Sustainability Model for the Valsequillo Lake in Puebla, Mexico: Combining System Dynamics and Sustainable Urban Development

Jorge A. Duran-Encalada
Business Administration and Marketing Department
Business and Economics School
Universidad de las Américas Puebla
Sta. Catarina Mártir, Cholula
72820 Puebla, México
jorgea.duran@udlap,mx

Alberto Paucar-Caceres
Manchester Metropolitan University Business School
Aytoun Building, Aytoun Street, Manchester, M13GH, UK
a.paucar@mmu.ac.uk

Abstract

This paper reports on an on-going project on urban sustainability of the Valsequillo Lake in Puebla, Mexico and the Puerto Aura to be developed in this region. The purpose of the study is to build a simulation model to explore the dynamic interaction of the dimensions inherent in sustainable urban development. After a systematic review of Sustainable Urban Development (SUD) frameworks and tools used in various part of the world, the paper designs a model that considers the variables that intervene in SUD and proposes a System Dynamics model to simulate the dimensions that intervene in a sustainable development of this type and to anticipate the consequences of the decision making process. The structure and inter-relationships of the model sectors are described, the sustainability indicators in each sector explained; preliminary conclusions are drawn stating that a complete run of the model simulating a 20 years horizon in monthly periods is expected when the full data from the Puerto Aura master plan becomes available.

Keywords: Sustainable development; urban planning; environmental assessment methods; system dynamics; simulation; multi-methodology

Introduction

This paper takes the view that sustainable development, especially, urban sustainable development is a complex issue and to tackle it, we need to take a systemic and holistic view. From this it follows that a combination or integration of methods and frameworks drawn from different fields of knowledge is increasingly necessary. Successful multi-methodological approaches have been reported in the systems, management science and operational research communities. Multi-methodology in Management Science is the name given to the practice that combines and links techniques, methods and methodologies from the same or different systems thinking paradigms, Mingers (1997a, 1997b), Mingers and Brocklesby (1996), Jackson (1997, 1999) amongst others. This practice is not alien to the System Dynamics (SD) community: over the last years there have been concerns and debate, amongst members of the System Dynamics community, about its links with other systems methodologies and about its philosophical principles, role and position within more wider theories, Lane (2000; 2001a; 2001b. Conceptually and methodologically, the paper can be seen as a contribution to the area of multi-methodological approaches in management science; the other aim of the paper is of course to report on a practical SD application on the important area of sustainable urban development. The conceptual framework of the paper is illustrated in Fig 1.

The paper reports on an on-going project on urban sustainability of a region in Puebla, Mexico: the Valsequillo Lake and the Puerto Aura to be developed in this region. The purpose of the study was, initially, to develop a simulation model to analyze the dynamism inherent in sustainable urban development. The paper considers the variables that intervene in a Sustainable Urban Development (SUD) and proposes a System Dynamics model to simulate the dimensions that intervene in a sustainable development of this type and in this way to anticipate the consequences of the decision making process. The horizon to be simulated is 20 years.

The structure of the paper is as follows: (1) some definitions and key issues relevant to sustainable development are introduced; (2) the role of local authorities in sustainable development is outlined; (3) some sustainable development proposals and initiatives from various countries (*Smart Growth* the *BEQUEST* amongst others) are discussed; (4) the main characteristics of the Puerto Aura project to be developed in the Valsequillo Lake region in Puebla, Mexico, are presented, describing the different areas included in the SUD conceptualization scheme of the project; (5) after reviewing different environmental impact assessment methods included in the *BEQUEST* toolkit, the *PROPOLIS* model is chosen as the most appropriate for the Puerto Aura project; (6) the suitability of systems dynamics modeling as the appropriate devise to explore the dynamics structure of the variables involved in sustainable urban development is then discussed; (7) the structure and inter-relationships of the model sectors, firstly in general terms, and later in detail, explaining the sustainability indicators in each sector is described; and finally (8) some conclusions are drawn stressing the fact that a complete run of the model simulating a 20 years horizon in monthly periods is expected when the full data from the Puerto Aura master plan becomes available.

1. Some definitions and key issues in sustainable development

The 1987 the Brundtland Commission on Environment and Development focused on the sustainability problem for the first time, defining sustainable development as a *'development that meets the needs of the present without compromising the ability of future generations to meet their own needs'* (WCED, 1987:43). According to Sachs, *et al* (1998), implicit in this statement, three values concerning intergenerational equity; the maintenance of constant natural capital; and international justice can be identified; and the key themes associated with these values are: (a) Eco-efficiency: how well natural resources are used and conserved; (b) eco-justice: how equitably the fruits of nature are distributed within and between generations; and (c) the precautionary principle, that is the need to adopt a of low risk criteria in decision making to avoid harm to future generations.

In 1992, at Earth Summit, held in Rio de Janeiro, the '*21 Agenda*' (a reference to the 21st Century) was set up, containing 27 principles on sustainable development. These set of principles attempted to tackle key issues of sustainable development in four areas that are interrelated: the environment; equity; participation; and futurity (Figure 2)

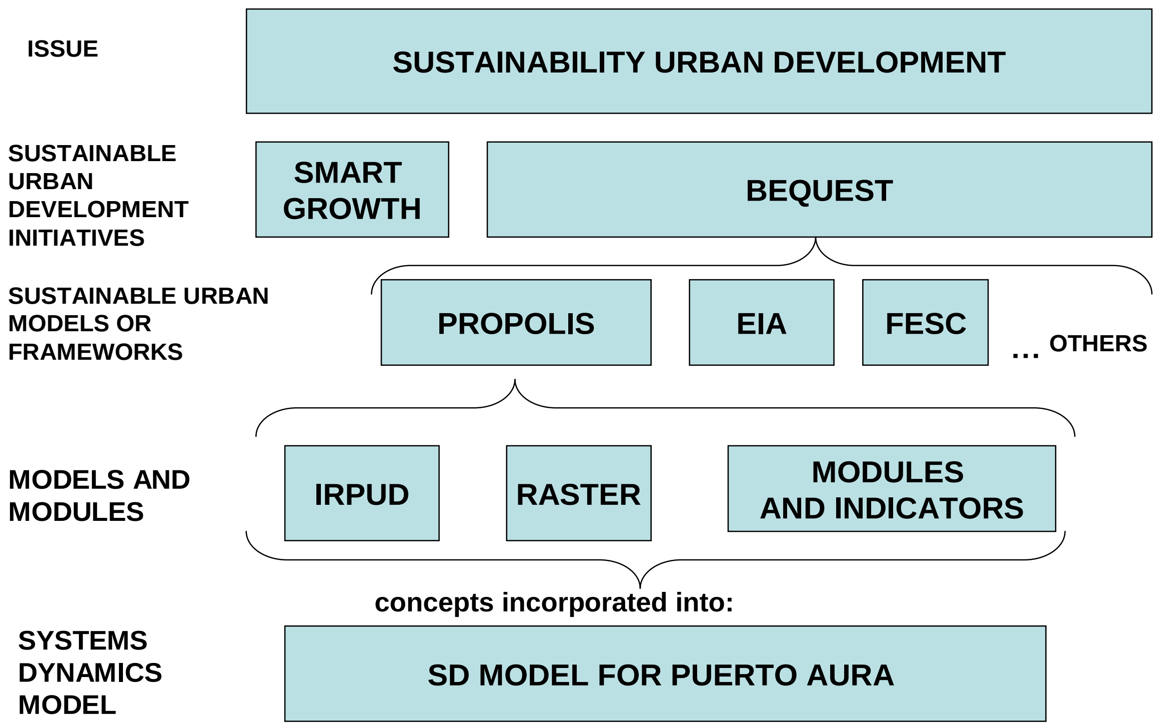
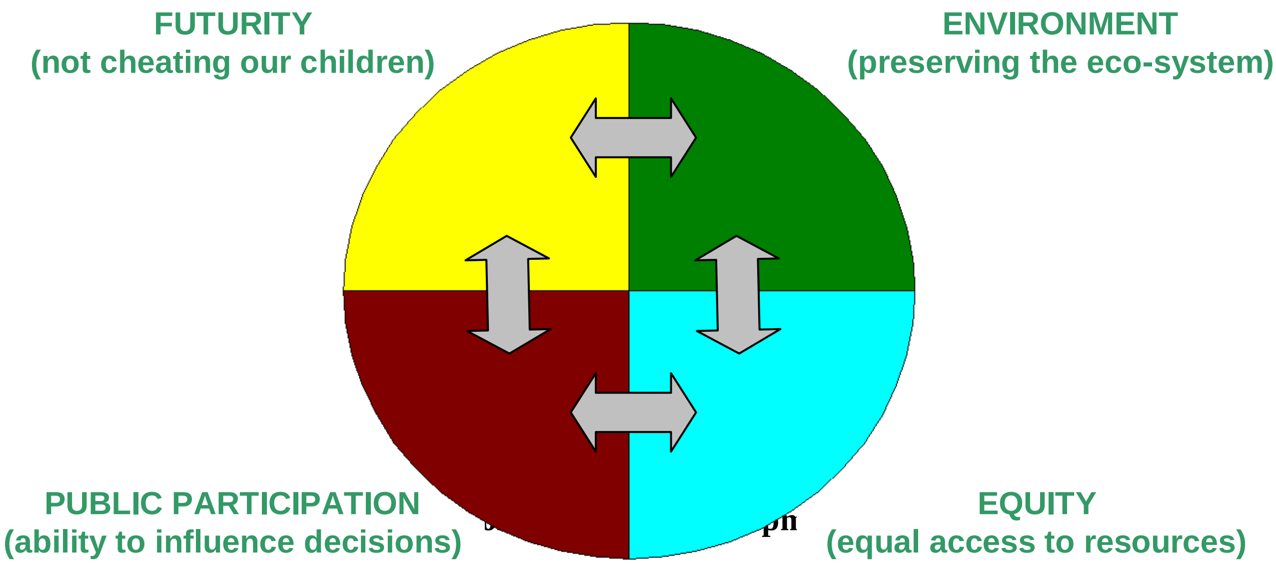


Fig. 1. Conceptual diagram of the Study: Combining System Dynamics and Sustainable Urban Development


FUTURITY
(not cheating our children)
ENVIRONMENT
(preserving the eco-system)
PUBLIC PARTICIPATION
(ability to influence decisions)
EQUITY
(equal access to resources)

In turn, each of these principles was defined in connection with its implications, for example: the principle *futurity* defined in terms of sustainable development entails the adoption of the guidelines such as:

- Renewable resources must not be consumed faster than the rate at which they are renewed.
- Non-renewable resources must not be consumed at a rate faster than that which they can be substituted for by a renewable resource.
- Waste substances must not be discharged to the environment faster than it can be assimilate them without impairment of ecosystem function.

2. Public Participation

Role of local authorities in sustainable development

As Figure 2 shows, one of the strands that contributes to a systemic definition of sustainable development is *Public Participation* and its role in influencing decisions. At a concrete level this takes the form of the role of local authorities on the sustainable development of their own communities. It is argued that municipalities can significantly advance community sustainability by building an infrastructure that meets green building standards, creating regulatory incentives which promote a sustainable economy, passing zoning legislation that establish sustainable patterns of land use, and procuring goods and services that meet environmentally and socially responsible standards (Quaid, 2002).

Based on the Rio *21 Agenda* and the experience of a large number of local governments, the International Council for Local Environmental Initiatives (ICLEI), a body that groups more than 6,000 municipalities around the world, developed a tool to assist local governments in their systematic efforts to develop sustainable communities. The tool consists of five steps for a municipal-led process towards sustainability (ICLEI, 2002):

(a) Establishing and effective and participatory process;
(b) Conduct a sustainability inventory;
(c) Set a community sustainability vision;
(d) Develop and implement a sustainability action strategy; and
(e) Monitor and evaluate progress.

3. Some Sustainable Urban Developments (SUD) proposals

Smart Growth initiative

From a much more urban perspective, in some European countries (mainly the UK and the Netherlands) and in the United States of America, a movement called '*Smart Growth*' emerged in the early 90s. This initiative proposed a set of principles which, to large extent, are aligned with the ICLEI proposed tool. *Smart Growth* principles have been explicitly adopted as part of the policy agenda by a growing number of local authorities in those countries (Tregoning, *et al.*, 2002).

The main purpose of Smart Growth is to improve quality of life in the cities by controlling and limiting urban sprawl. In order to achieve this, urban policy is based on achieving higher population densities in newly urbanizing suburbs, infilling and redeveloping mature areas and preventing very low-density estate-type development on the urban–rural fringe (Ibidem). The benefits expected from implementing these policies include: more efficient use of land, reduced car use and commuting distances, mixed land uses, reduced consumption of water and energy, greater efficiencies in the provision and use of infrastructural systems, improved variety of housing types, and greater housing affordability. Although in some cases an association between a higher density and these benefits is not clear enough (Alexander and Tomalty, 2002)[1], these initiatives allow us to observe the important role that local authorities can have on the sustainable development of cities and consequently on the quality of life topics.

BEQUEST

Building Environmental Quality Evaluation for Sustainability through Time (BEQUEST) is another important SUD proposal. BEQUEST is unique in that it bridges all scales of action from planning to component manufacture and it enables de various actors to see the full scope of the sustainable urban development problem (Kohler, 2002). BEQUEST is a Pan-European research initiative and was funded by the European Commission since its beginnings in the late 90's.

BEQUEST framework is composed of activities, sustainability issues, spatial levels, and time scales as shown in Fig. 3. Considering the issues of Sustainable Urban Development, the existing built environment is adapted over time in a way that supports more sustainable patterns of living and working. The various elements of sustainable urban development scope are depicted in en in Fig. 4.

According to BEQUEST, for a city to achieve Sustainable Urban Development, it needs to use resources in an efficient and equalitarian way, and within the environmental and social capacities from which the city itself depends on. BEQUEST has compiled a set of assessment methods that transcend the traditional environmental valuation techniques. Two general groups of methods (depicted in Table 1) are identified: (1) *environmental valuation'* -valuations of various types; and (2) *forms of sustainability assessment* - directed to value particular. The latter is in turn further divided into '*environmental appraisal'* (simple base-line classification) and '*environmental impact assessment'* (complex and advanced evaluations).

[1] A research undertaken by Alexander and Tomalty (2002) in 26 municipalities of British Columbia, Canada suggests that the density of communities is associated with efficiencies in infrastructure and with reduced automobile dependence, with the ecological and economic implications which flow from that. However, it does not necessarily correlate with greater affordability of housing or more access to green space.

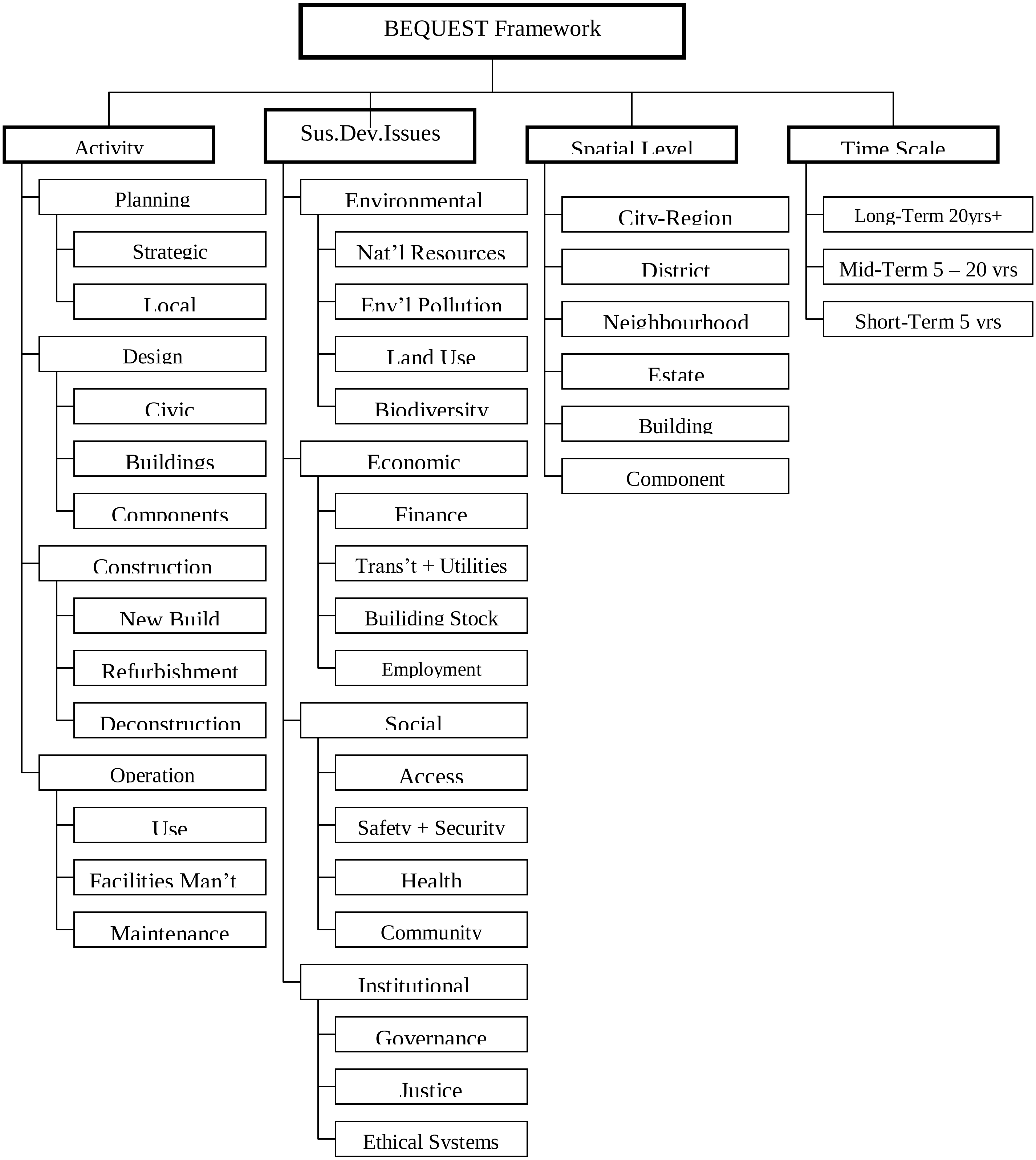


Figure 3. BEQUEST framework (from: Deakin, *et al.*, 2002: 176)

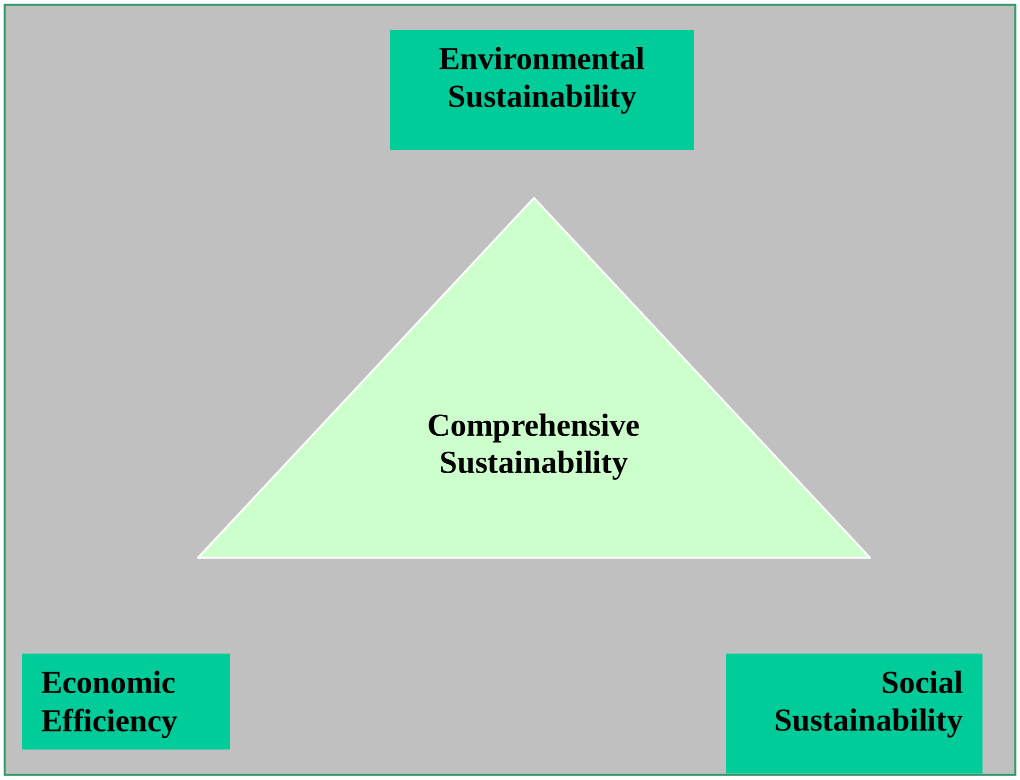


Figure 4. Sustainability dimensions (from: Lautso et al., 2004: 29)

Environment	Forms of Sustainability Assessment	
	Environmental Appraisal	**EIA**
Contingent valuation	Compatibility matrix	Project
Cost benefit	Eco-profiling	Strategic
Hedonic analysis	Ecological footprint	• Economic
Multi-criteria	Environmental auditing	• Social
Travel cost theory	Flag method	Community evaluation
	Spider analysis	BEES
		Eco-points
		Green Building Code
		MASTER framework
		Meta-analysis (Pentagon method)
		NAR model
		Quantitative city model
		Regime analysis
		SPARTACUS
		Sustainable city model
		Sustain. Communities
		Sustainable regions
		Transit-oriented settlement

Table 1. Environmental assessment methods (from : Deakin, *et al.*, 2002: 182**)**

Figure 5a maps the Assessment Methods considered by BEQUEST. The inter-related activities (planning, design, construction and operation) of the urban life cycle, sustainable development issues, spatial level, and time scales are represented in the map. It illustrates the strength of representation spread across the range the interrelated activities. The figure illustrates that it is the urban life cycle; sustainable development issues; spatial level; and time scales of the planning policy and infrastructure design activities, which are the most important forms of assessment represented in Fig. 5a.

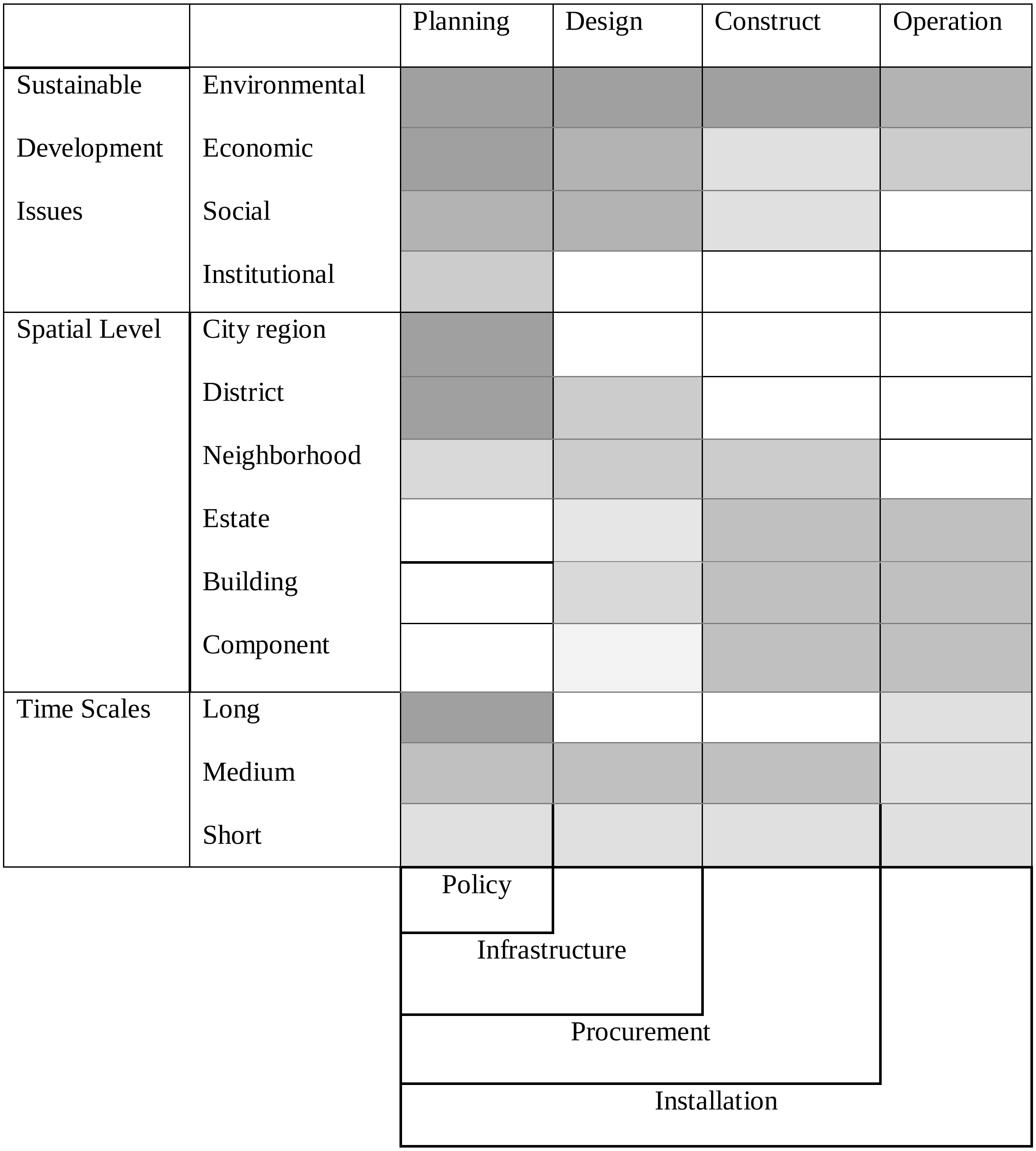


Figure 5a. Assessment methods

Note: The shading is indicative of the "intensity scores", or "frequency" by which the assessment methods address the sustainable urban development issues in question. (rom: Deakin, *et al.*, 2002: 183)

BEQUEST has also developed a toolkit as a tool for decisions support system; these depicted in Fig. 5b include:

(a) a common protocol for procuring a sustainable built environment;
(b) a directory of urban sustainability assessment methodologies;
(c) a directory of external advisors on assessment practice and protocol actions; and
(d) a common language and vocabulary developed within the network.

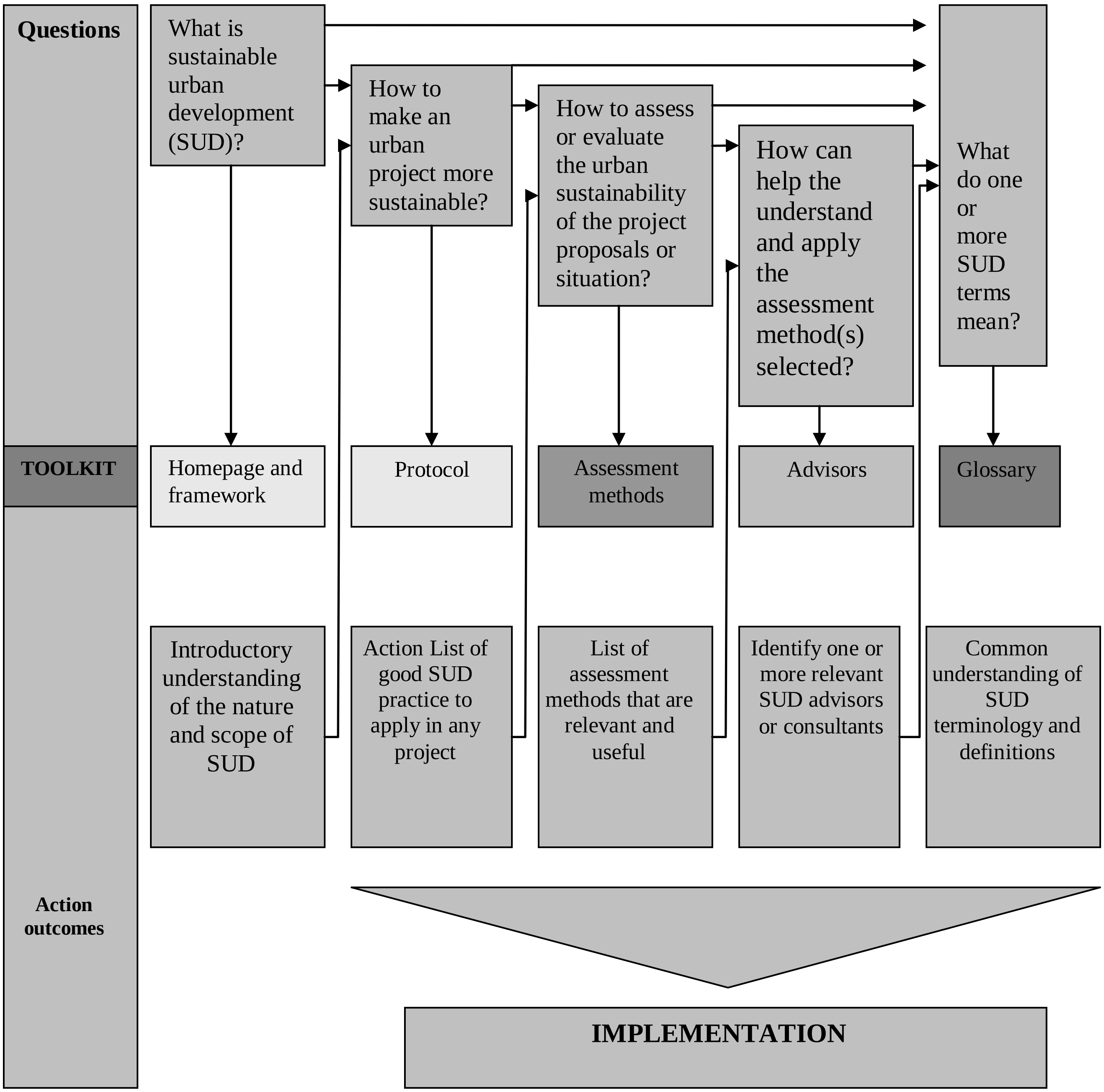


Figure 5b. Decision making using the BEQUEST toolkit (from: Hamilton, *et al*., 2002: 111)

In the following sections a description of the main characteristics of Puerto Aura Urban Development Project described the urban planners is outlined. Then an assessment of the SUD methods previously reviewed is outlined to identify the more suitable one.

4. The Puerto Aura project in the Valsequillo lake region.

The Puerto Aura project has been designed as a sustainable development surrounding the Valsequillo Lake in Puebla, Mexico. Current polluted conditions of the lake calls urgently for implementing actions to clean and rescue the lake. However, due to its proximity to the cities of Puebla (2 million inhabitants) and Atlixco (70,000 inhabitants), this development clearly shows urban characteristics. On the one hand, the area close to the lake has become an alternative for channeling the city of Puebla growth. On the other hand, the project could be an effective way to promote sustainable development for those communities already living in the area.

Although the project is still in an early phase, it has already been defined the characteristics under which development will take place. This development is depicted on the 'Lake of Valsequillo and surroundings' map shown in Figure 6; and includes the following areas:

- Hydrological micro-basin delimitation.
- Present and potential land use definition, based on the Protected Natural Areas (PNA) Bill.
- The Division into zones ('zoning proposal'); a proposal based on a thematic crossing matrix.
- Land usage characteristics proposed as "sustainable cells".

Zoning was developed using data bases provided by INEGI (Statistics, Geography and Information National Institute in Mexico) and the Planning Office of the State of Puebla Government.

The project area was divided in two parts: the 'micro-basin of the lake' and the 'zoning proposal' which was based on criteria set up in the Regulations of the Ecological Equilibrium and Environment Protection General Law relating to Protected Natural Areas (PNA, Article 49). These are shown on Fig. 7 and described as follows:

Nuclei zones, whose main purpose is the ecosystem preservation in the medium and long terms, and is composed of the following sub-zones:

- **Protection:** it refers to the land, within the protected natural area, which has been slightly impaired, as well as relevant or fragile ecosystems and natural phenomena that require a special care to ensure its preservation in the long term.
- **Restricted usage:** it comprehends the land in good conservation and where there is a will to preserve the ecosystem present conditions, moreover to improve them when this is required. Exceptionally, some commercial activities will be allowed to take place in this land as far as these do not modify the ecosystem and are subjected to strict control rules.

Buffer zones, whose main objective is to ensure that commercial activities taken place in the area are directed towards sustainable development, establishing at the same time the necessary conditions to achieve ecosystem conservation in the long term. This zone is composed by the next sub-zones:

- **Traditional use:** it consists of the land where natural resources have been used in a traditional and continuous way without impairing substantially the ecosystem. These activities are related mainly to satisfying socioeconomic and cultural needs of the inhabitants of the protected zone.
- **Sustainable provision of natural resources:** these are the lands where natural resources can be taken advantaged of and that due to the use and conservation needs in the long term, it becomes necessary that productive activities are done under sustainable provision schemes.
- **Sustainable provision of agro systems**: land which is used at present for agricultural and cattle uses.
- **Special provision**: land, generally with a small extension, that possesses natural resources which are essential for social development and these should be exploited without causing damage to the ecosystem, modifying the landscape substantially, nor causing irreversible environmental impacts.
- **Public usage:** this is a land with natural attractions for leisure and recreation activities, where it is possible to bring a large number of visitors as far as they do not exceed the ecosystem capacity.
- **Human settlements:** land where there is a substantial modification and the original ecosystem has disappeared due to human settlements that took place before the land was declared as protected natural area.
- **Recovering:** it is the land where natural resources have been severely damaged o modified, and has become the main objective of recovering and regenerating programs.

Based on the aforementioned criteria, an architectonic urban plan has been undertaken. This plan designates land usage in a study area of 119,681 acres and a project area of 54,325 acres. For the area concerning the project, a polygon was traced with a conceptual zoning proposal which considers the methodology to build a protected natural area in which different ‘sustainable cells’ are envisaged. This is shown in Figure 8.

- High level ecological hotel infrastructure
- Thematic parks
- Business center
- Sports area
- 1 and 2 medium level residential zones
- 1 and 2 high level residential zones
- Master EMU (environmental managed unit)[2]

A set of measurements criteria of the planned project for both occupied and built surface, are presented in Table 2.

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[2] This is a figure established in the Mexican legislation which aims at preserving fauna, flora and people living conditions in rural areas in a sustainable way.

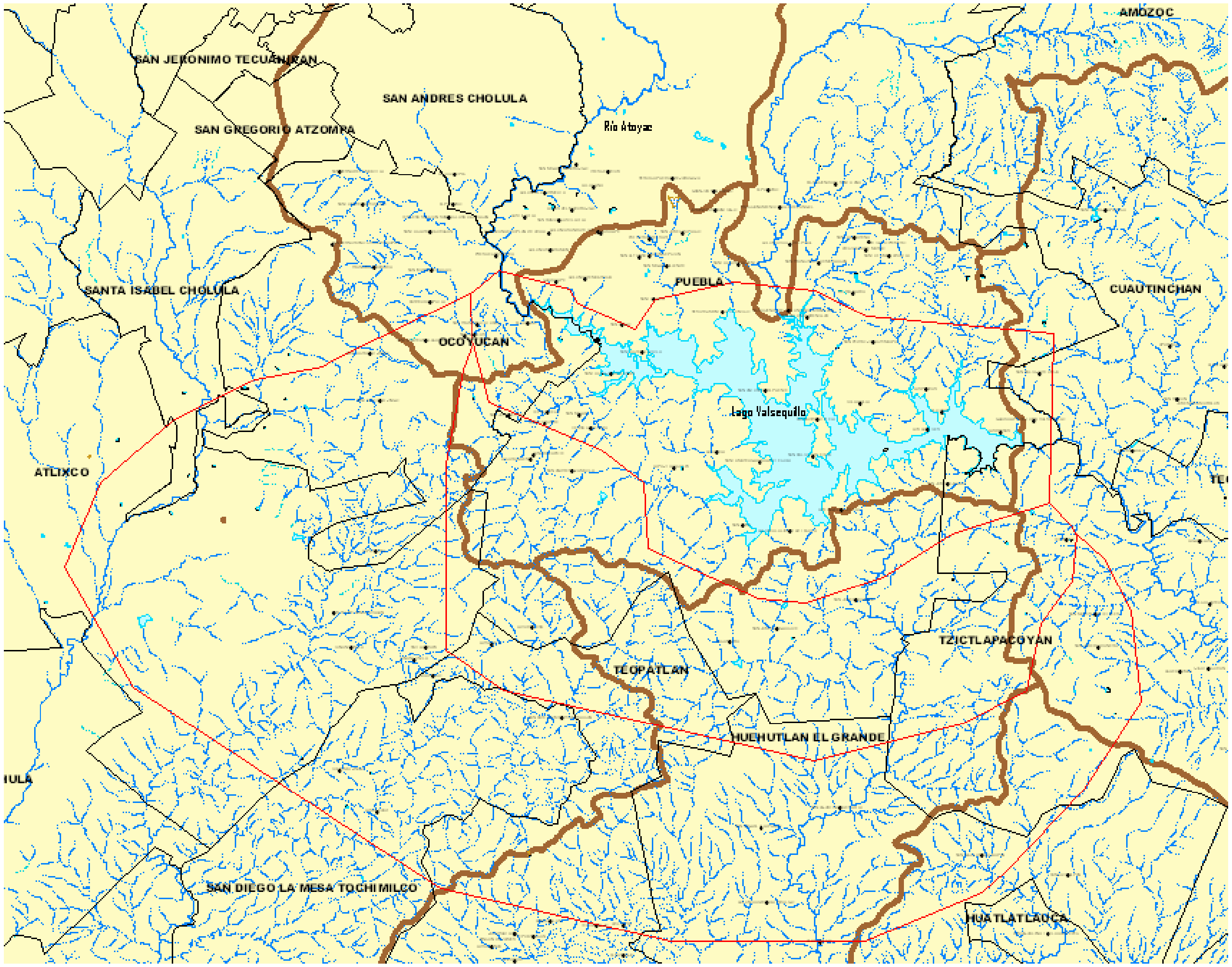


Figure 6. Valsequillo lake and surroundings (from: Business Partner Consulting (BPC) 2005)

Figure 7: Integration of Protected Natural Area (PNA) - Puerto Aura (from: BPC, 2005)

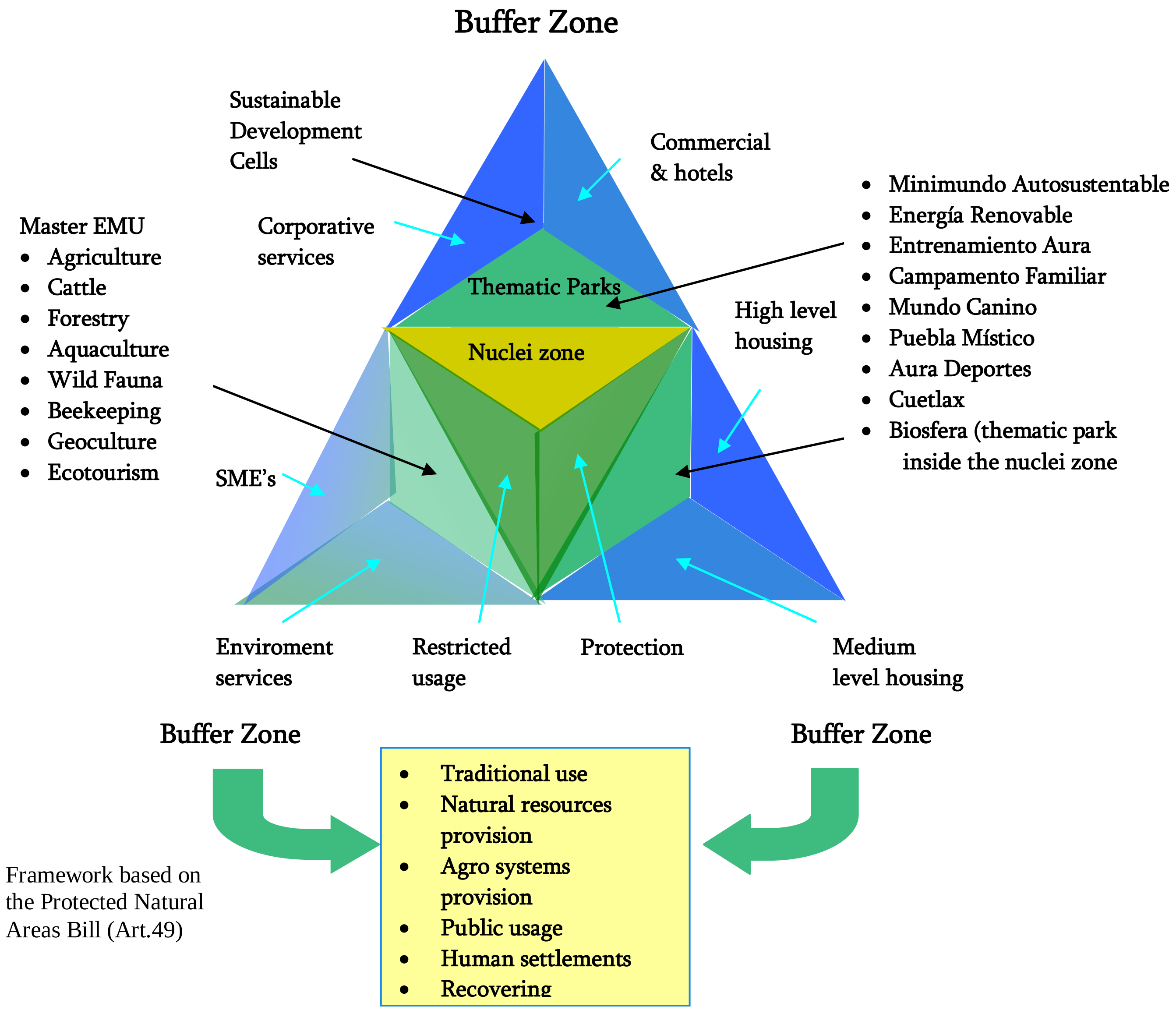
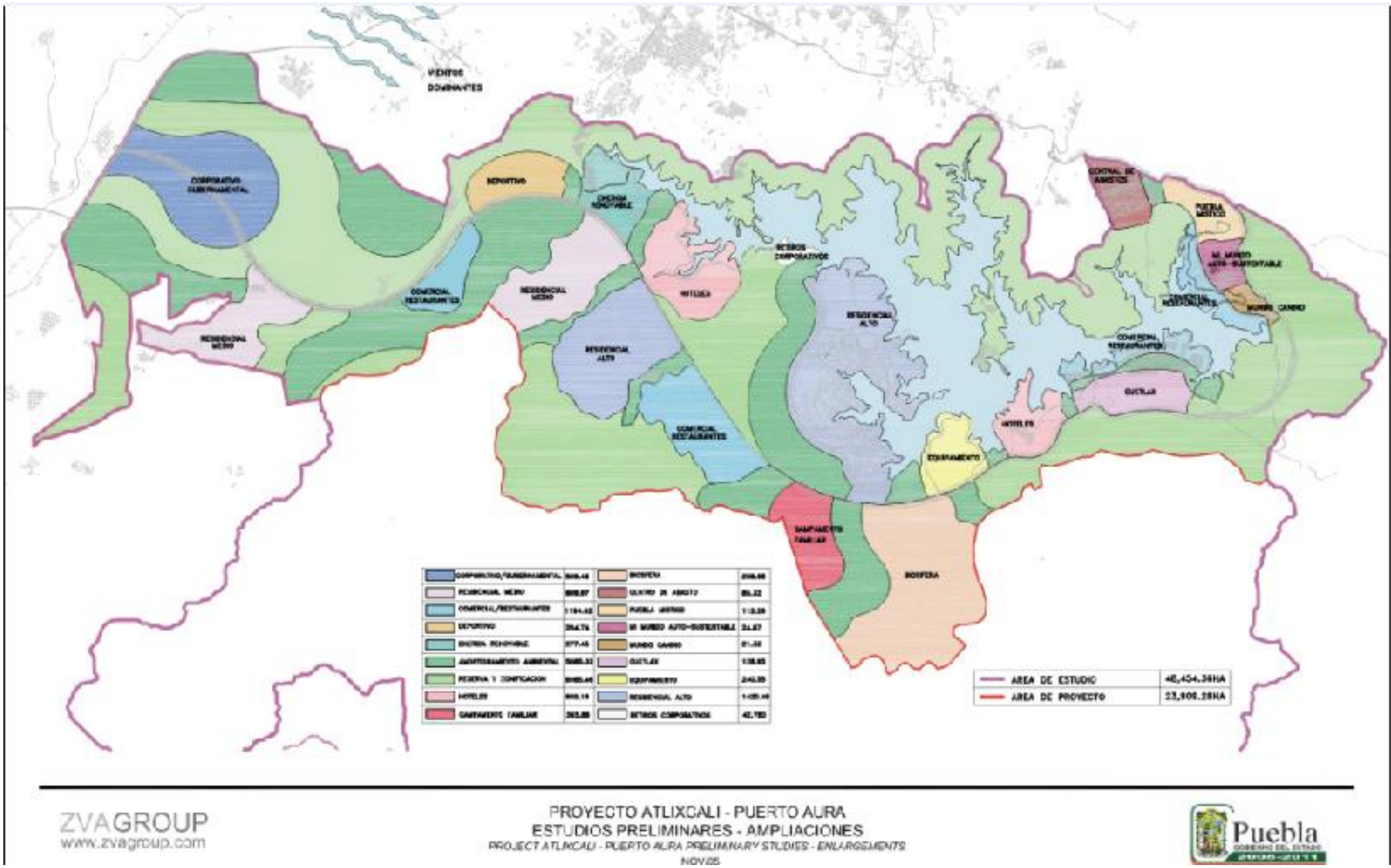


Figure 8. Sustainable urban development study and project areas



AREA DE ESTUDIO	48,454.3600
AREA DE PROYECTO	21,993.5650
AREA DE LAGO	2,881.8000

AREAS POR USO	Hectáreas
CORPORATIVO/GUBERNAMENTAL	841.7090
RESIDENCIAL MEDIO	946.6550
RESIDENCIAL ALTO	1,823.0290
COMERCIAL/RESTAURANTES	1,003.3970
DEPORTIVO	262.3480
CENTRO DE ABASTO	185.6010
AREA HOTELERA	655.6630
EQUIPAMIENTO	242.5010
PARQUES	2,289.1180
UMAS	4,517.9600
RESERVA	9,225.5840

PARQUES TEMATICOS	Hectáreas
ENERGIA RENOVABLE	260.1590
BIOSFERA	1,061.8700
PUEBLA MISTICO	180.6800
MI MUNDO AUTOSUSTENTABLE	113.7250
MUNDO CANINO	66.8450
CUETLAX	259.1990
CAMPAMENTO FAMILIAR	303.8600
RETIRO CORPORATIVO	42.7800

RESIDENCIAL ALTO 1	
PORCENTAJE DE OCUPACION	12.34%
PORCENTAJE DE CONSTRUCCION	24.69%

RESIDENCIAL ALTO 2	
PORCENTAJE DE OCUPACION	16.24%
PORCENTAJE DE CONSTRUCCION	32.47%

RESIDENCIAL MEDIO 1	
PORCENTAJE DE OCUPACION	28.66%
PORCENTAJE DE CONSTRUCCION	57.32%

RESIDENCIAL MEDIO 2	
PORCENTAJE DE OCUPACION	12.20%
PORCENTAJE DE CONSTRUCCION	24.39%

CORPORATIVO/GUBERNAMENTAL	
PORCENTAJE DE OCUPACION	8.36%
PORCENTAJE DE CONSTRUCCION	33.46%

DEPORTIVO	
PORCENTAJE DE OCUPACION	3.05%
PORCENTAJE DE CONSTRUCCION	8.39%

COMERCIAL	
PORCENTAJE DE OCUPACION	25.95%
PORCENTAJE DE CONSTRUCCION	64.89%

CENTRO DE ABASTO	
PORCENTAJE DE OCUPACION	19.81%
PORCENTAJE DE CONSTRUCCION	39.62%

AREA DE EQUIPAMIENTO	
PORCENTAJE DE OCUPACION	14.85%
PORCENTAJE DE CONSTRUCCION	38.97%

AREA HOTELERA	
PORCENTAJE DE OCUPACION	3.56%
PORCENTAJE DE CONSTRUCCION	28.44%

RESIDENCIAL ALTO 1	Hectáreas
AREA TOTAL	656.7990
AREAS VERDES	447.9320
VIALIDADES	56.4670
AREA TOTAL DE LOTES	152.4000
NUMERO DE LOTES (500M2)	3,048
OCUPACION DE SUELO	81.0768
M2 DE CONSTRUCCION	1,621,536

RESIDENCIAL ALTO 2	Hectáreas
AREA TOTAL	1,166.2300
AREAS VERDES	659.2280
VIALIDADES	151.6640
AREA TOTAL DE LOTES	355.3380
NUMERO DE LOTES (500M2)	7,107
OCUPACION DE SUELO	189.3390
M2 DE CONSTRUCCION	3,786,780

RESIDENCIAL MEDIO 1	Hectáreas
AREA TOTAL	435.7970
AREAS VERDES	253.2705
VIALIDADES	28.2890
AREA TOTAL DE LOTES	154.2375
NUMERO DE LOTES (400M2)	3,856
OCUPACION DE SUELO	124.9020
M2 DE CONSTRUCCION	2,498,040

RESIDENCIAL MEDIO 2	Hectáreas
AREA TOTAL	510.8580
AREAS VERDES	328.2700
VIALIDADES	55.4050
AREA TOTAL DE LOTES	127.1830
NUMERO DE LOTES (400M2)	3,180
OCUPACION DE SUELO	62.3084
M2 DE CONSTRUCCION	1,246,168

CORPORATIVO GUBERNAMENTAL	Hectáreas
AREA TOTAL	841.7090
AREAS VERDES	157.9670
VIALIDADES Y ESTACIONAMIENTOS	128.8660
AREA TOTAL TERRENOS ASIGNADOS	140.8010
AREA DE EXPANSION	414.0750
OCUPACION DE SUELO	70.4000
M2 DE CONSTRUCCION	2,816,000

PARQUES	
PORCENTAJE DE CONSTRUCCION	2%

UMAS	
PORCENTAJE DE CONSTRUCCION	2%

DEPORTIVO	Hectáreas
AREA TOTAL	262.3480
AREAS VERDES Y PEATONALES	129.3034
VIALIDADES Y ESTACIONAMIENTOS	18.6790
AREA DE EXPANSION	105.4237
OCUPACION DE SUELO	8.9419
M2 DE CONSTRUCCION	223,547.50

COMERCIAL	Hectáreas
AREA TOTAL	198.2570
AREAS VERDES	69.0350
VIALIDADES Y ESTACIONAMIENTOS	71.4610
OCUPACION DE SUELO	57.7610
M2 DE CONSTRUCCION	1,444,025

COMERCIAL 2	Hectáreas
AREA TOTAL	467.7470
AREAS VERDES	235.3455
VIALIDADES Y ESTACIONAMIENTOS	142.7345
OCUPACION DE SUELO	89.6670
M2 DE CONSTRUCCION	2,241,675

COMERCIAL 3	Hectáreas
AREA TOTAL	167.6610
AREAS VERDES	64.4520
VIALIDADES Y ESTACIONAMIENTOS	33.5760
OCUPACION DE SUELO	69.6330
M2 DE CONSTRUCCION	1,740,825

COMERCIAL 4 (MUELLE)	Hectáreas
AREA TOTAL	169.7320
AREAS VERDES	122.1060
VIALIDADES Y ESTACIONAMIENTOS	4.2650
OCUPACION DE SUELO	43.3610
M2 DE CONSTRUCCION	1,084,025

CENTRO DE ABASTO	Hectáreas
AREA TOTAL	185.6010
AREAS VERDES	81.1150
VIALIDADES Y ESTACIONAMIENTOS	67.7230
OCUPACION DE SUELO	36.7630
M2 DE CONSTRUCCION	735,260

HOTELES (8 NIVELES APROX.)	Hectáreas
AREA TOTAL	655.6630
AREAS VERDES	619.2390
VIALIDADES Y ESTACIONAMIENTOS	13.1130
OCUPACION DE SUELO	23.3110
M2 DE CONSTRUCCION	1,864,880

DESCRIPCION EQUIPAMIENTO	Ha construcción
ESCUELAS	10.0000
CENTROS DE SALUD	10.0000
RELLENOS/TIRADEROS	2.0000
POZOS Y PLANTA DE TRATAMIENTO DE AGUAS	3.0000
OTROS (POLICÍA, BOMBEROS, ETC.)	69.5026

Table 2. Definition of areas and parameters of Puerto Aura project (from: Adapted from ZVA, 2006)

5. Modeling the Puerto Aura project: Selection of SUD environmental methods

With the aid of the BEQUEST toolkit, relevant information to projects similar to Puerto Aura was collected and analyzed. First, the inherent characteristics of the project were defined, and then, those forms of sustainability assessment that were found relevant for this type of projects were analyzed. The review process for analyzing environmental assessment methods and selecting the most appropriate one was based on considering the following criteria combination framed in the BEQUEST toolkit:

a) planning activities;
b) environmental, economic, social and institutional sustainable development issues;
c) city region spatial level; and
d) long time scale, for more than 20 years.

Six environmental assessment methods were reviewed:

- **Environmental appraisal of development plans (EADP**) is an explicit, systematic and iterative review of development plan policies and proposals to evaluate both their individual and combined impacts on the environment (Department of Environment, 1993). It is an integral part of the plan making and review process, which allows the evaluation of alternatives. It is based on a quantifiable baseline of environmental quality. The process is primarily judgmental and based on the general knowledge and expertise of the team of officials involved. Because it was not possible to make explicit the data on which this method is based we decided against its use..
- **Community impact evaluation (CIE)** takes account of the total costs and benefits on a community and brings out the incidence of such costs and benefits on the various community sectors (Lichfield, 1996). The analysis identifies the community sectors (producers on site, producers off site, and consumers) that would be affected by a project or plan, describes the kind of impact on them, defines their sector objectives, finally notes the unit of measurement and valuation of the impact and indicates the sector preferences on project alternatives. In the 90's the method was integrated with impact assessment methods. This method seemed to have some advantages for our project.
- **Environmental Impact Assessment (EIA)** covers projects located in urban and rural areas. The EIA principles are useful in the urban environmental and quality of life issues although the majority of EIA projects are industrial or located outside urban areas (http://europa.eu.int/comm/environment/eia). Due to the fact that EIA refers more to projects than activities it was decided not to select this method for our project.
- **Financial Evaluation of Sustainable Communities (FESC)** aims at evaluating viability of sustainable communities as a development option (http://research.scpm.salford.ac.uk/bqtoolkit/tkpages/ass_meth/methods/amfesc_4.html). The object of the assessment is to use the development value (planning gain) released from the change of use (from agricultural to housing and commercial uses) to fund any infrastructure costs (including: land stabilization, roads, water, drainage, landscaping, recreation, school, etc.) associated with the development of sustainable communities. The assessment is based on a detailed cash flow (discounted) analysis of the income from land transfer and the costs of providing the infrastructure. Because of its bias towards financial issues, it was unsuitable for the Puerto Aura project.
- **System for Planning and Research in Towns and Cities for Urban Sustainability (SPARTACUS)** assesses sustainability implications of urban land use and transport policies. The core of the system is a computerized land use transport interaction model, MEPLAN. MEPLAN can be used for analyzing the impacts of e.g. transport investment, regulatory, pricing or planning policies on e.g. overall mobility; modal split; journey times; household's movement; and job and production costs of firms. The SPARTACUS method builds on the results of the model to calculate values for sustainability. Sustainability is understood as consisting of environmental and social sustainability and economic efficiency. The environmental and social indicators are aggregated into indices using user-given-indicator-specific weights and value functions. The social indicators include a set of justice indicators which assess the justice of the distribution of certain impact among socio-economic groups (Lautso y Toivanen, 1999). The methodology of SPARTACUS is being further developed in the PROPOLIS project which is the method we described next.

- **Planning and Research of Policies for Land Use and Transport for Increasing Urban Sustainability (PROPOLIS)** represents an advance over the SPARTACUS model because it incorporates transportation and land usage models (TRANUS and IRPUD), besides the environment-spatial module (Raster). Because of the PROPOLIS characteristics, in terms of its holistic approach, spatial definition, flexibility, and proved application and usefulness in seven European cities (Helsinki, Dortmund, Inverness, Naples, Vicenza, Bilbao and Brussels), it was chosen as a basis for the Puerto Aura SUD model.

6. Planning and Research of Policies for Land Use and Transport for Increasing Urban Sustainability (PROPOLIS) model

The objectives of PROPOLIS are to research, develop and test integrated land use and transport policies by providing a set of tools and comprehensive assessment methodologies in order to define sustainable long-term urban strategies and their effects.

Urban sustainability is viewed by PROPOLIS from three perspectives: *environmental*; *social;* and *economic*. Each one of these dimensions is divided into themes and each theme comprises a set of indicators. Indicators under each dimension and its themes are used to measure the state of sustainability for a set of policies. In addition to indicators a set of background variables is defined to help to understand and illustrate the different impacts of tested policies. This is the way that PROPOLIS brings the fourth perspective of the BEQUEST framework, the *institutional*.

Indicators values are based on integrated land use and transport model outputs which are further processed with tools developed for desegregation of data, economic evaluation, decision-making support and presentation of results. Because of the linkages between the urban lands use, transport and environment aspects are at the core of PROPOLIS modeling process, in the following sections these areas are described.

6.1 Urban land use, transport and environment

That urban land use and transport are closely inter-linked is common wisdom among planners and the public. The set of relationships implied by the land-use transport feedback cycle can be summarized in Figure 9.

Figure 9. The land-use transport feedback cycle; from: Lautso et al., 2004: 54.

A number of integrated urban land-use transport systems are in use today, (Wegener, 1994, 1995, 1998a, 2003; EPA, 2000). However, urban modelers, have for a long time ignored ecological aspects of the process simulated in their models and have only recently been prompted to redirect their attention from economics to environmental impacts of land use and transport policies. Environmental subsystems relevant for urban land-use transport models can be classified under the headings of resources (energy, water and land), emissions (gases, water quality, soil, solid waste, noise) and emissions (air dispersion, noise propagation, surface/ground water flows).

In order to upgrade land-use transport (LT) models to become land-use transport environment (LTE) models some problems have to be overcome. One of them refers to defining relevant feedback processes, and another is related to problems of spatial resolution. To solve the feedback problem, modelers must add environmental factors to the explanatory variables of the preference functions used in the models and re-calibrate the models. Preference or utility functions based on environmental externalities are bound to vary for households, firms, investors and developers, travelers, shippers and transport operators.

In the case of spatial resolution, the problem consists in environmental effects that are felt and perceived at much smaller scale than the average zone size en the models. In particular air pollution and noise intrusion require a much higher spatial resolution than large zones in which the internal distribution of activities and land uses is not known. In order to solve this problem PROPOLIS makes use of the *Raster module*, in which the land use pattern within zones is disaggregated to much smaller *raster* cells. The Raster module maintains the zone organization of the land-use transport models and adds a disaggregated raster-based representation of space for some specific environment and social impact sub-models. However, the issue is only partially solve because a fully integrated spatially disaggregate land-use transport environment model currently does not exist worldwide. It is difficult to feed the information on environmental impact back into the model as the land-use transport models used in PROPOLIS are based on zone aggregates, and the desegregation to raster cells is performed only after the simulation runs have been completes. Therefore, although all impact is taken into account there is a limited feedback, as shown in figure 10:

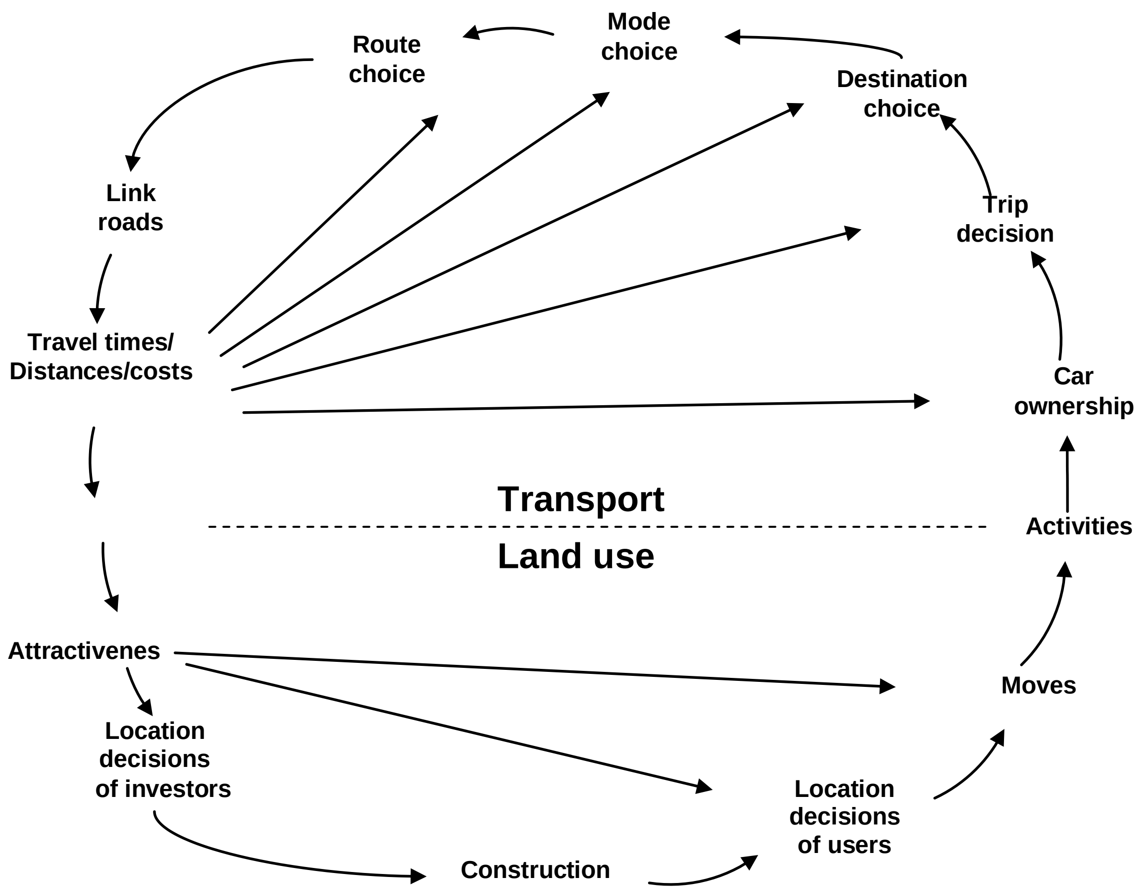


Figure 9. The land-use transport feedback cycle; from: Lautso et al., 2004: 54.

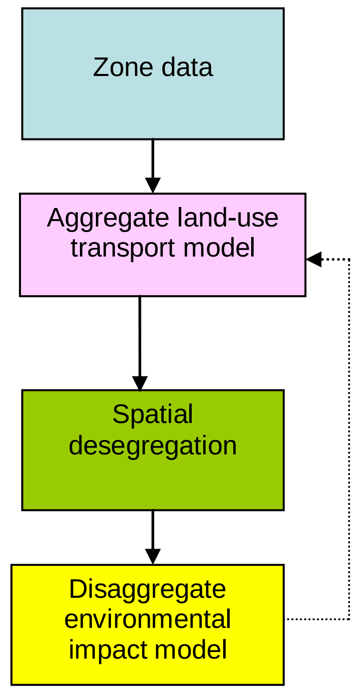


Figure 10. Land-use transport and environment model in PROPOLIS (from: Lautso, *et al*., 2004: 66)

The analytical framework of PROPOLIS is a sequence of databases, models and tools whose main components and data flows are illustrated in general terms in Figure 11. This describes a process stretching from inputs via behavior modeling and sustainability impact modeling to outputs in terms of indicators and evaluation and presentation procedures.

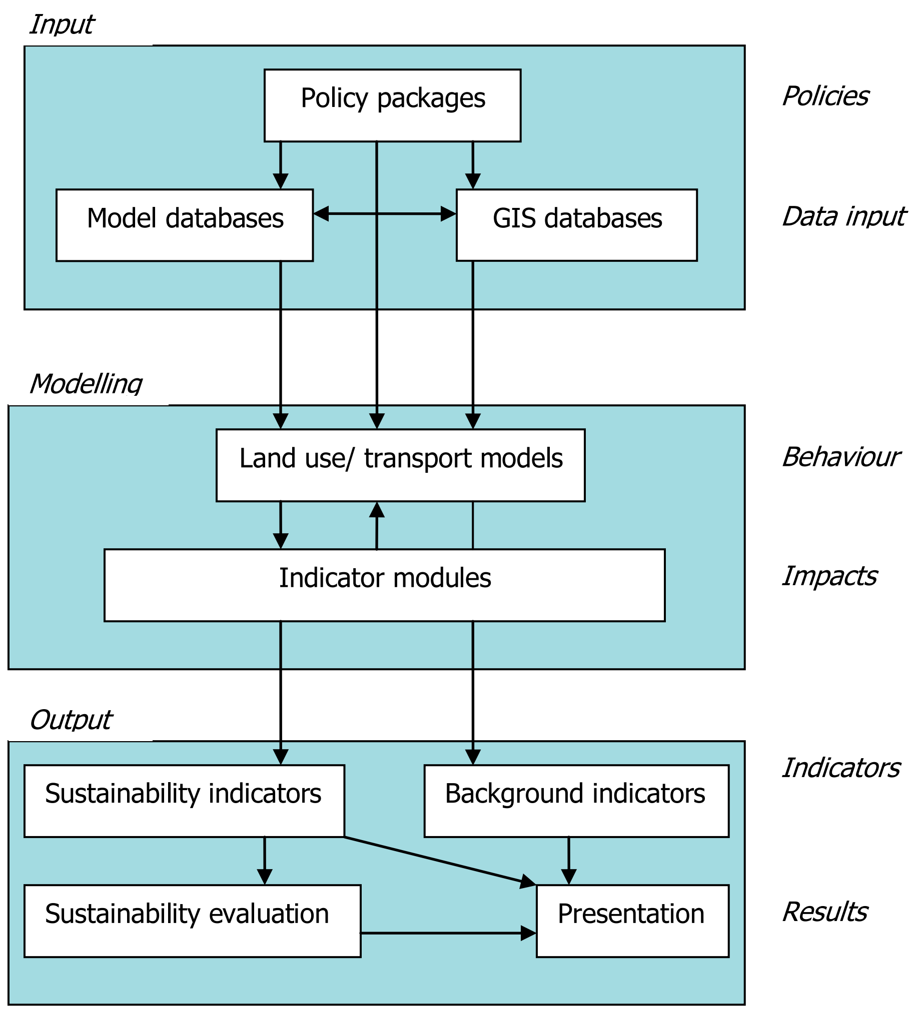


Figure 11. The PROPOLIS analytical framework (from: Lautso et al., 2004: 73)

In the modelling part, the land-use transport models simulate the effects of the policies in terms of changing zonal activities such as pollution or employment and changing mobility pattern resulting in different modal splits and different link loads. A number of indicators modules receive the output of the land-use transport models and calculate raw values of the sustainability indicators. The output consists of raw sustainability indicator values, which are further processed in a sustainability evaluation model.

Next, we describe the land-use transport model selected as a basis for the Puerto Aura project, and later the associated indicator modules, including the environmental ones.

5.2 Land-use and transport model

In order to simulate the land-use transport section model, PROPOLIS uses in turn a model developed by the Institute of Spatial Planning of the University of Dortmund (IRPUD). This is a simulation model of intraregional location and mobility decisions in a metropolitan area (Wegener, 1983, 1985, 1996, 1998b, 1999). It receives its spatial dimension by the subdivision of the study area in zones connected with each other by transport networks containing the most important links of the public transport and road networks as an integrated multimodal network including all past and future network changes. It receives its temporal dimension by the subdivision of time into periods of one or more years' duration.

The model predicts for each simulation period intraregional location decisions of industry, residential developers and households, the resulting migration and travel patterns, construction activity and land-use development and the impacts of public policies in the fields of industrial development, housing, public facilities and transport. Figure 12 shows a schematic diagram of the major subsystems considered in the model and their interaction and of the most important policy instruments.

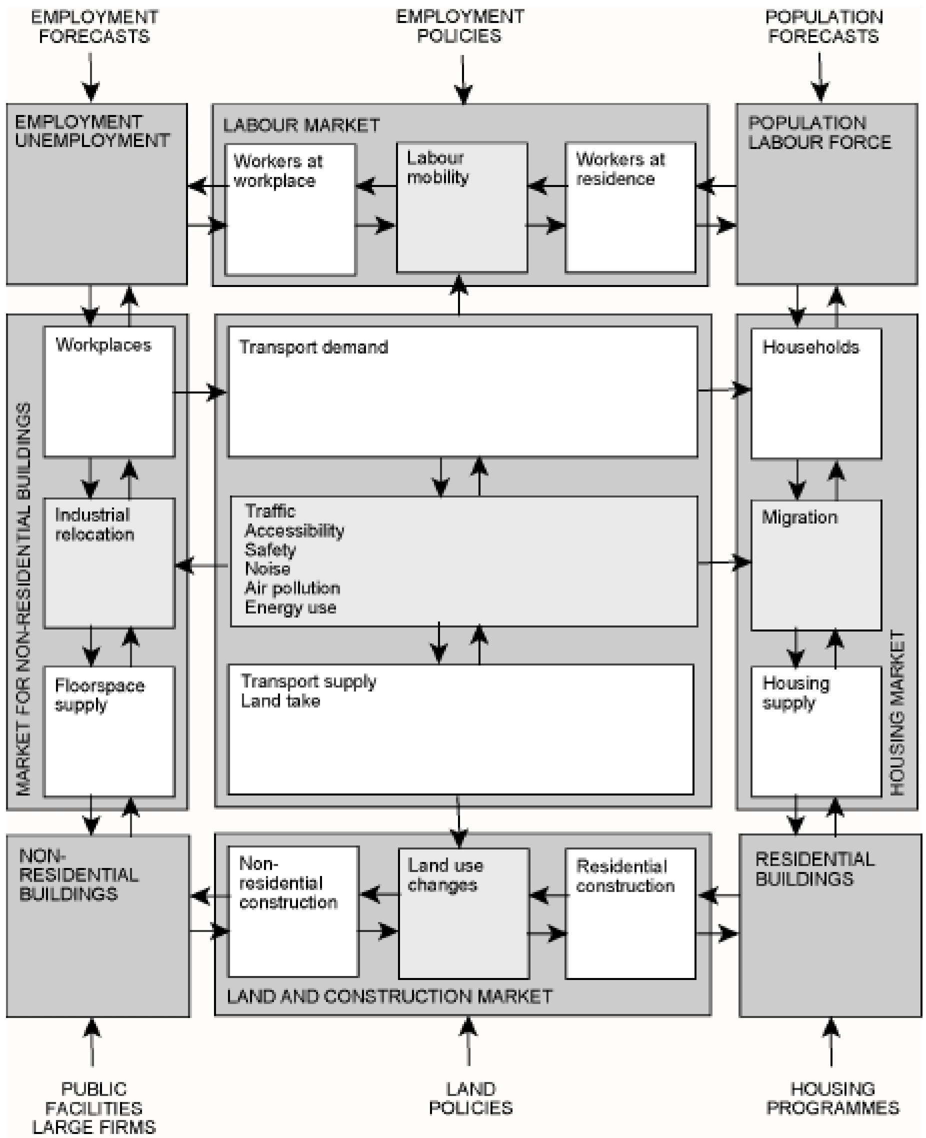


Figure 12. The Institute of Spatial Planning of the University of Dortmund (IRPUD) model
(from: Lautso et al., 2004: 82)

The four square boxes in the corners of the diagram represent the major stock variables of the model; population, employment, residential building (housing) and non-residential building (industrial and commercial workplaces and public facilities). The actors representing these stocks are individuals or households, workers, housing investors and firms. These actors interact in five submarkets of urban development. The five submarkets treated in the model and the market transactions occurring in them are:

- labour market: new jobs and redundancies;
- the market for residential and non-residential buildings; new firms and firm relocations;
- the housing market: immigration, outmigration, new households and moves;
- the land and construction market: changes of land use through new construction, modernisation and demolition; and
- the transport market: trips.

For each submarket, the diagram shows supply and demand and the resulting market transaction. Choice in the submarkets is constrained by supply (jobs, vacant housing, vacant land, industrial and commercial floor space) and guided by attractiveness, which in general terms is an actor-specific aggregate of neighbourhood quality, accessibility and price. The large arrows in the diagram indicate exogenous inputs; these are either forecasts or regional employment and population subject to long-term economic and demographic trends or policies in the fields of industrial development. From the analysis of the PROPOLIS and in particular the IRPUD model, some aspects appear to be very relevant for the Puerto Aura project:

1) The model shows the dynamics of the economic, social and environmental dimensions implied by urban policy.
2) The model identifies non-linear interactions and feedback among those dimensions.
3) The interactions between land-use and transport alternatives are at the core oft he model.
4) Even though it would be desirable to operate at a disaggregate spatial area, as shown by the *Raster* module in PROPOLIS, the present state of the Puerto Aura project makes it unlikely. However, as it will be shown later, it is possible to examine feedback among different types of activities located in different locations of the planned urban area.

5.3 Indicator modules

There are three indicator modules in PROPOLIS, environmental, economic and justice. The environmental indicators are included in the Raster module which also contains social and economic indicators. Although the spatial desegregation for the Puerto Aura project is far from the level achieved by the *Raster* module, some indicators included in this module are still valid for larger zones. Out of the eleven sustainability indicators provided by the Raster module, five were adapted to the Puerto Aura project. One indicator related to water availability, not included in Raster, was added in our model. Due to the scarcity of this natural resource in many areas in Mexico, it was important to include an indicator focused on water sustainability in the model. The following are the environmental indicators selected for the Puerto Aura project:

- Noise level
- Available water per house
- Pollutants per capita (SOx, NOx y HC)

- Gas per capita (GGE)
- Clandestine solid waste per capita
- Land coverage

In PROPOLIS there is a clear recognition that indicators in the economic module depend to a large extent on the existing particular policies in a city region. Nevertheless, PROPOLIS recommends that indicators based on fully specified cost benefit analysis will provide a sufficiently good approximation for measuring economic sustainability. Based on this suggestion, the following indicators were chosen for the Puerto Aura project:

- Employment rate
- Business dynamism
- Traffic congestion

The justice module is based on indicators which focus on equity in the distribution of social, economic and environmental impacts and benefits. The spatial disaggregation of the Raster module permits to assess those impacts among the different socioeconomic groups in the area. Again, as in the case of the environmental module, some of the indicators treated in PROPOLIS related to social issues in this module were taken for defining the social indicator in the Puerto Aura project, as follows:

- Number of inhabitants per household
- Education service level (at different educational levels)
- Health service level
- Other services level

6. The Puerto Aura Sustainable Urban development System Dynamics (SD) model

As it was indicated various SUD related initiatives (i.e.: Smart Growth and BEQUEST) were surveyed; from these we consider BEQUEST, a general framework that allows to select specific methods and models, we believe, was suitable to the Vasquesillo project; smart Growth proved to be too focus and its less flexible urban development policies assumed that these policies will satisfied the social and environmental needs but failed to make them explicit. BEQUEST toolkit seemed flexible enough for our case; in particular the PROPOLIS model (in turn, PROPILIS uses IRPUD and Raster to integrate land use, transport amongst other variables). However, to make the *Raster module* operational, detailed definitions of the project spatial variables are necessary which is not available at the moment. Because of this, we decided to design a Systems Dynamics model (SD) that: (i) uses some of the concepts imbedded in the IRPUD model of Urban development; and (ii) incorporates the structural dynamics of the aggregated variables currently available (had detailed information being available, the *Raster* module would have been used).

System Dynamics and sustainable growth

Cavana and Ford (2004) made a thorough review of applications of SD to wide variety of environmental and resources systems during the past four decades. From this review, they outlined the initial influence of "Limits of Growth" (Meadows *et al.*, 1972) in the early 1970s, and the role played by the System Dynamic Society in the past few years in contributing to a growing awareness of environmental and resources problems. The surge of interest was also attributed to publications of special issues of System Dynamic Review devoted to sustainable development (Saeed and Radzicki,1998) and to "The Global Citizen" (Sterman, 2002), and other initiatives like the establishment of the Environmental Dynamics Special Interest Group of the System Dynamics Society by Tasso Perdicoulis. From these works, one can confirm that SD is an ideal methodology to analyze the complexity which is normally present in sustainability issues (Randers, 2000; Springael, et al., 2002) and to promote public participation on environment topics (Hale, 1993; Gregory, 2000; Diets and Stern, 1998; and Stave, 2002).

When one considers the publications related to urban policy, the work of J. Forrester in Urban Dynamics (1969) comes to the forefront. The trajectory of the behavior, growth, overshoot, and stagnation of an urban area, observed in the Forrester model, has been broadly analyzed in other contexts. These models have arrived at similar conclusions to those of Forrester, showing how policies that in the short run appear to revitalize the urban area, such as construction of low-income housing, in the long term are rather detrimental, or neutral in the best scenario. (Mass, 1974; Schroeder, et al., 1975; Eskinasi and Rouwette, 2004) In a recent study, Sanders and Sanders (2004) elaborated a model that differentiated 16 zones of an urban area and through it they tried to go beyond the limitations of Forrester model. They allowed interrelationships among the zones and with the wider surrounding environment, and by means of gravitational models they included spatial considerations in the model. The results achieved by the model lead them to conclude:

> *The system dynamics methodology proves to be flexible and appropriate in analyzing urban systems, despite the fact system dynamics has never become an established method of urban planning (cf Alfed 1995). The flexibility is made clear in the development of the current model and the omissions of the Forrester model in the eyes of its critics have been included to a large extent. (p.28)*

Despite the major surge of publications of SD and sustainable development in different areas, the application of sustainable development in an urban context, regarding the three dimensions already mentioned, is still rather scarce, nonetheless there are two works, relevant to our study we review next.

Stave (2002) used a SD approach to the problem of congestion and its environmental consequences in Las Vegas. In the elaboration of this study, the author counted with a broad participation of representatives of different sectors of the city, and the model lead them to detect counterintuitive behavior that allowed them to propose more effective and efficient transportation measures, based mainly on promoting higher vehicle occupancy.

Another example was the Radzicki and Seville´s model for the city of Sterling, Massachusetts (1993). In this model they described the interrelationships of different urban areas (school, land commerce, industry, municipal light, population and housing) and their effects on the quality of life and fiscal policy of the city. In contrast to Forrester, quality of life instead of availability of jobs was used to reflect the city attractiveness. This quality of life was influenced negatively by a crowding of population, rising ratio of commercial and industrial structures to total structures, and electrical and tax rates that rose above the level people expected. Conversely quality of life was influenced positively by school quality and town services in excess of what people expected.

As a result of running the model the authors could test policy changes for a 60 years horizon, concluding *"the only claim that can be made is that the model can accurately trace through the implications of the assumptions that are being made and the knowledge that is being represented."* (Ibidem, p.488)

So, considering these previous works, our involvement in Sustainable Urban Development issues, we believe that at this point in the project, Systems Dynamics modelling proves to be useful and advantageous to capture the essence of the project features, mainly because:

- Relates different SUD dimensions in a dynamic way.
- Shows feedback processes among different sectors in those dimensions.
- Differentiates accumulations or levels from activities or flows in the system.
- Allows to simulate different policy or institutional decisions.

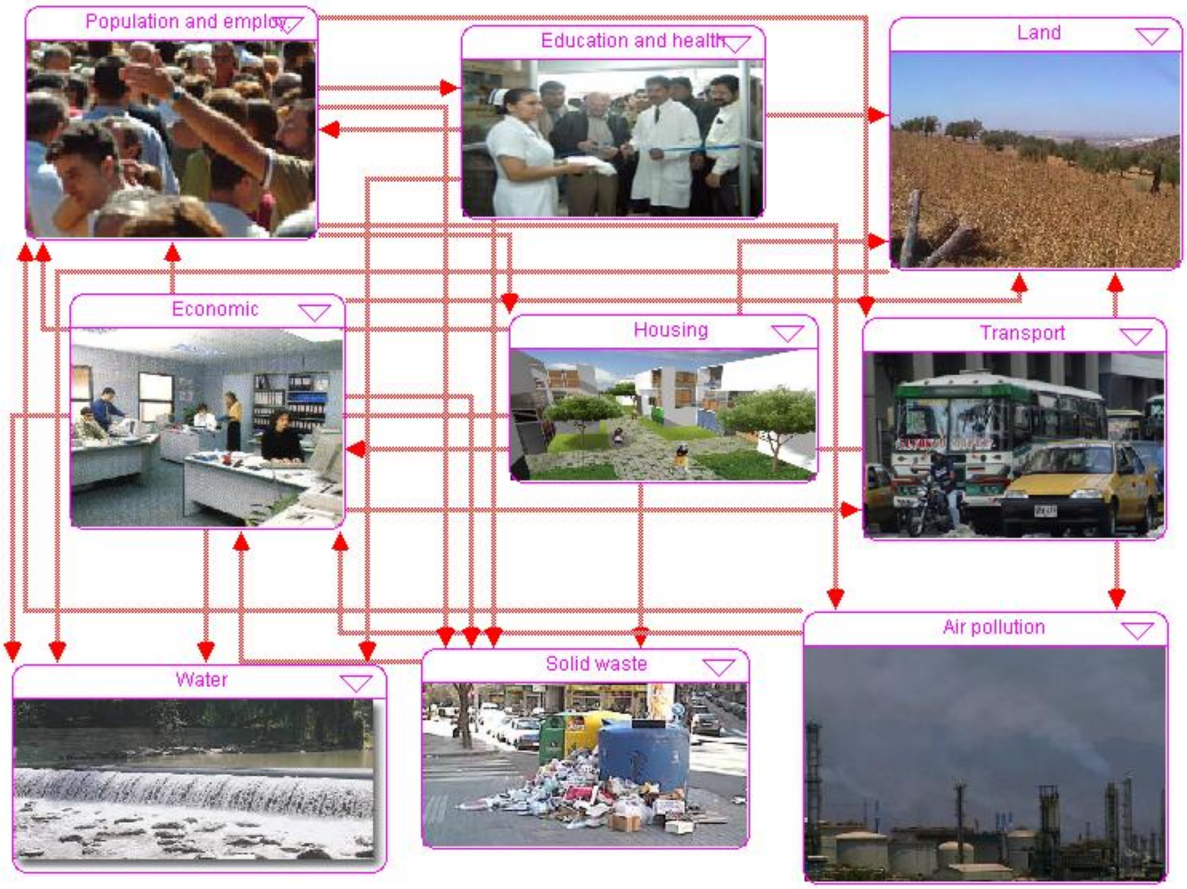
Table 3 shows the dimensions and sectors which are included in the SUD Puerto Aura simulation model:

Dimension	Sector
Social	Population and employment Housing Education and health
Economic	Economic Transport
Environmental	Water Air pollution Solid waste
Institutional	Land

Table 3. Dimensions and sectors of the SUD Puerto Aura model

The inter-relationships among the different sectors of the model 9 (a type of context diagram) are described in Fig. 13. In order to understand these interactions a detailed description of the model follows, pointing out the indicators which are obtained in each one of the sectors.

Figure 13. Inter-relationships between the various sectors included in the model



6.1 Population and employment Sector

The main chain in this sector describes the transition of the population in Puerto Aura through different age groups and working status, Figure 14. During their working age, people can be grouped as out of the active economic population (AEP), as part of the employed and unemployed, or in retirement. At any time, the **employment rate (indicator 1)** can be estimated. Also, population can vary according to net migration in the area.The main feedbacks that come to the population and employment sector from other sectors are centered on the attractiveness to migrate to the zone as influenced by:

- Economic: business openings.
- Air pollution: pollutants and greenhouse gas emissions.
- Housing; availability of empty houses.
- Education and health; services capacities

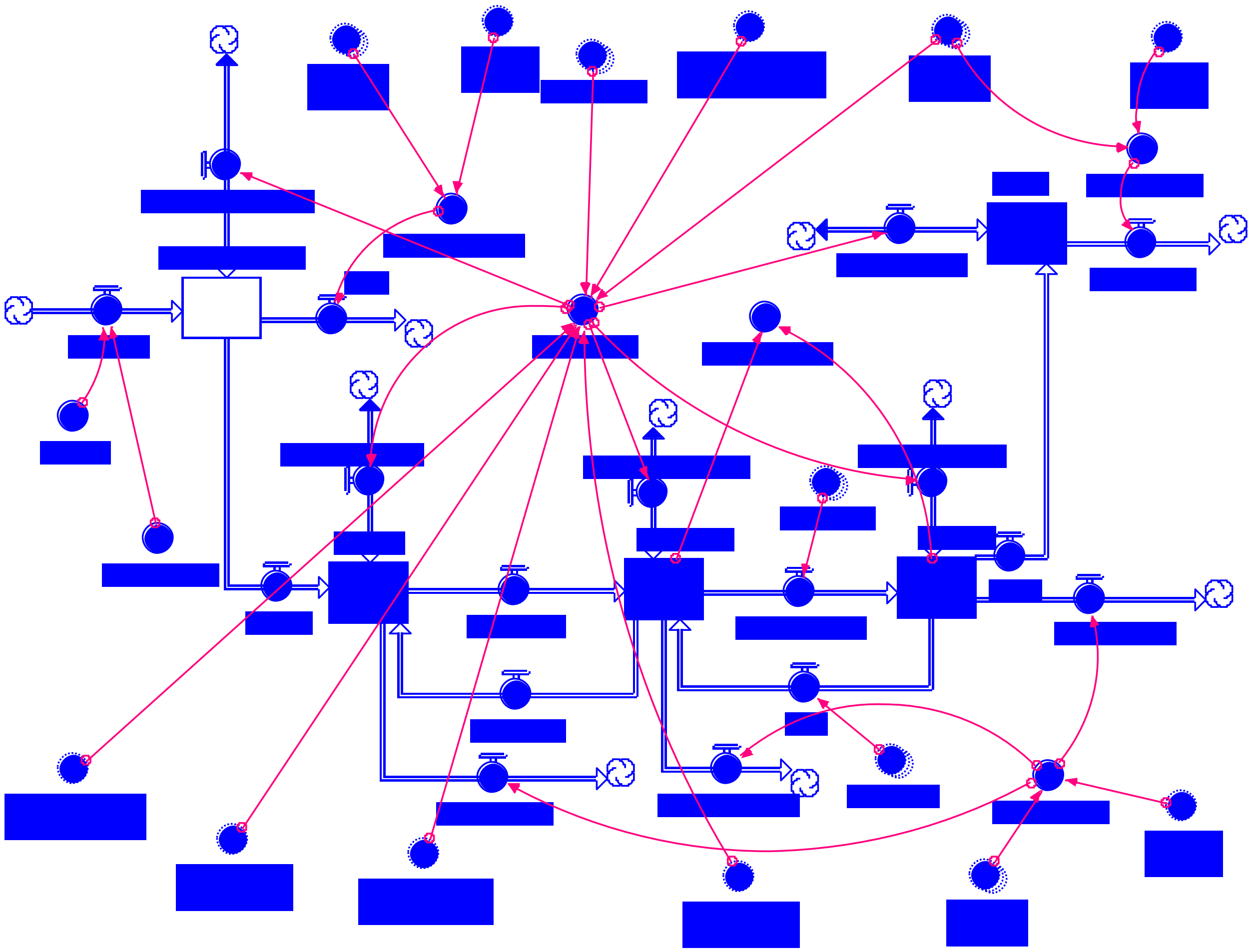


Figure 14. Population and employment sector, Source: Duran-Encalada and Paucar-Caceres

6.2 Housing sector

This sector is composed by housing in construction, occupied and empty (Figure 15). The demand for housing comes from the population in the zone and the living standards defined by policy. The model considers three main types of housing, high, medium and popular. Throughout the simulation the model indicates the average **number of inhabitants per household (indicator 2).**

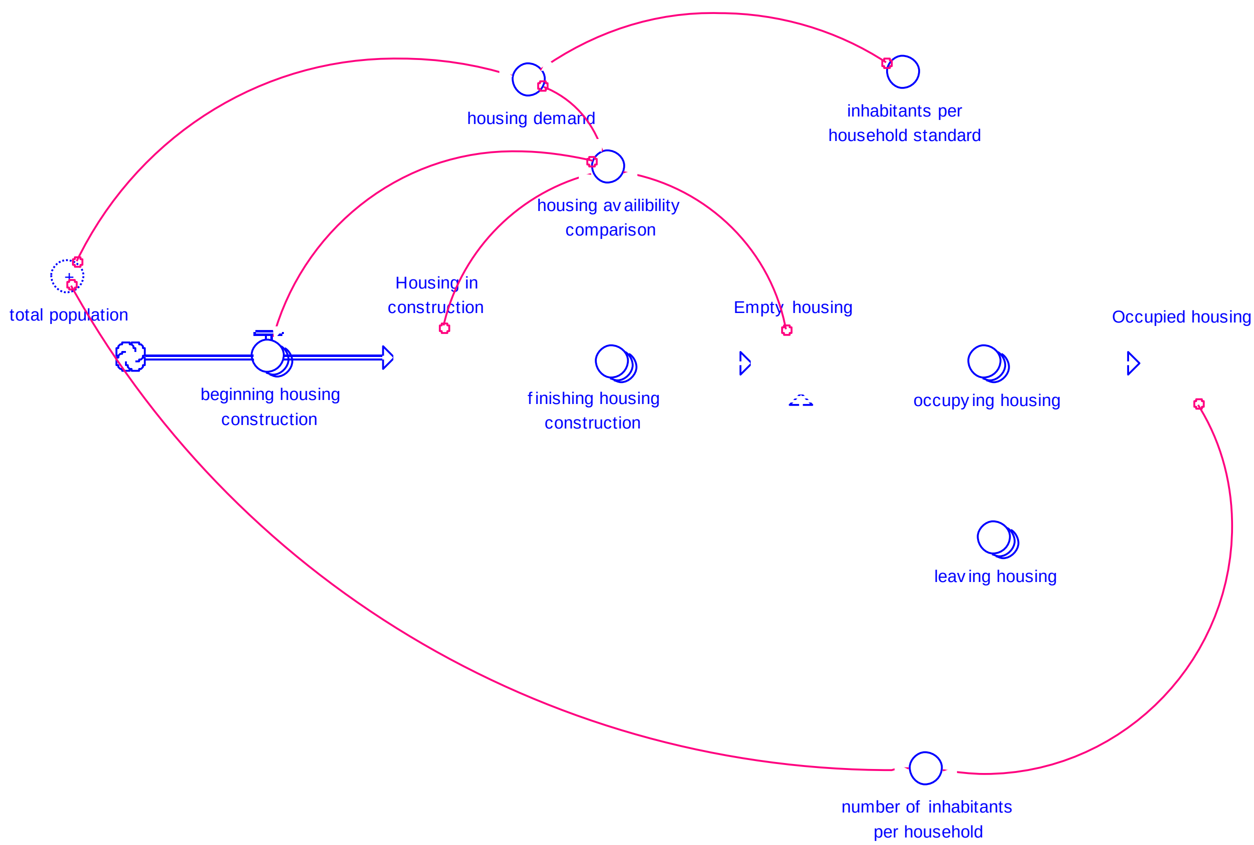


Figure 15. Housing sector, Source: Duran-Encalada and Paucar-Caceres

6.3 Education and health sector

This sector takes account of the demand made by the population for education services at different levels: pre-primary, primary, secondary, higher medium (technical and high school), and higher education (undergraduate and graduate) (Figure 16). A comparison is made between levels of demand and existing service capacities, and where demand exceeds the supply level a decision to increase capacity is taken, beginning by school construction activities. In a similar vein, the sector includes the health service and other public services demanded by the local population (lighting, security, among others). As a result of the sector dynamism the following indicators are obtained: **education service level (at different educational levels), health service level and other services level (indicators 3, 4 y 5).**

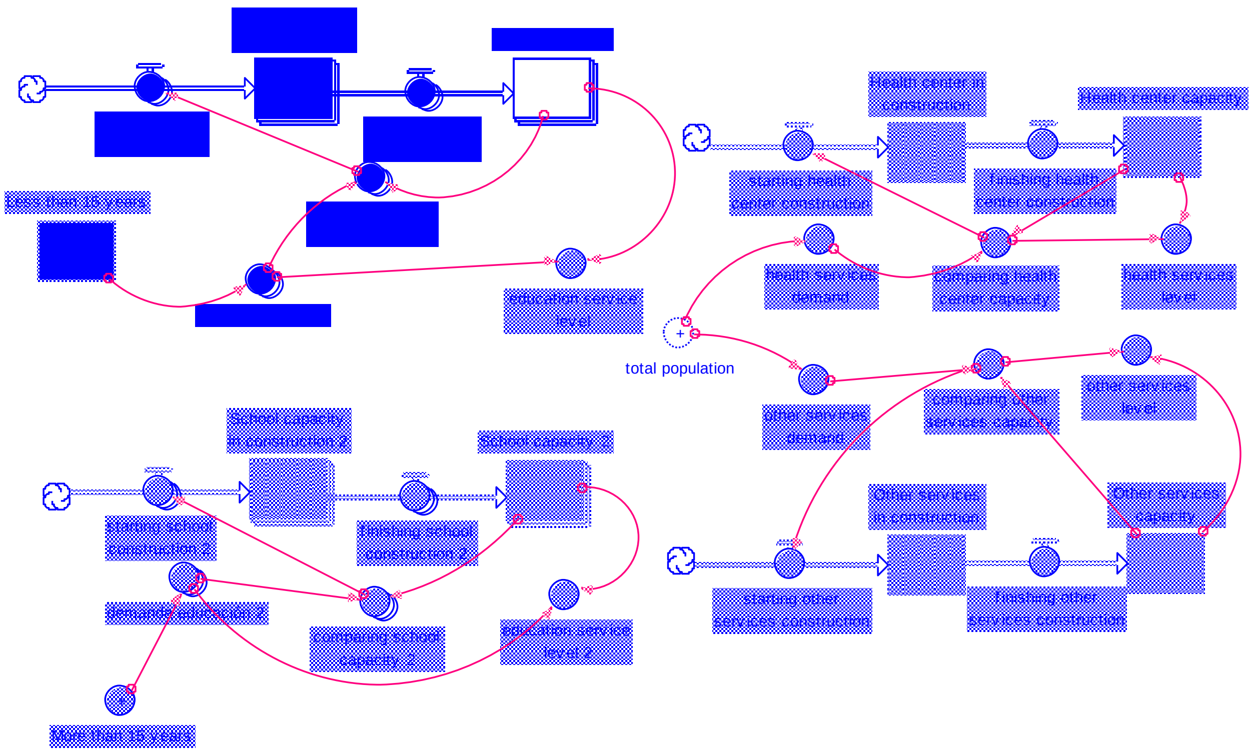


Figure 16. Education and health sector, Source: Duran-Encalada and Paucar-Caceres

6.4 Economic sector

In this sector new business openings and closings are registered, as well as the number of jobs created or made redundant, respectively (Figure17). Firms are classified according to different types of economic activities that have been planned for Puerto Aura: environmental managed units (EMU's), corporative offices, government services, hotel, sports, public services, thematic parks and commerce. Dynamism in the sector is the result of two main variables, the GDP growth rate and the attraction of visitor to the zone. The attractiveness for visiting the different amenities in the zone is affected negatively by the accumulation of solid waste, air pollution and traffic congestion in the area. Also, the occupancy of buildings by firms is monitored in this sector, triggering new building construction whenever needed. The indicator that comes from this sector is **business dynamism (indicator 6)**

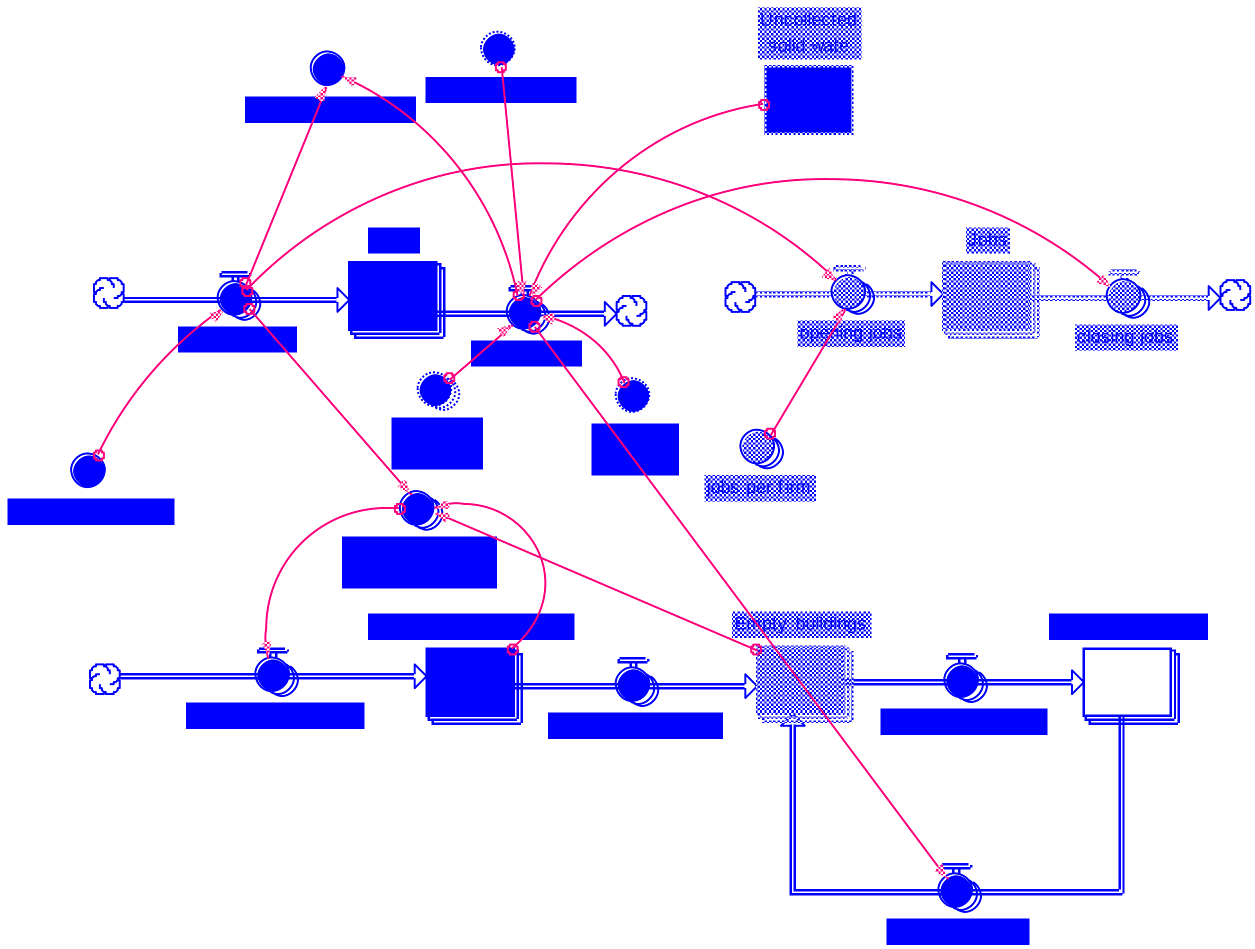


Figure 17. Economic sector, Source: Duran-Encalada and Paucar-Caceres

6.5 Transport sector

This sector includes the existing automobile stock which is determined by the population and public transportation facilities in the zone (Figure 18). The existing road network and those under construction are considered in this sector too. Four types of commuting patterns are identified in the zone: to work and to commercial areas for the local population, to amenities by visitors, and to work by non-local people, mainly those coming from the city of Puebla. The commuting, road capacity and vehicle stock are used to estimate **traffic congestion (indicator 7) and noise level (indicator 8)** in the zone.

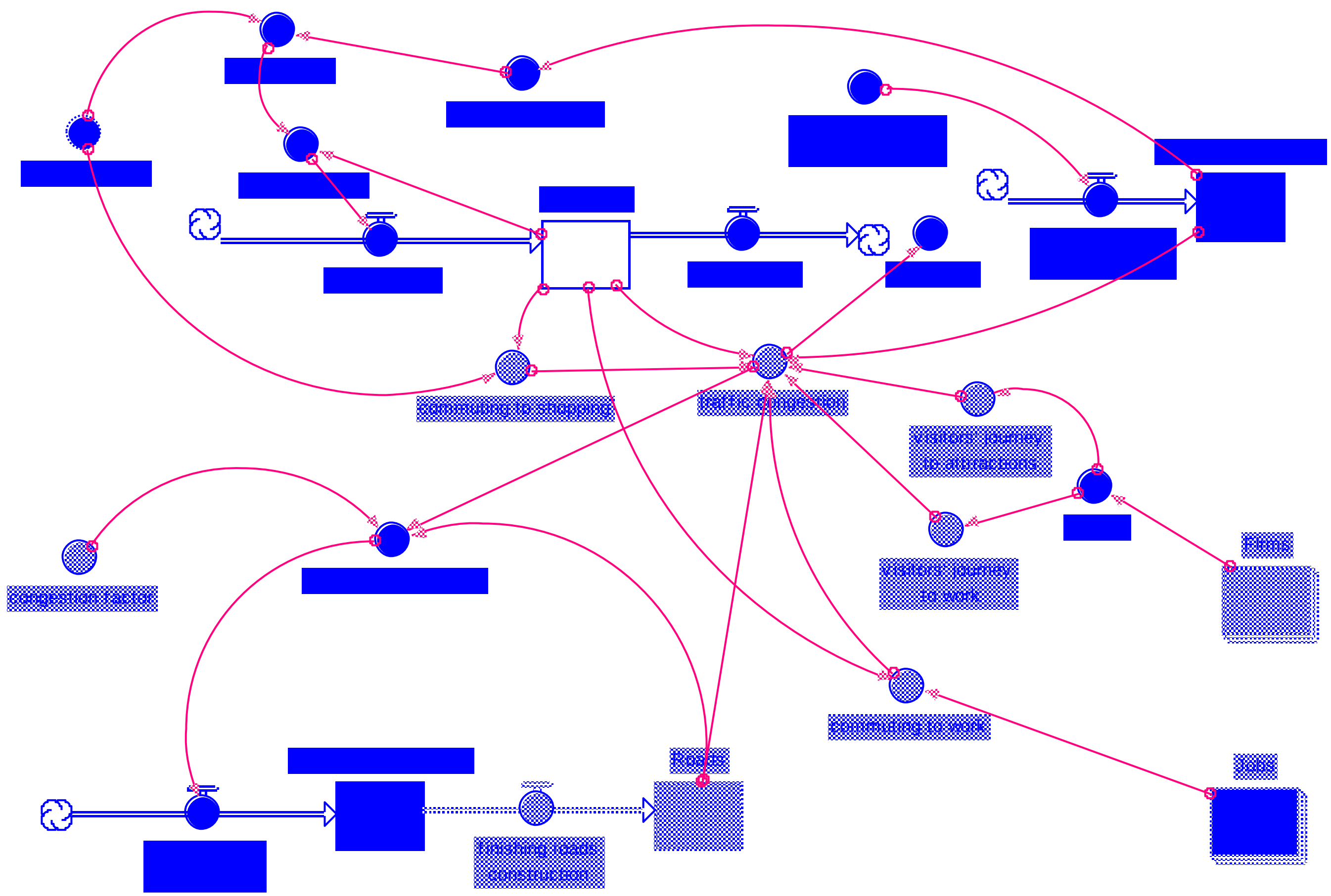


Figure 18. Transport sector, Source: Duran-Encalada and Paucar-Caceres

6.6 Water sector

The water consumption by residential, business, schools, health and medical centers, and other services provided in the zone is registered in this sector (Figure 19). If the water available becomes insufficient, some infiltration and well perforation works are carried on in order to provide more water to the region. However, infiltration capacity is reduced by the covered urban floor space in the zone. Consumed water is partially recovered by the water treatment plants and is brought back to the system for consumption. The indicator chosen in this sector was the **available water per house (indicator 9).**

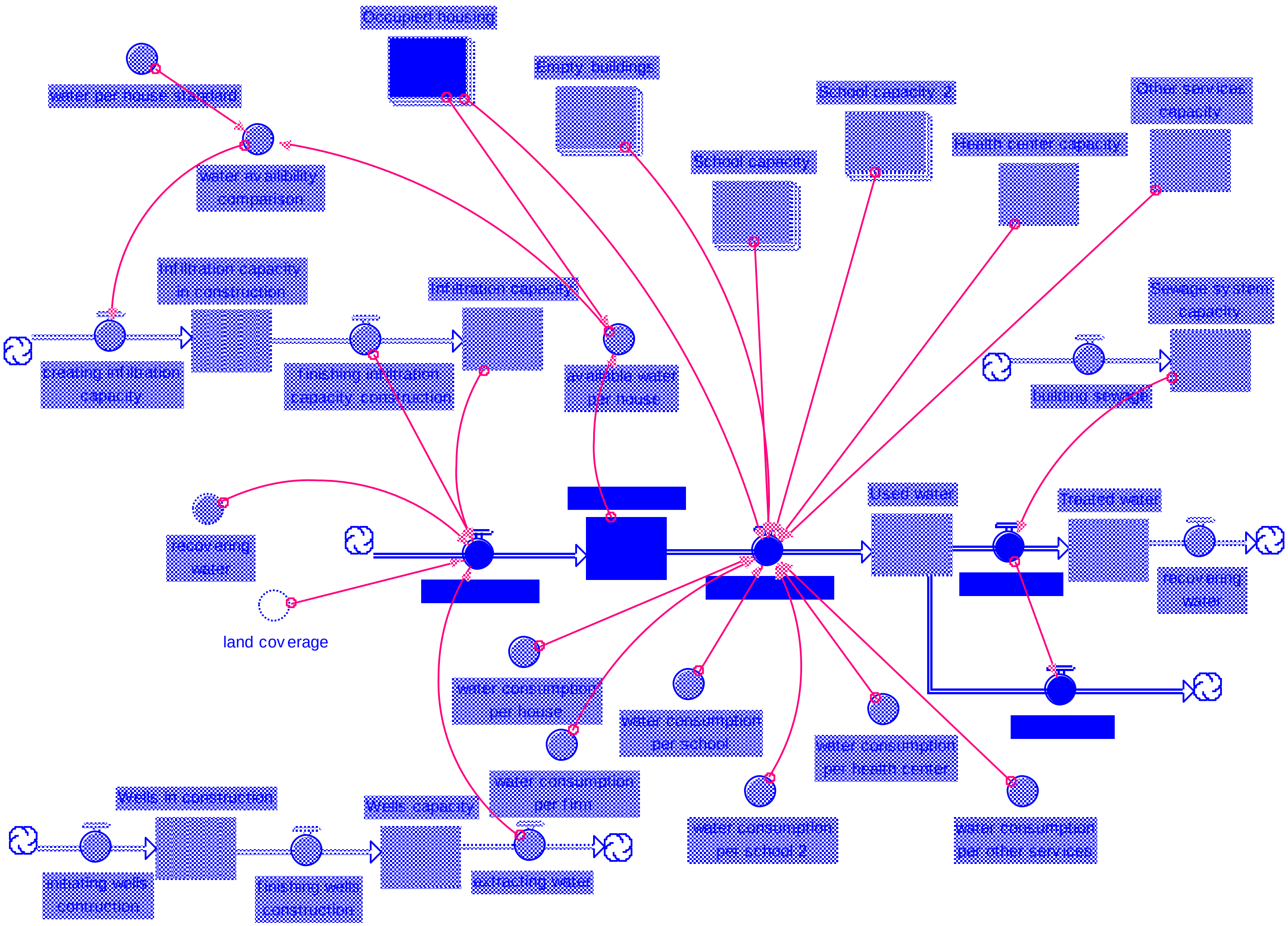


Figure 19. Water sector, Source: Duran-Encalada and Paucar-Caceres

6.7 Air pollution sector

Air pollution is the result of the vehicle stock, traffic congestion and commuting in the zone (Figure 20). Two types of contaminants are produced and registered, primary pollutants (SOx, NOx, and HC), and greenhouse gas emissions (GGE). From these and the total population in the zone, two indicators are obtained in this sector, **pollutants per capita (indicator 10) and gas per capita (indicator 11).**

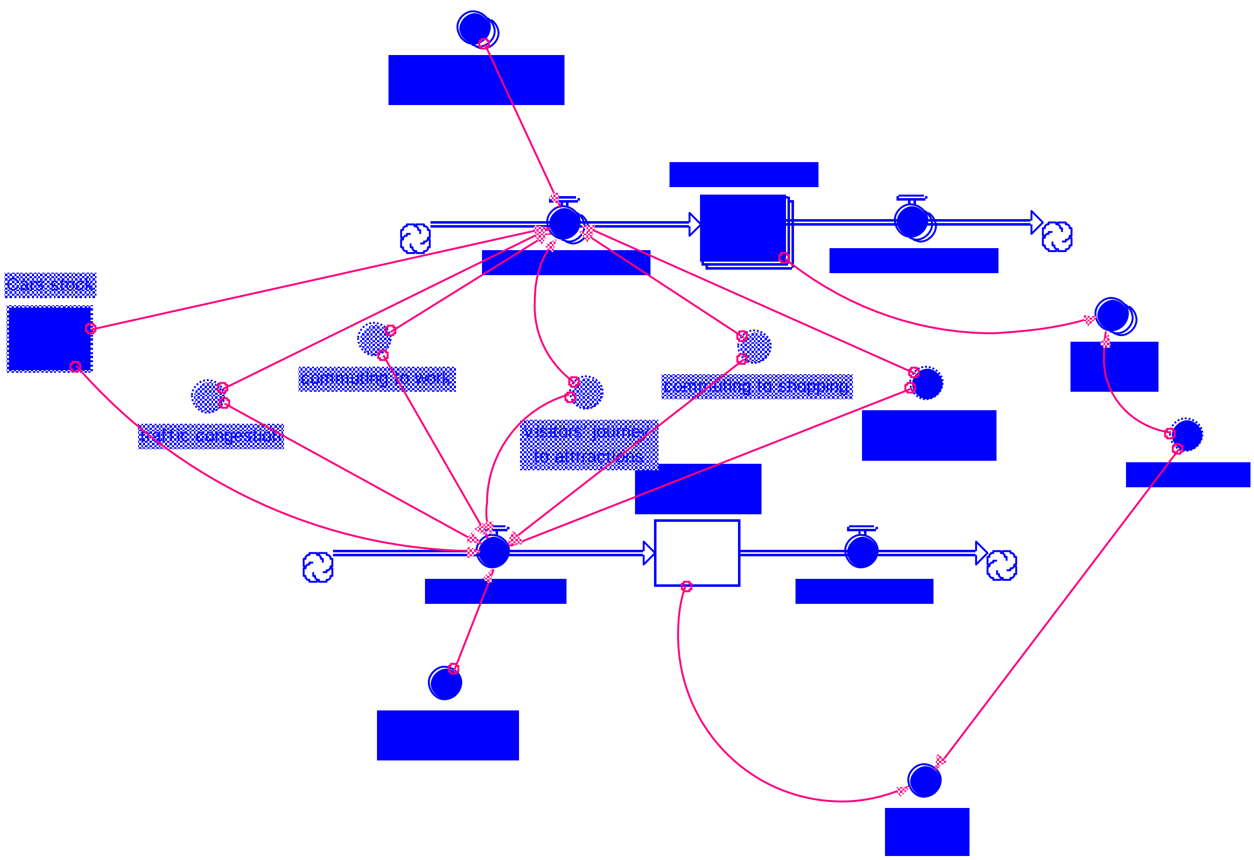


Figure 20. Air pollution sector, Source: Duran-Encalada and Paucar-Caceres

6.8 Solid waste sector

This sector shows the solid waste produced by households, business, schools, health and medical centers, and other services activities (Figure 21). This waste can end in two different places. First, it can be collected and then taken to public deposits where some portion is recycled. Second, waste could be accumulated in derelict land and streets without control. The clandestine organic and non-organic waste is dispersed in longer periods by natural biological and chemical processes. The **clandestine solid waste per capita (indicator 12)** is obtained in this sector.

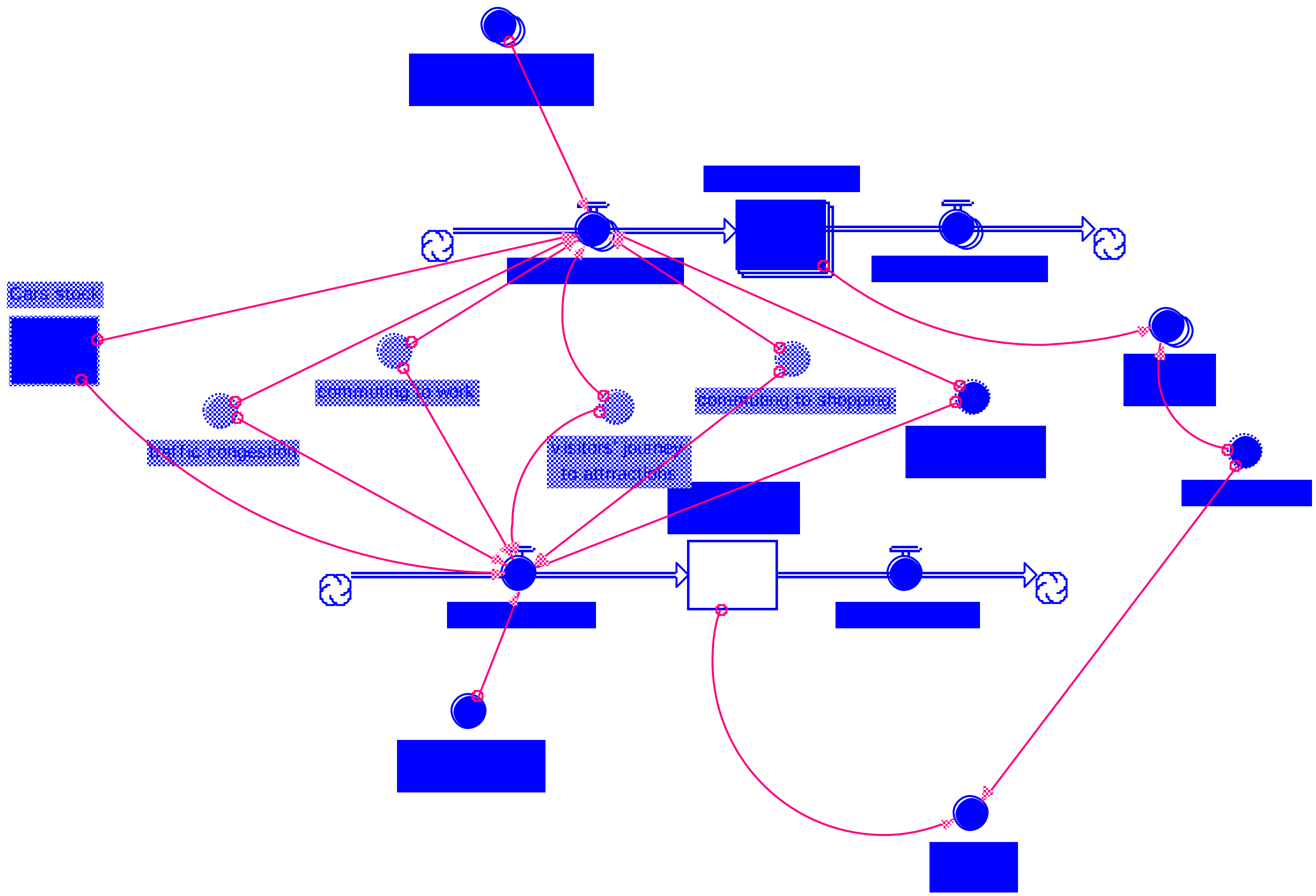


Figure 21. Solid waste sector, Source: Duran-Encalada and Paucar-Caceres

6.9 Land sector

The land sector shows that land which has been used for urbanization, as housing, commercial buildings, roads, and other urban facilities (Figure 22). When land is allocated to urbanization, the green areas diminish as indicated by the **land coverage (indicator 13).**

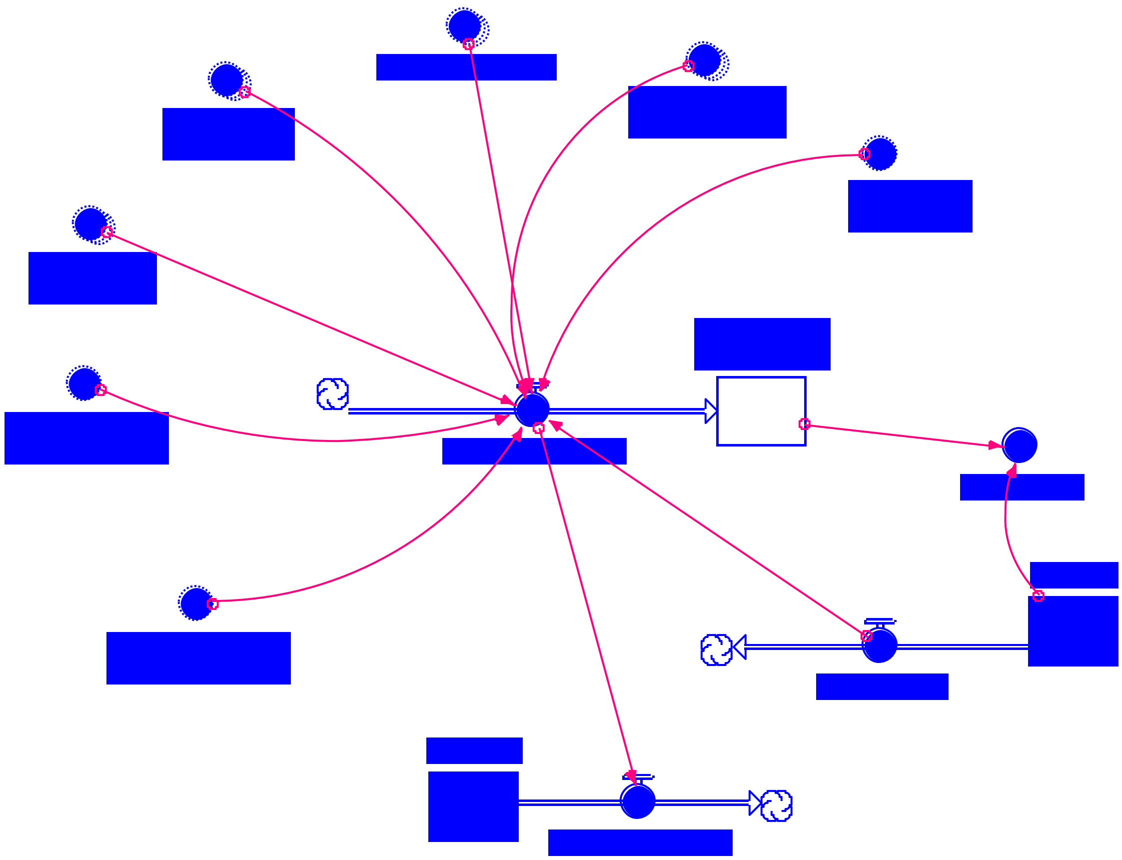


Figure 22. Land sector, Source: Duran-Encalada and Paucar-Caceres

7. Conclusions

- To tackle the issues of sustainability faced by the Puerto Aura (Valsequillo lake in Puebla, Mexico), different sustainable perspectives were examine;, in particular those associated with sustainable urban development (SUD). It has been argued that the framework proposed by Building Environmental Quality Evaluation for Sustainability through Time (BEQUEST) seems to be the most appropriate given the characteristics of Puerto Aura project. BEQUEST covers a whole range of methodologies and models for assessing environmental impacts for urban areas. BEQUEST has holistic features covering economic, social, environmental and institutional dimensions departing from the most inherent characteristics of urban areas as represented by land use and transport.

- Key concepts from the PROPOLIS model, a holistic and flexible model were also selected to be applied to the Puerto Aura case. In turn, the IRPUD model, as part of PROPOLIS, proposes concrete interactions between land-use and transport. Another part of PROPOLIS, the *Raster* module, complements these interactions connecting them to environmental variables. PROPOLIS proposals are flexible enough that can be applied to planning activities, to a spatial level that deals with a city region, for a horizon that goes beyond 20 years, and can be adapted to deal with particular sustainability indicators whose weight depends also on the city region's distinctive characteristics. Based on PROPOLIS, some SUD indicators were proposed for Puerto Aura project.

- Even though the broad coverage provided by PROPOLIS, the current stage of progress of the Puerto Aura project does not permit by now a disaggregated spatial analysis, as proposed by the *Raster* module. So, based still on PROPOLIS framework, a Systems Dynamics model was designed; the model captures the dynamic interactions that Sustainable urban development dimensions imply. SD inherent capability for analyzing systematically these inter-relationships, feedback processes, and its capacity for simulating consequences of different policies or institutional decision making, made SD as the most appropriate basis for modeling Puerto Aura project.

- The model structure and the relationships of the variables were described by sectors. The model was made operational with the Ithink 7.0 software and is prepared to simulate a 20 years horizon in monthly periods, that is, 240 months in total. At the moment, the model is in its trial stage, we hope to run it fully when the data from the Puerto Aura master plan becomes available; these data will enable the model to simulate policy decisions whose consequences in the medium and long terms will be then examined. Once the Puerto Aura master plan is finished it will provide a preliminary plan for the timing of the different areas included in the SUD project and will permit the model to simulate different scenarios.

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