The transit system consists of two radial metro lines extending for a total of 36 km, with a single interchange in the central station. Other seven regional rail lines connect the surrounding urban areas to the city centre. As regards the car use, Rome has a very high level of automobile ownerships (more than 700 per 1,000 persons) and the road network is highly congested. In large part of the historical centre, access by car is permitted only to the residents.

The Base Scenario (2011) was set using data Census and documents and previous research produced by the Municipality of Rome (Agency of Mobility). The design of future scenarios required some assumptions on the evolution of the number of residents and jobs as well as of the development of transport networks and housing stock. The total expected number of residents and jobs, was estimated for the year 2031, according to the demographic evolution of the Municipality Rome forecast by the Italian National Statistical Institute (ISTAT).

Table 1. Increase of new built-up areas in different scenarios and in the five concentric ring of the study area w.r.t. the Base Scenario

	New built-up areas				
Scenarios	**city center (ring1)**	**ring2**	**ring3**	**ring4**	**suburban periphery (ring5)**
	(ha)	*(ha)*	*(ha)*	*(ha)*	*(ha)*
CMP- City Master Plan	-	0.54 (+0.03%)	30.03 (+0.77%)	185.98 (+9.68%)	947.67 (+48.03%)
Sprawl	-	-	-	-	1164.22 (+59.01%)
Compact	-	585.31 (+32.53%)	578.91 (+14.90%)	-	-
TOD_A	-	-	437.54 (+11.36%)	564.07 (+29.36%)	162.61 (+8.24%)
TOD_B	-	-	-	636.91 (+33.15%)	532.26 (+26.98%)

With regards to the new housing stock, the total number of additional housing units (i.e. square meters housing) was kept fix in each future scenario (i.e. equal to 11.6 million square meters as forecast by the City Master Plan), whereas the distribution among the zones varies (Table 1).

In Figure 3 the increase of built up areas are shown with regard to the Base Scenario, in the City Master Plan, Sprawl, Compact and in two different TODs scenarios, as also reported in Table 1, which shows the different distribution of built up areas in the five concentric rings of the metropolitan area and the percentage variation with regards to the Base Scenario.

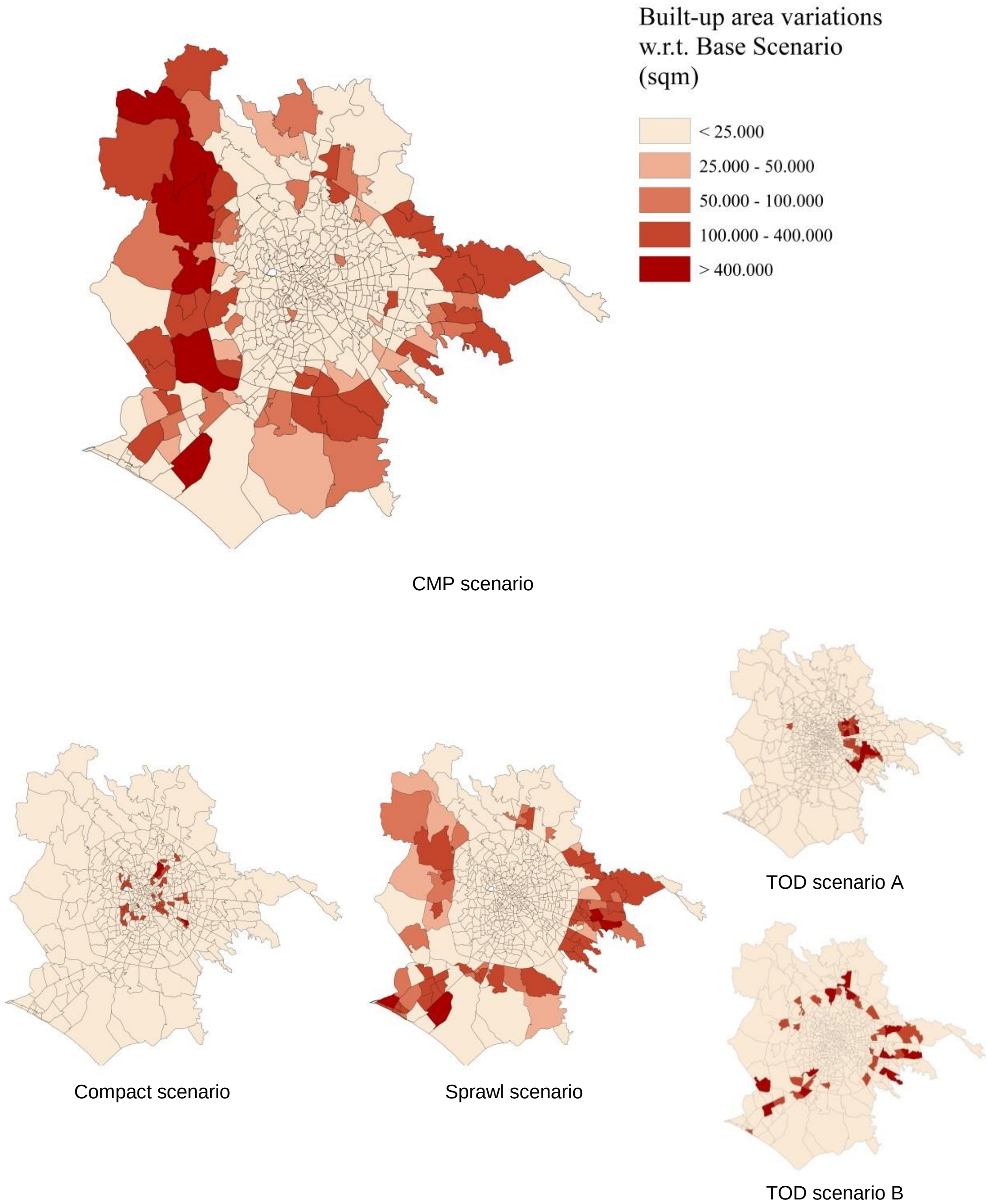
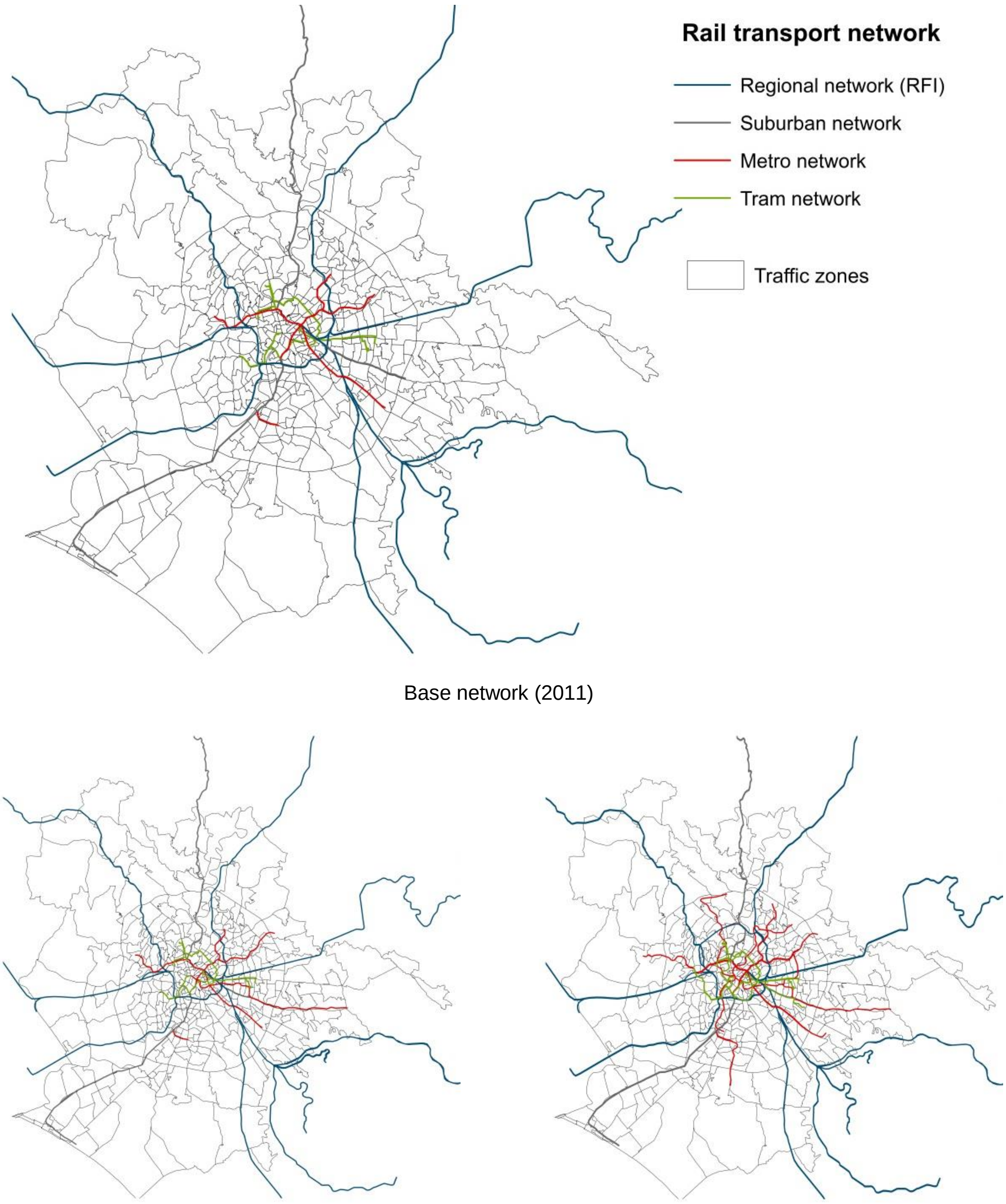


Figure 3. Built-up area differences in the different scenarios w.r.t the Base Scenario.

Two different public transport networks (including regional, suburban, metro and tram lines and stations) were considered in the simulation of future scenarios (Figure 4):

- Complete network (C), consisting of all the projects including in CMP;;
- Partial network (P), including a subset of projects (already funded) of the (complete) CMP network.



Base network (2011)

Partial network

Complete network

Figure 4. Zoning with base rail network (2011), Partial and Complete rail network

In total, eight scenarios of future spatial developments were designed (Table 2), assuming different distributions of built-up areas and of transport networks.

Table 2. Spatial development scenarios in the application to Rome

		DIFFERENT TRANSPORT NETWORK		
		Base network (2011)	Partial network	Complete network
Different distribution of built-up areas	Base scenario (2011)	BS		
	City Master Plan CMP		CMP_P	CMP_C
	Compact		COMPACT_P	COMPACT_C
	Sprawl		SPRAWL_P	SPRAWL_C
	TOD		TOD_A_P	TOD_B_C

The second step of the application consisted of the simulation of the designed scenarios, and finally in the computation of the economic, environmental and social indicators previously identified (tables 3 and 4).

Table 3. Comparison of scenarios with partial rail network w.r.t trend scenario with partial network

Domain	Indicator	Units	CMP scenario	Δ% from CMP scenario _P		
				Scenarios with Partial network		
				Sprawl_P	Compact_P	TOD_A_P
Economic	Travel time by car	Minutes	32.8	2.0%	-2.1%	-2.3%
	Travel time by public transport	Minutes	30.3	-0.6%	-8.9%	-6.0%
	Construction costs	Million Euro	14,916	44%	-5.0%	-4.0%
Environmental	Land development	Milliion m^2	5,586	159.0%	-15.7%	-0.3%
	Density in the city center	(Inh+jobs)/ha	188	-10.7%	17,1%	-0.30%
	Commuting trips by car and motorbike	n	271,582	-5.7%	-12.4%	-8.3%
	Commuting trips by public transport	n	84,563	-4.9%	18.0%	6.2%
	CO2 emissions deriving from car use	Tons	792	-7.6%	-24.4%	-17.0%
Social	Accessibility to job by car	index	39.7	-8%	12.6%	12.6%
	Accessibility to job by public transport	index	19.7	-2%	24.8%	18.8%
	Accessibility inequality by public transport	index	0.4	-10%	-67.3%	-45.2%
	Housing property value in the city center	index	51.7	-15.3%	10.3%	-5.0%

Table 4. Comparison of scenarios with complete rail network w.r.t trend scenario with complete network

Domain	Indicator	Units	CMP scenario	Δ% from CMP scenario_C Scenarios with Complete network		
				Sprawl_C	Compact_C	TOD_B_C
Economic	Travel time by car	Minutes	34.7	18.4%	-19.9%	-19.7%
	Travel time by public transport	Minutes	31.0	-6.2%	-12.4%	-8.0%
	Construction costs	Million Euro	23,660	28.0%	-3.0%	-1.0%
Environmental	Land development	Milliion m^2	7,770	114.5%	-11.2%	-0.2%
	Density in the city center	(Inh+jobs)/ha	186	-12,6%	20.80%	-2.7%
	Commuting trips by car and motorbike	n	255,877	-0.7%	-7.8%	-1.9%
	Commuting trips by public transport	n	98,836	-17.8%	3.6%	-12.0%
	CO2 emissions deriving from car use	Tons	741	-13.5%	-26.2%	-15.4%
Social	Accessibility to job by car	index	35.8	20.4%	47.6%	39.6%
	Accessibility to job by public transport	index	21.5	-4.9%	23.1%	8.5%
	Accessibility inequality by public transport	index	0.6	-8.3%	-68.3%	-9.3%
	Housing property value in the city center	index	51.8	-18.7%	15.9%	-7.2%

With reference to the economic goal, the compact scenario present all ameliorative indicators values with regards to the correspondent Master Plan scenarios with both partial and complete network extensions. In fact to the compact scenario correspond the major reduction in travel time by car (-2.1% with partial network and -19.9% with complete network) and in travel time by public transport (-8,9% with partial network and -12.4% with complete network). Also to TODs scenarios correspond a reduction of travel time in relation to the Master Plan scenario and in particular with the partial network (-2.3%). Similarly the other percentage variations are ameliorative and alike to the compact scenarios values. On the other hand the sprawl scenarios are characterized by an increase of travel times by car (+2.0% with partial network and +18.4% with complete network). Travel times by public transport in the sprawl scenario with the partial network are almost the same estimated in the Master Plan scenario and travel time is also reducing but with a lower value (-6%) with the complete network. As regards the construction costs for new built up areas and infrastructures, compact and TOD scenarios consent some cost reduction (-5% with partial and -3% with complete network) compared to the Master Plan, while the sprawl scenario present a great increase of construction cost, related to new primary and secondary urbanization structure's costs (+44% and +28% respectively with partial and complete networks).

In relation to the environmental goal, compact scenario again presents the best ameliorative assessment in comparison to the TOD and sprawl scenarios, with the exception of the increase of activities density in the city centre. Sprawl scenario is characterized by the highest land consumption, i.e. more that 100%, whereas in compact and TOD scenarios, land consumption is respectively -15.7% and -0.3%. Same pattern arises with the complete network extension. Jobs and inhabitants densities in the city centre increase significantly in the compact scenario (+17,1% and +20.80% respectively with the partial and the complete network) with the negative consequent of having more population exposed to noise and local pollution (since the city centre is the most congested area of the city), and, consequently, direct negative health impacts. In the TOD scenario the reduction of density is -0.30% with the partial network and -2.7% with the complete network. The sprawl scenario on the other hand would allow a reduction of densities in central areas (-10.7% with the partial network and -12.6% with the complete network) with regards to the Master plan scenario. As regard the modal share, in the three scenarios with the partial network the car share is less that in the Master Plan scenario, and in particular the car trips are decreasing more in compact scenario (-12.4%), followed by the TOD scenario (-8.3%) and finally by the sprawl scenario (-5,7%). Also with the complete network the trend is similar but with smaller values. As regards the public transport trips, the compact scenario correspond to a higher value of public transport use, with an increase of +18% with partial network and +3.6% with the complete network. In TOD scenario the public transport trips are more than in the Master plan (+6.2%) only with the partial network, while is reducing (-12%) with the complete rail network. In the sprawl scenario, commuting trips by public transport are always less than in the Master Plan, both with the partial network (-7.6%) and with the complete network (-17.8%). Finally, as regard the CO2 emissions and energy consumption deriving from car use, the compact scenario shows the best results with a reduction on -24% with the partial network and -26.2% with the complete network. Also the TOD and the sprawl are ameliorative, but the sprawl scenario reductions are less significant (-7.2% with the partial and -13.5% with the complete network).

As regard the indicator measuring the social goal, the compact scenario shows the highest increase of accessibility levels by public transport (+24.8% with the partial network and +47.6% with the complete network), the highest decrease of accessibility inequality and the highest transport inequality decrease (-67.3% with partial and -68,3% with complete network). Also in the TOD scenarios the level of accessibility by car and by public transport increase (+12.6% by car and +18.8% by public transport with the partial network; +39.6% by car and +8.5% by public transport with the complete network). In the sprawl scenario accessibility by car and public transport reduce with the partial network, while increase with the complete network, but in any case with lower percentage than compact or the TOD scenarios.

On the other hand, a social disadvantage related to the compact scenario is the great increase of housing property values in central areas consequent to further densification in the city centre (+10.3% with the partial network and +15.3% with the complete network), whereas are reducing in the sprawl scenario (-15.3% with the partial network and -18.7% with the complete network) and with a smaller percentages also in the TOD scenario (-5.0% with the partial network and -7.2% with the complete network).

Finally, figures 5 and 6 show a comparison of the two groups of indicators for the partial transport network and for the complete network. It can be observed that no significant difference emerges within the three different urban form scenarios, with the exception of the land consumption impacts(much higher in the sprawl scenarios). Moreover, a big difference on environmental effects and travel behaviour occur when changing the extension of the transport network. In other words, the percentage variations are amplified when the transport network is more developed and more connected. This seems to be coherent with some literature (Mees, 2010), stating that the bigger impact on travel behaviour is given by network supply and connectivity, instead than by the density distribution of activities.

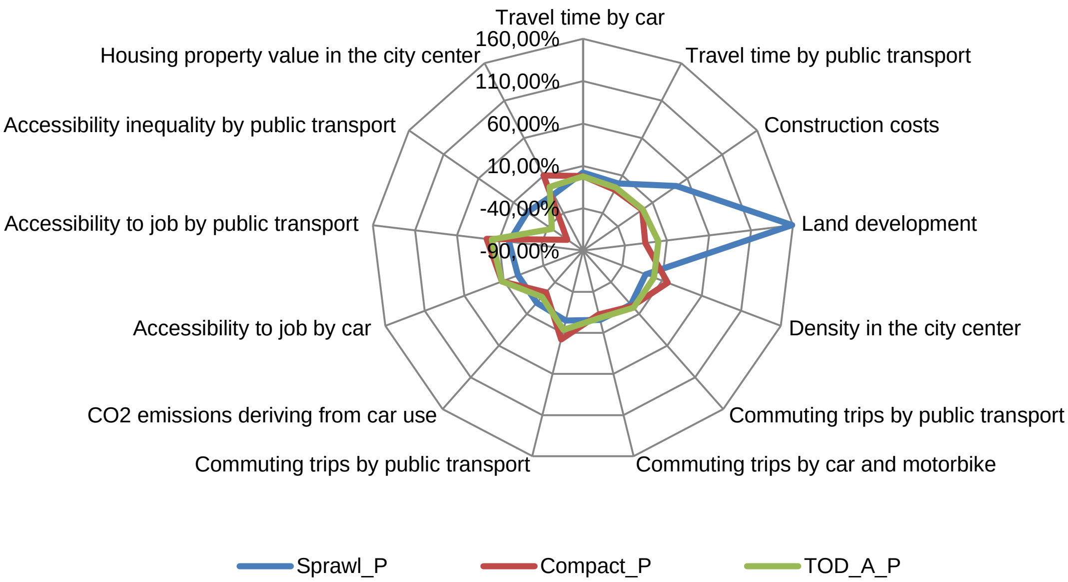


Figure 5. Comparison of compact, TOD and sprawl urban form according sustainability criteria (Partial scenario)

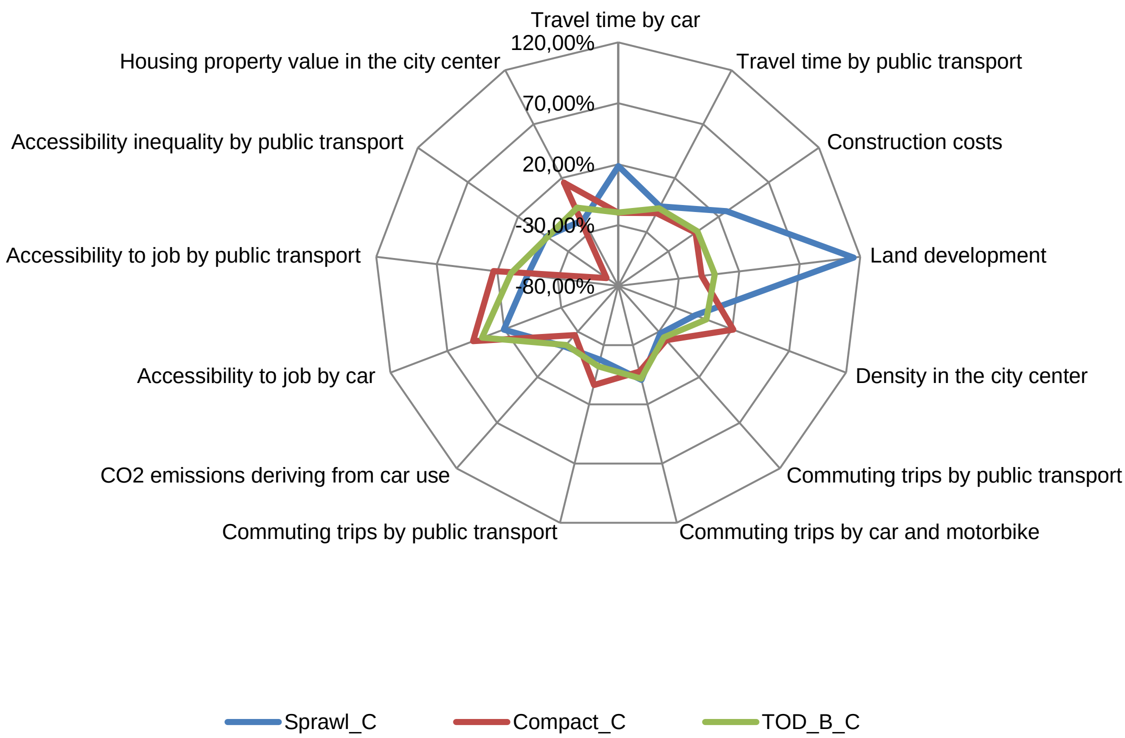


Figure 6. Comparison of Compact, TOD and sprawl urban form according sustainability criteria (Complete scenario)

5. CONCLUSIONS

Based on integrated land-use and transport modelling architecture, the research provides empirically based insights on the relation between urban form and sustainability, in terms of economic, environmental and social goals.

Different scenarios of urban development have been assessed for an empirical case study, with respect to transport network performance as well as social and environmental impacts. Results show that at the city level different urban development forms (i.e. compact, sprawl, TOD) have found to differ in their sustainability, and in particular the compact development appears to better off others form of spatial development. However, compact development imply an increase of urban congestion level and also an increase of dwelling prices in some areas of the city, which could create social exclusion and segregation of peripheral areas.

Moreover, the results of the simulations carried on, have been here discussed using average values for the entire urban areas, whereas more noticeable impacts and different trends will be estimated at a smaller scale, focusing on impacts at the scale of single neighbourhood.

No big differences between the sprawl and the Master Plan scenarios are proved in our analysis in respect to some indicators, as the variation of commuting trips by car or by public transport, or the travel times by public transport and the accessibility values. This can be explained by the fact that the Master Plan scenario is similar to the sprawl scenario, in terms of distribution of activities and services in peripheral areas of the city.

Another consideration regards the use of accessibility indicators for scenarios assessment. The classic transport performance indicators, as the travel time reductions in the three scenarios are not substantially different, whereas changing accessibility values can be observed. From the comparison of the classic transport performance indicator and the accessibility ones, it is clear that the first cannot be conclusive in an integrated transport and and-use planning analysis; this should rather be accompanied also by accessibility and other social-oriented indicators.

ACKNOWLEDGEMENTS

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