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Urban Eco-Efficiency and System Dynamics Modelling

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Summary

The study tested the feasibility of dynamic modelling tools in assessing urban eco-efficiency. This was done by utilising presently available dynamic modelling software and by integrating available assessment tools of urban eco-efficiency developed for the City of Helsinki to the software.

The study was experimental in its nature. The used input data were more or less speculative to test the functionality of the model. That is why the test results like eco-efficiency impacts are not relevant as such. The real result is the experience of the arrangement of linkages between used parameters and factors and the complexity of their relationships.

The experiment revealed that there is a big potential in dynamic modelling devices for the urban planners, designers and other developers. The potential is not yet recognised well enough and more experiments and novel development efforts are needed.

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Preface

Assessment of urban development is generally based on static models of economic, social or environmental impacts (the three pillars of sustainability). Dynamic models have been used mostly for prediction of population and employment changes as well as for other macro-economic issues. This *feasibility study* was arranged to test the potential of dynamic modelling in assessing eco-efficiency changes during urban development. The test became relevant after recent development of assessment tools of urban eco-efficiency for the City of Helsinki and simultaneous availability of new dynamic modelling software. This possibility was recognised at VTT Technical Research Centre of Finland during the IBEN project (Eco-efficient Intelligent Built Environment).

The study was conducted under the supervision of the IBEN project and its leader, key account manager Jouko Törnqvist.

The integration of dynamic modelling and assessing urban eco-efficiency was realised by research scientist Petr Hradil (dynamic modelling) and chief research scientist Pekka Lahti (assessing eco-efficiency, urban development) who also are the main authors of this report. Senior scientist Appu Haapio wrote chapter 2 with references to some environmental assessment tools. The IBEN project leader Jouko Törnqvist and some of the researchers participated in the brainstorming and feedback discussions arranged during the study period.

The authors wish to encourage further feedback to the results of the study and also continuation of this kind of experimental efforts to help urban developers in their task to improve urban sustainability.

Espoo 13.7.2012

Authors

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1 Introduction

The proposed model combines evaluation of urban eco-efficiency with systems dynamics modelling (Figure 1). The Urban Eco-Efficiency System Dynamics model is hereafter referred to as "UEE-SysDyn" model.

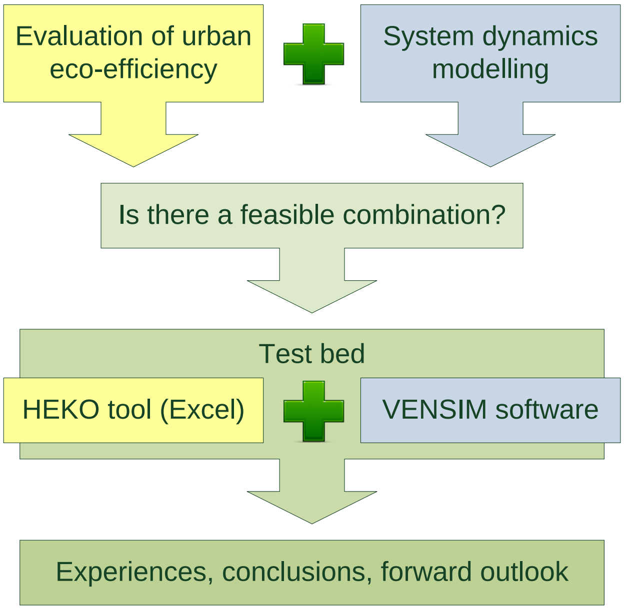


Figure 1 The main idea of the study and the tools used in the test bed.

The modelling experiment acts as a test bed and a pilot study representing a first step in a foreseen modelling process aiming at a feasible tool of the eco-efficiency evaluation for urban developers. The model at this stage tries to answer the basic question whether the dynamic modelling approach brings new useful and fruitful aspects to urban planning and decision-making when considering their contribution to global issues of sustainability and climate change. The basic structure and elements of the developed dynamic model are quite conventional in the dynamic modelling discipline. *The factors, variables, dynamic links, parameters and other elements of the test bed model are not to be considered as suggestions for the correct or ideal structure of an urban dynamic model but only as examples of possible elements in the future development of this kind of models.*

The elements of eco-efficiency criteria involved in the model are derived from an existing development work and experience at VTT. The modelling has been developed during long experience of different assessment assignments of the eco-efficiency of the urban development on national, regional, city and residential area levels. The latest phase of the assessment modelling has been the HEKO tool for the City of Helsinki.

The novelty of the current modelling effort lies in its attempt to integrate classic assessment procedure of a static object (like a single industrial product, a refrigerator, car or a combination of products like a house or in this case a specified urban area) to a dynamic environment (like urban development). Within the wide spectrum of assessment disciplines and aspects this work concentrates in the eco-efficiency of the built environment. The previous dynamic models[1] [2][3][4][5] dealing with urban development are more focusing on typical socio-economic variables like population, work force, jobs, production output, employment, migration etc. and less on features of the built environment or its essential qualities or other properties.

The model proposed by Forrester concentrates on the **dynamic simulation of business sector** and all the related indicators in the urban area such as housing, labor and taxes.

The model of the City of Accra in Ghana [6] simulates the **dynamic changes in road construction** to avoid the traffic congestion and reduce the air pollution (Figure 2). Especially the modelling of "attractiveness of driving" seems to be usable in the UEE-SysDyn modelling case.

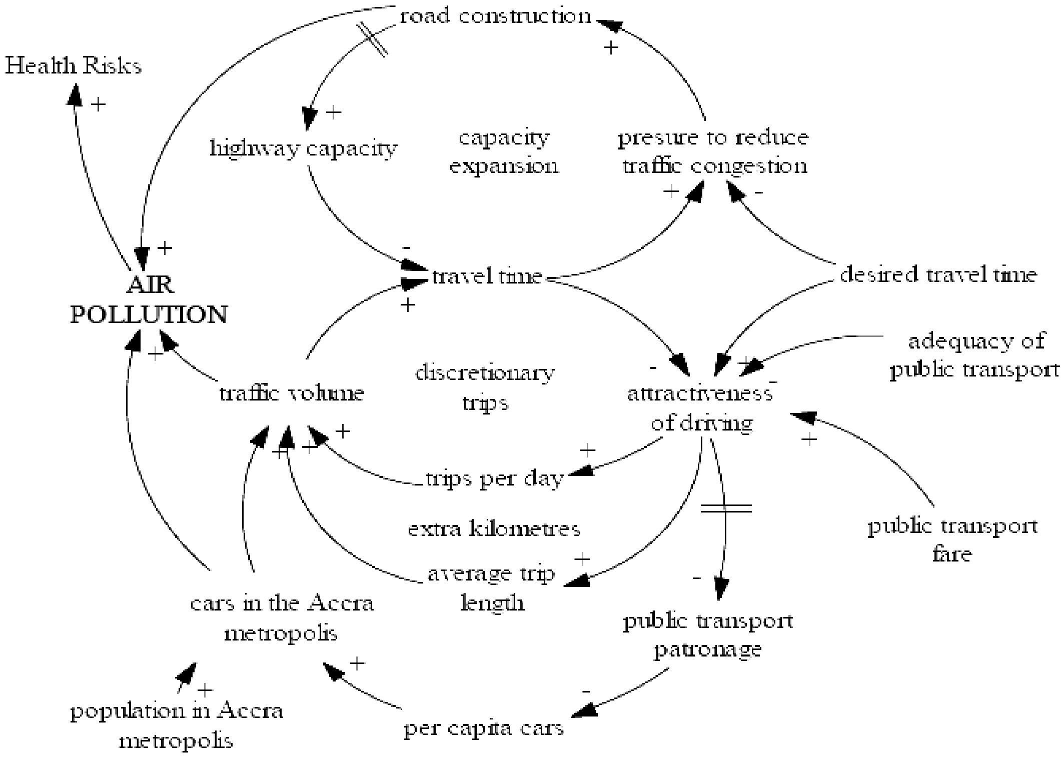


Figure 2 The model of the City of Accra in Ghana [6].

[1] see most notably Jay Forrester's work presenting his dynamic simulation models at MIT in 1960s applied first in industrial processes (1961) where after he implemented the ideas in urban development (1969) as well as on a global level (1973). Later on the same type of dynamic modelling became famous in the works of Club of Rome and published under the title Limits to Growth (Meadows et al. 1972).

2 Existing assessment tools for ecological urban development

This chapter describes briefly three examples of most commonly known assessment tools for urban ecology. These are in the order of appearance in the market CASBEE for Urban Development (Japan), BREEAM Communities (UK), and LEED for Neighbourhood Development (USA).

2.1 CASBEE for Urban Development

Comprehensive Assessment System for Building Environmental Efficiency - CASBEE is a joint research and development project of Japanese government, industry and academia. The co-operation started in 2001. CASBEE's product family covers Housing scale, Building scale and Urban scale (CASBEE, 2010). CASBEE for Urban Development (CASBEE-UD) is a standalone tool. CASBEE-UD focuses on the assessment of urban areas, the phenomena of conglomeration of buildings, infrastructure and the outdoor spaces. The interior of the buildings are excluded from CASBEE-UD. The individual buildings can be evaluated with Building scale CASBEE. The product family also includes CASBEE for an Urban Area + Buildings (CASBEE-UD+) which enables the use of CASBEE-UD together with Building scale assessment [8].

In the assessment, a hypothetical boundary is drawn around the designated area. The assessment addresses the environmental quality (Q_{UD}) within that boundary, and the environmental load (L_{UD}) beyond that boundary. Both Q_{UD} and L_{UD} comprise three main categories. All these six categories are evaluated and scored separately. The categories are compounded using the formula **Error! Reference source not found.** to generate an indicator for Building Environmental Efficiency in Urban Development (BEE_{UD}) [8].

$$BEE_{UD} = \frac{Q_{UD}}{L_{UD}} \quad (1)$$

Each major category, from $Q_{UD}1$ to $LR_{UD}3$, comprises 4–6 medium-level categories. L is first evaluated as LR (load reduction). The medium-level categories are divided into minor categories as required. The minor categories are graded on 5 levels; 1-5, level 3 being the reference level. In addition, the weighting coefficients are applied to calculate the results. The coefficient cannot be changed [8].

- $Q_{UD}1$ - Natural Environment (microclimates and ecosystems)
- $Q_{UD}2$ - Service functions for the designated area
- $Q_{UD}3$ - Contribution to the local community (history, culture, scenery and revitalization)
- $LR_{UD}1$ - Environmental impact on microclimates, façades and landscape
- $LR_{UD}2$ - Social infrastructure
- $LR_{UD}3$ - Management of the local environment.

CASBEE-UD is for assessing building groups. They can vary from a few adjoining plots to hundreds, or thousands plots with non-built land (e.g. roads, parks). The assessment tool can be utilized in the development of “new towns”. The designated areas are divided into two types according to their floor-area ratio having different weighting coefficients:

- City-centre type = high usage development (floor-area ratio > 500%)
- General type = general developments (floor-area ratio > 500%) [8].

Since the assessments are time consuming, CASBEE has introduced a brief version of the conventional standardised version. However, simplifying issues may influence the assessment - it may diminish the stringency of the assessment. Therefore, CASBEE has made it harder to earn high-level assessment within the brief version [8].

In addition to various bar charts and radar charts, CASBEE uses five scale rating: Excellent (S), Very Good (A), Good (B+), Fairly Poor (B-) and Poor (C) [8].

Table 1. Rating of CASBEE for Urban Development with required BEE (Building Environmental Efficiency) and Q (Quality) values [8].

Ranks	Assessment	BEE value, etc	Expressions
S	Excellent	BEE ≥ 3.0, Q ≥ 50	☆☆☆☆☆
A	Very Good	BEE = 1.5–3.0	☆☆☆☆
B+	Good	BEE = 1.0–1.5	☆☆☆
B-	Fairly Poor	BEE = 0.5–1.0	☆☆
C	Poor	BEE = less than 0.5	☆

2.2 BREEAM Communities

BREEAM Communities is based on the established BREEAM methodology. BREEAM Communities focuses on mitigating the overall impacts of development projects within the built environment. Moreover, it provides an opportunity for the project to show their environmental, social, and economic benefits to the local community [7]. In the BREEAM Communities certification, criteria are divided into eight categories of sustainability:

- Climate and energy - focuses on reducing the project’s contribution to climate change,
- Community - supports vibrant communities and encourages to integrate with surrounding areas,
- Place shaping - provides a framework for the design and layout of the local area,
- Ecology and Biodiversity - aims at conserving the ecological value of the site,
- Transportation - focuses on sustainable transportation options, and encouraging walking and cycling,
- Resources - emphasises sustainable and efficient use of resources,

- Business - aims at providing opportunities for local businesses and creating jobs in the region,
- Buildings - focuses on the overall sustainability performance of buildings. [7]
- Each category consists of a number of issues - criteria. Altogether, there are 51 criteria; 23 of them are compulsory. Credits are awarded according to performance - from 1 to 3 points. These credits are added together to produce a single overall score (Table 2).

Table 2. Ratings of BREEAM Communities [7].

BREEAM Communities Rating	% score
UNCLASSIFIED	< 25
PASS	≥ 25
GOOD	≥ 40
VERY GOOD	≥ 55
EXCELLENT	≥ 70
OUTSTANDING*	≥ 85

* There are additional requirements for achieving a BREEAM *Outstanding* rating.

2.3 LEED for Neighbourhood Development

LEED for Neighbourhood Development (ND) integrates the principles of smart growth, urbanism and green building into a neighbourhood design rating system. It emphasises land use and environmental considerations in the United States. The rating system was developed by the U.S. Green Building Council (USGBC) for national use. The pilot was launched in 2007, the actual rating system a few years later, in April 2010.

There are no limits to the size of the project; however, it is reasonable to include at least two buildings into the project. Very large projects, over 320 acres, could be divided into smaller projects. The projects can be parts of neighbourhood, whole neighbourhoods, or even multiple neighbourhoods. The location of the project area plays a crucial role in the certification process. LEED ND is for following destinations:

- Infill site
- Adjacent site
- Existing site
- Retrofit the suburbs
- Moreover, utilisation of brown fields is recommended.

In LEED for Neighbourhood Development (ND) rating system, designated area is assessed against different criteria. These criteria can be divided into three main categories, and two additional categories (Table 3). All three main categories consist of prerequisites and credits. Total points from the main categories are 100 points. It is possible to achieve 10 bonus points from the additional categories. The higher the points, the better the rating:

- 40+ points Certified

- 50+ points Silver
- 60+ points Gold
- 80+ points Platinum.

Several credits of the main categories are interlinked; achieving one credit may help achieving other credits. Therefore it is wise to analyse the target of the certification together with the interlinked credits. On the other hand, this could be seen as optimising and minimising the work load.

Table 3. LEED-ND main categories and additional categories [7]).

Total points	100 + 10 = 110
Smart location and linkage	27
Neighbourhood pattern and design	44
Green infrastructure and buildings	29
Innovation and design process	6
Regional priority	4

Smart Location and Linkage (SLL) favours the development of cities and suburban areas. In addition, the utilisation of brown fields is recommended. Development, improvement, revitalisation and vicinity of services are important aspects. By favouring public transportation and bicycle and pedestrian traffic, auto dependency is hopefully being reduced - the public health issues would also require it. Furthermore, SLL tries to minimise different environmentally harmful effects and protect areas, populations and water bodies.

Neighbourhood Pattern and Design (NPD) emphasises bicycle and pedestrian traffic from different viewpoints, such as health, safety, habitability, and easiness. NPD also favours public transportation aim to reduce auto dependency. NPD reaches for rich neighbourhood - interactive neighbourhood with tenants, services and social interactions. Moreover, different aspects of solutions are pointed out. Effects of building a park area, for example, can be analysed from several viewpoints: social interaction, storm water or heat islands.

Green Infrastructure and Buildings (GIB) devotes to decreasing environmental impact caused by construction and maintenance of buildings and infrastructure. Energy and water efficiency are emphasised, as well as minimisation of amount of waste and promotion of recycling. GIB focuses on minimisation of harmful environmental impacts and protection of living conditions of existing flora and fauna. Moreover, at least one of the buildings in the certified area has to be certified with a LEED certificate. Additional certified buildings may bring in extra points.

2.4 Comparison of the tools

The criteria of the urban assessment tools were divided into seven categories. The categories with the main issues are presented in Table 4. The chosen categories with main issues were common among the three assessment tools, except “Wellbeing”. It was included because the role of the inhabitant is often acclaimed to be increasing in the decision making.

Table 4. Categories with main issues.

Categories	Issues covered
Infrastructure	Design principles, Communities, Buildings in the area, Heat islands, Policy and Governance
Location	Land use, place shaping, Policy and Governance, Affordable housing
Transportation	Public transport, Pedestrian and bicycle way, Private cars, Parking, Telecommuting
Resources and Energy	Waste management, Use of materials, Conservation, Non-renewables, Renewables
Ecology	Nature, Biodiversity, Water management
Business and Economy	Employment, New business, Telecommuting
Well being	Quality of life, social infrastructure, urban context

The boundaries of the categories partly overlap. Therefore, it is difficult to place some of the criteria; they could be placed on several categories. In this review, however, criteria are placed once; to the category they affect most (Table 5).

Table 5. Comparison of the tools.

	BREEAM		CASBEE		LEED		TOTAL	
CATEGORIES	Criteria	%	Criteria	%	Criteria	%	Criteria	%
Infrastructure	12	24	36	45	17	32	65	35
Location	7	14	3	4	5	9	15	8
Transportation	11	22	6	8	8	15	25	14
Resources and Energy	7	14	14	18	8	15	29	16
Ecology	9	18	14	18	14	26	37	20
Business and Economy	5	10	2	0	1	2	8	4
Well being	0	0	5	9	0	0	5	3
TOTAL	51	100	80	100	53	100	184	100

3 The basic concepts of the proposed model

3.1 Urban eco-efficiency

The core of the model is the calculation and simulation of **urban eco-efficiency** *UEE* as the ratio of the quality of life *QL* and environmental load *EL*. Which is common approach in the existing eco-efficiency assessment tools (see Chapter 2)

$$UEE = \frac{QL}{EL},$$

which is graphically represented in the system dynamics model (Figure 3).

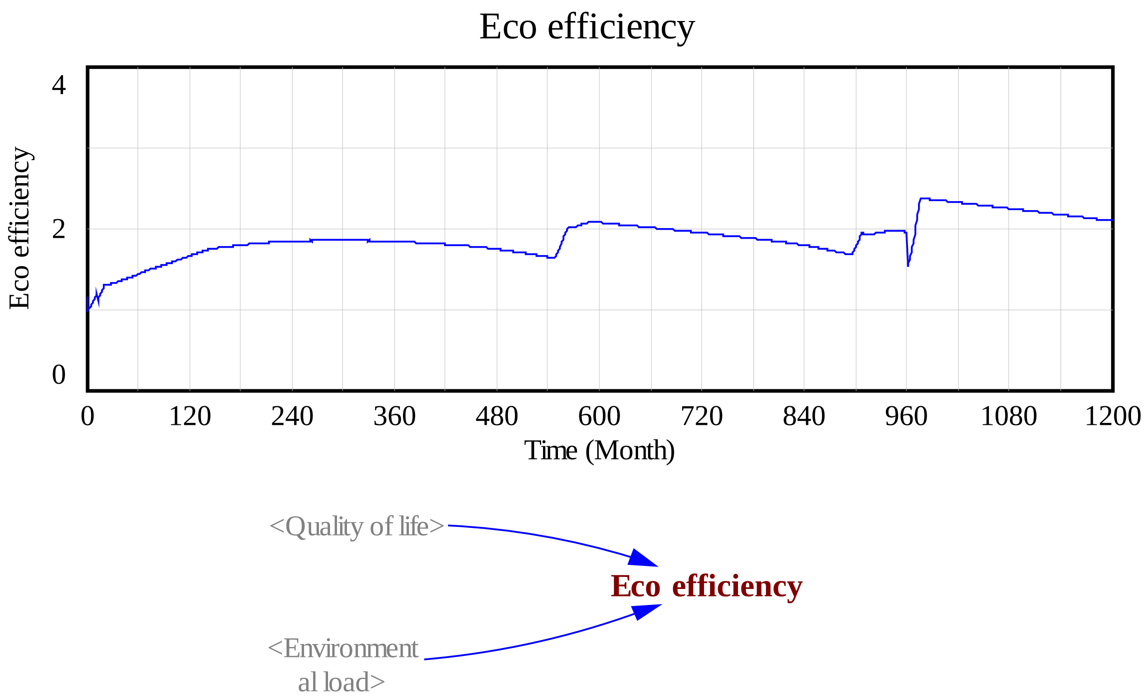


Figure 3. Eco-efficiency as the core of the system dynamics model (below). The graph (above) presents the simulated development of the eco-efficiency in a theoretical test case.

Both *QL* and *EL* are relative numbers from 0 to 1 (0 is the lowest possible quality or load at given time and 1 represents the highest possible quality or load).

The problem of such model arises when the environmental load is very low and the small difference in *EL* creates much bigger differences in eco-efficiency (Figure 4). The solution can be by introducing a classification of eco-efficiency with unequal class sizes (e.g. in CASBEE, see Table 1) or different method of *UEE* calculation.

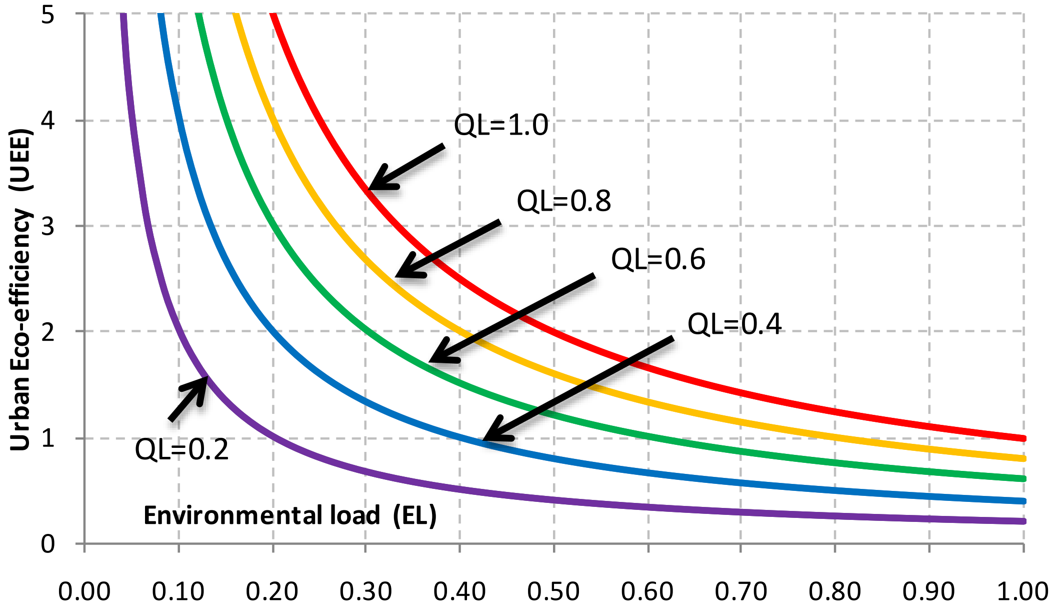


Figure 4. Urban eco-efficiency for different EL and QL values.

The following classification is fitted to the ranges (from 0 to 1) of environmental load and quality of life that are used in our proposed tool:

Table 6. UEE classification and respective values.

Urban eco-efficiency class	UEE values
UEE A++	more than 8
UEE A+	from 4 to 8
UEE A	from 2 to 4
UEE B	from 1 to 2
UEE C	from 0.5 to 1
UEE D	from 0.25 to 0.5
UEE E	from 0.125 to 0.25
UEE F	less than 0.125

3.2 Quality of life

The **quality of life** *QL* is the weighted average of four partial qualities (Figure 5) described in chapters 4.2–4.5 in more detail (*QH* - quality of housing, *QS* - quality of services, *QA* - area attractiveness, *QT* - quality of transport).

$$QL = a_1 \cdot QH + a_2 \cdot QS + a_3 \cdot QA + a_4 \cdot QT$$

In this pilot phase, the constants a_1 to a_4 are set to equal values ¼, but can be also weighted in a different way, like percentages from 0 to 100%.

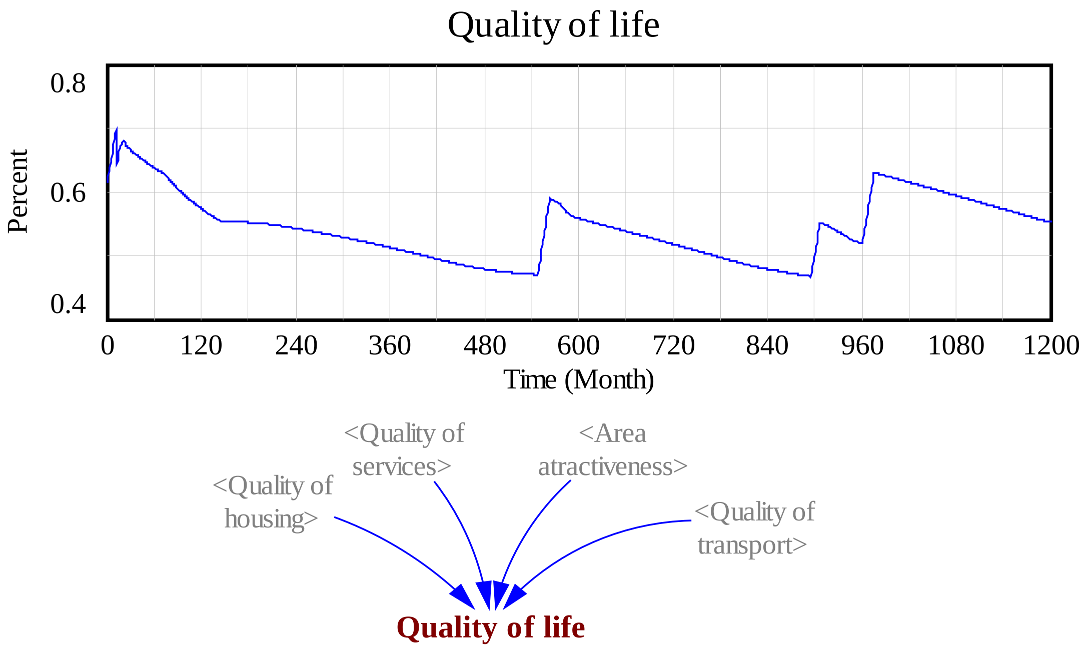


Figure 5. The quality of life is composed of four sub-models of different quality factors (below). The graph (above) presents the simulated development of the quality of life in a theoretical test case.

3.3 Environmental load

The **environmental load** *EL* is the weighted average of three partial loads (Figure 6): energy load *ENL* emissions and waste load *EWL*, and environmental load from building activities *EBL*.

$$EL = j_1 ENL + j_2 EWL + j_3 EBL \,.$$

In this pilot phase, the constants j_1 to j_3 are set to equal values ⅓, but can be also weighted in a different way, like percentages from 0 to 100 %.

The basic values of energy load (*ENL**) as well as emissions and waste load (*EWL**) are recalculated from the average HEKO indicators *HI* of groups “ENERGY” and “CARBON AND MATERIAL CYCLES” (see Attachment A: Issues and criteria of eco-efficiency assessment in HEKO tool) to range from 0 (the lowest possible load, i.e. 100 plus HEKO index deviation *HID*) to 1 (the highest possible load, i.e. 100 minus HEKO index deviation *HID*)

$$ENL^* = \frac{100 + HID_{Energy} - HI_{Energy}}{2 \cdot HID_{Energy}} \text{ and } EWL^* = \frac{100 + HID_{Cycles} - HI_{Cycles}}{2 \cdot HID_{Cycles}}$$

Additionally, the environmental load is always relative to the number of people occupying the simulated area. In residential areas it is normally the number of inhabitants, but in other types of areas it is recommended that the number of inhabitants and jobs in the area are summarized. The influence of occupancy on the environmental load *OCF* is included so that the minimum occupancy creates always the maximum load $EL = 1$.

$$ENL = ENL^* + (1 - ENL^*)OCF \text{ and } EWL = EWL^* + (1 - EWL^*)OCF$$

The occupancy factor *OCF* (from 0 to 1) is calculated according to the following equation:

$$OCF = \left(k_1 \frac{PL - I}{PL} + k_2 \frac{JL - J}{JL} \right),$$

where *I* and *J* are number of inhabitants and jobs, and *PL* and *JL* are the population and jobs limits. In this pilot phase, the constants k_1 and k_2 are set to equal values ½, but can be also weighted in a different way, like percentages from 0 to 100%.

The value of **building load** *EBL* is related to the building activities *BA* (that are non-zero only for short periods of time) and the average of HEKO indicators related to the building process (indicators no 3 earthmoving, no 4 contaminated soil and no 6 structural quality of soil for building purposes, see Attachment A). It creates temporary increased environmental loads during the building periods.

$$EBL = BA \frac{100 + HID_{Build} - HI_{Build}}{2 \cdot HID_{Build}}$$

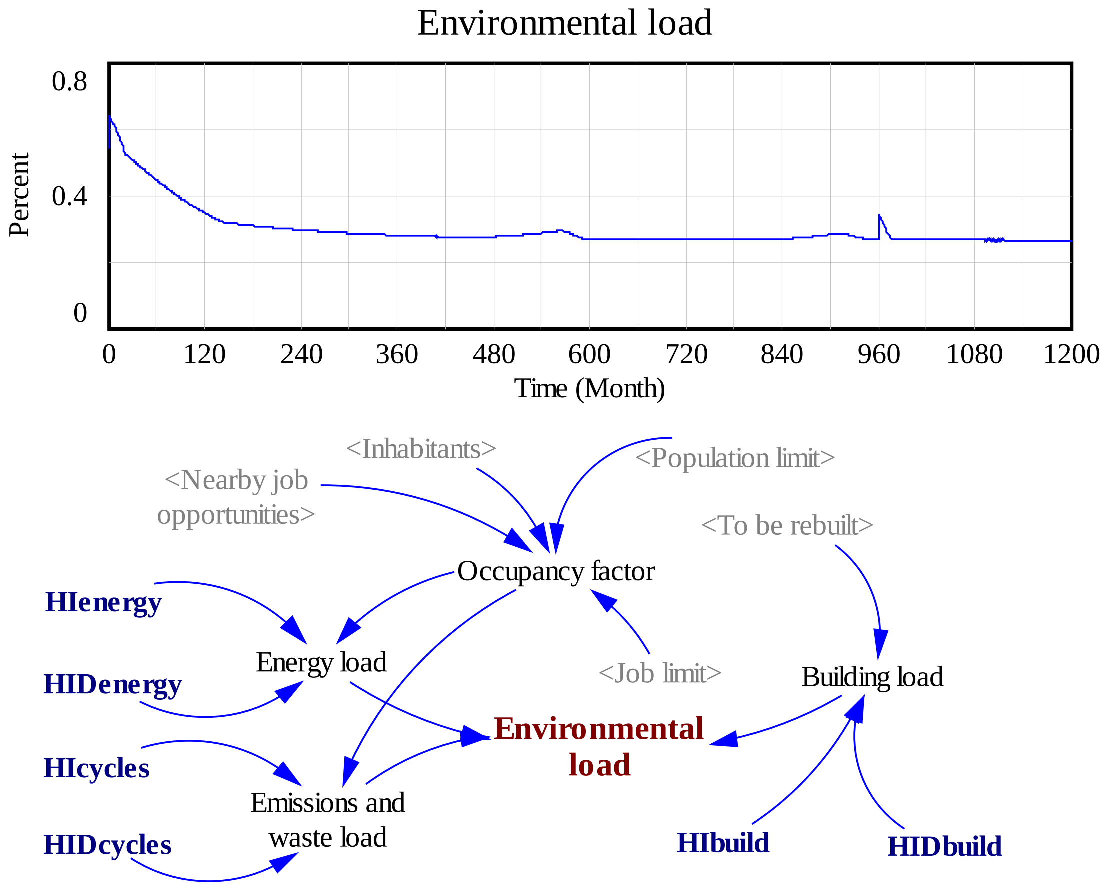


Figure 6. The environmental load is based on an index calculated according to the HEKO tool and affected by the number of inhabitants and jobs, and the population and job limits in the area (below). The graph (above) presents the simulated development of the environmental load in a theoretical test case.

4 Model segments

4.1 Population dynamics

The population change rate is calculated from basic birth rate (births per 1 000 people per year), death rate (deaths per 1 000 people per year) and net immigration rate. "Additional net immigration" is accounted for, if the quality of life *QL* in the area compared to the average *QL* in surrounding areas (within the same commuting area, like the city region) reaches a certain level. That can be beneficial when all the city parts are simulated at the same time.

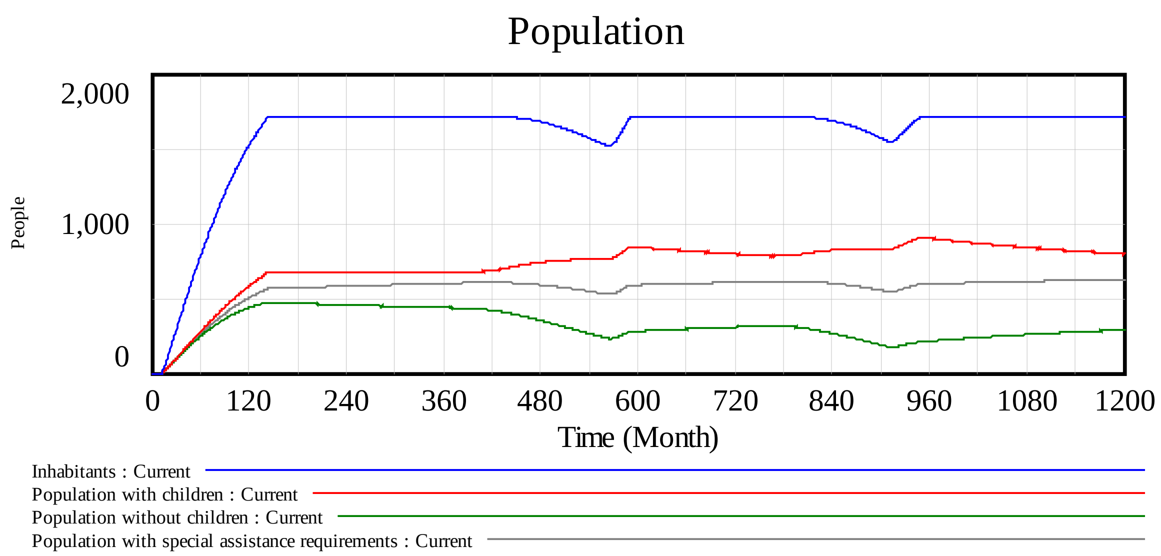


Figure 7. The graph describing the simulated development of inhabitants in the area in a theoretical test case.

The main part of the basic stock variable, the **total population** *I*, is the number of inhabitants, which is calculated as a sum of the population with children I_A, population without children I_B and the number of people requiring special assistance I_C.

The number of people in families with children I_A is based on the migration rate of families with children M_A and the birth rate B. Additionally, it is assumed that the average number of children in families is 2, and therefore for every new born child one adult inhabitant (in average) is moved from the group without children I_B to the group with children I_A.

$$I_A = \int (B + M_A - T_1)dt \text{, where } T_1 = I_A/(12 \cdot 16) - \min(B; I_B) \text{ in } \textit{People/Month.}$$

The transfer T_1 to the group without children I_B is 1/16 of the population with children per year (this means one 16-years old child and one adult of an average family) and the total population in group I_B is the sum of integrals of these transfers together with the migration rate M_B.

$$I_B = \int (T_1 + M_B - T_2)dt \text{, where } T_2 = (I_A + I_B)/(12 \cdot 70) \text{ in } \textit{People/Month.}$$

The last group I_C represents the number of people requiring special assistance. So far the transfer T_2 from group I_B is 1/70 of the families with and without children per year. Also the total population of group I_C is calculated from the migration rate M_C and decreased by the death rate D.

$$I_C = \int (T_2 + M_C - D)dt$$

All the basic rates are recalculated to *People/Month.*

$$B = \begin{cases} I \cdot BB/12000 \; if \;\; I < PL \\ 0 \, else \end{cases} \text{ and } D = I \cdot BD/12000 \text{ (}PL\text{ is the population limit)}$$

Table 7. population dynamics constants.

Constant name	Units	Description	Initial setting	Comments
Basic birth rate *(BB)*	*People/ 1 000·Year*	People born per 1 000 inhabitants during one year	10.9	From EU statistics
Basic death rate *(BD)*	*People/ 1 000·Year*	People died per 1 000 inhabitants during one year	9.7	From EU statistics
Basic migration rate *(BMR)*	*People/ 1 000·Year*	People moving in and out of the area per 1 000 inhabitants during one year (net)	3.1	From EU statistics Positive = immigration Negative = emigration
Average surrounding QL *(ASQL)*	*0 to 1*	Average quality of life in the surrounding area)	0.5	Has to be set according to the real situation. Influences internal movement of people within the region.
Maximum additional migration rate *(MAM)*	*People/ Month*km²*	Number of people per month moving in and out of the 1 km² area when the difference between local and surrounding quality of life reaches the maximum (1).	100	Rough estimate

QL - Quality of life expressed as number from 0 (the lowest possible at current time in the whole region) to 1 (the highest possible at current time in the whole region)

The **migration rate** M comes from basic migration BM and additional migration AM:

$$M = \begin{cases} 0 \; if \;\; I \geq PL \, and \;\; BM + AM > 0 \\ 0 \; if \;\; I \leq 0 \, and \;\; BM + AM < 0 \\ BM + AM \;\; else \end{cases},$$

where the basic migration BM is calculated in the same way as birth and death rates B and D.

$$BM = I \cdot BMR/12000,$$

while the additional migration *AM* depends on the difference between the quality of life *QL* and average surrounding quality *ASQL* and represents the migration from/to the neighbourhood areas. The maximum possible additional migration rate (when the life quality difference is 1) is equal to *MAM* multiplied by the total land area *TA*.

$$AM = (QL - ASQL) \cdot MAM \cdot TA$$

The response of additional migration AM is 12 months delayed.

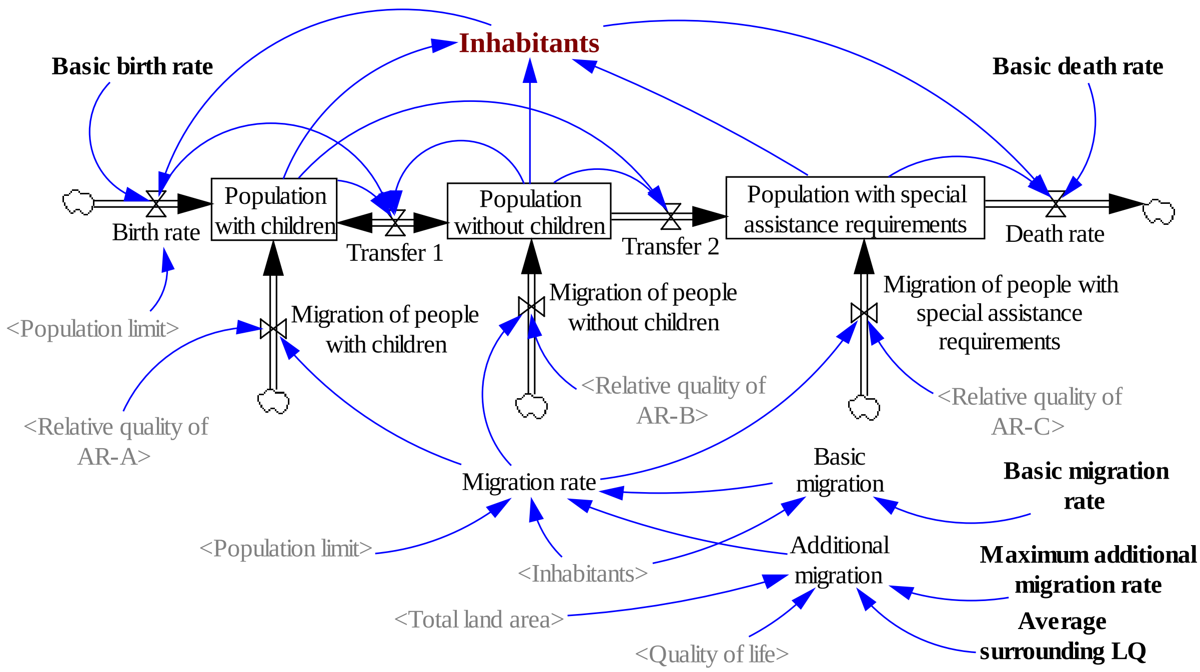


Figure 8. The population dynamics.

The migration rate *M* is then divided into three migration rates M_A, M_B and M_C according to the basic attractiveness of the area for each group of inhabitants.

$$M_A = \frac{Q_{AR,A}}{Q_{AR,A} + Q_{AR,B} + Q_{AR,C}} M ,$$

$$M_B = \frac{Q_{AR,B}}{Q_{AR,A} + Q_{AR,B} + Q_{AR,C}} M ,$$

$$M_C = \frac{Q_{AR,C}}{Q_{AR,A} + Q_{AR,B} + Q_{AR,C}} M .$$

The attractiveness factors $Q_{AR,A}$ to $Q_{AR,C}$ originate from the data provided by [1].

4.2 Quality of housing

Basic degradation of building structure HD_1 (not possible to repair) includes also the aging of the basic housing concept - e.g. room design and other technical things). Additionally, the secondary degradation HD_2 (e.g. by using) is added.

This can be repaired when the overal *QH* reaches the minimum value *MinQH*. Rebuilding starts when the maximum *QH* is too low (it is set to 2x minimum *QH*).

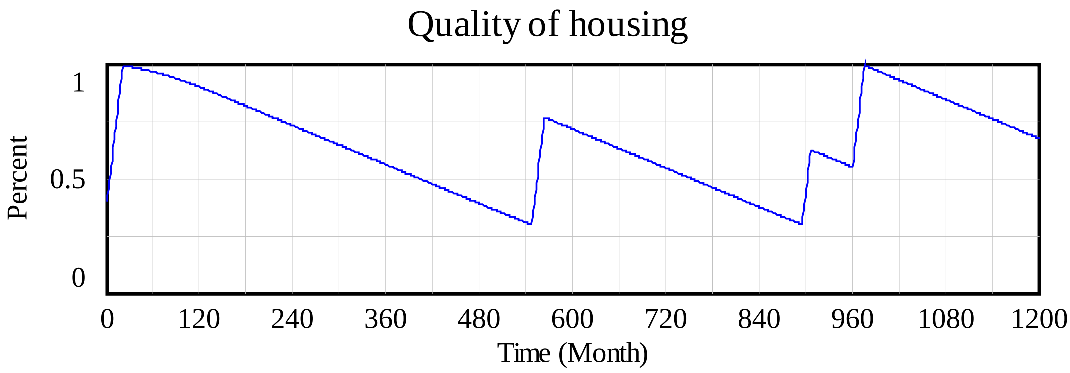


Figure 9. The graph describing the simulated development of the quality of housing in the area in a theoretical test case.

The **quality of housing** *QH* is calculated as integral of degradation rate *HD*, repair rate R_1 and rebuild rate R_2, where repair and rebuild values are non-zero only for short periods of time. The quality of housing is limited by minimum and maximum values *MinQH* and *MaxQH*; therefore it can be also any value between 0 and 1.

$$QH = \int (-HD + R_1 + R_2)dt \text{, initial value } IQH$$

The **maximum quality of housing** *MaxQH* is constantly decreasing (basic degradation rate HD_1) but can be restored while rebuilding (*MaxQH* restore rate R_3) to the initial value *PQH*. Here, the basic idea represents not only the aging of non-repairable housing parts but more importantly the obsolete building materials, building design, technologies and so on (the same house built in the future will get always lower quality assessment).

$$MaxQH = \int (-HD_1 + R_3)dt \text{, initial value } IQH$$

The **basic degradation rate** HD_1 (in *QH/Month*) is calculated directly from the housing service life *HSL*:

$$HD_1 = IQH/(12 \cdot HSL)$$

The **total degradation rate** *HD* (in *QH/Month*) is composed from the basic one HD_1 and the secondary degradation HD_2 normalized to the housing occupancy (ratio of *I* and *PL*):

$$HD = HD_1 + HD_2(I/PL)$$

Table 8. The constants of the quality of housing.

Constant name	Units	Description	Initial setting	Comments
Initial QH *(IQH)*	*0 to 1*	The initial quality of housing	0.4	The value of QH in time 0
Planned QH *(PQH)*	*0 to 1*	The quality of housing design.	1.0	Can be lower than 1 on purpose (e.g. low cost housing).
Minimum QH *(MinQH)*	*0 to 1*	The level of *QH* when a repair/maintenance action is needed to restore *QH* to the maximum level	0.3	Note: if the "maximum *QH*" decreases to the level of double "minimum *QH*", repair actions are not considered as feasible and rebuild action is started
Housing service life *(HSL)*	*Years*	The theoretical time when the quality of initial housing design (the overall design, functionality, structural and material durability, safety, aesthetics etc.) reaches 0 , i.e. becomes obsolete)	100	Rough estimate
QH degradation by using *(HD_2)*	*QH/ month*	The maximum speed of additional degradation that can be repaired	0.001	Rough estimate Note: the real speed depends on the level of occupancy
Building speed *(BS)*	*QH/ month*	The speed of restoration or rebuilding actions	0.05	Rough estimate

QH - Quality of housing expressed as number from 0 (the lowest possible at current time in the whole region) to 1 (the highest possible at current time in the whole region)

Repairing action R_1 starts when the quality of housing *QH* reaches the minimum quality of housing *MinQH*. Then the value of repair rate R_1 is equal to the building speed *BS*. The action stops when the *QH* is restored back to the maximum possible quality *MaxQH* (even if the housing is repaired to its initial state, the quality assessment is decreasing with time and it is represented by *MaxQH* value).

Building action R_2 is similar but it is triggered in the beginning and when *MaxQH* reaches 2 times *MinQH* (repairing would not be feasible any more). Not only the *QH* is restored but also *MaxQH* increases to its planned value *PQH*. This means that the housing was completely rebuilt (with better technologies, materials, etc…) to achieve the same quality assessment as in the initial time.

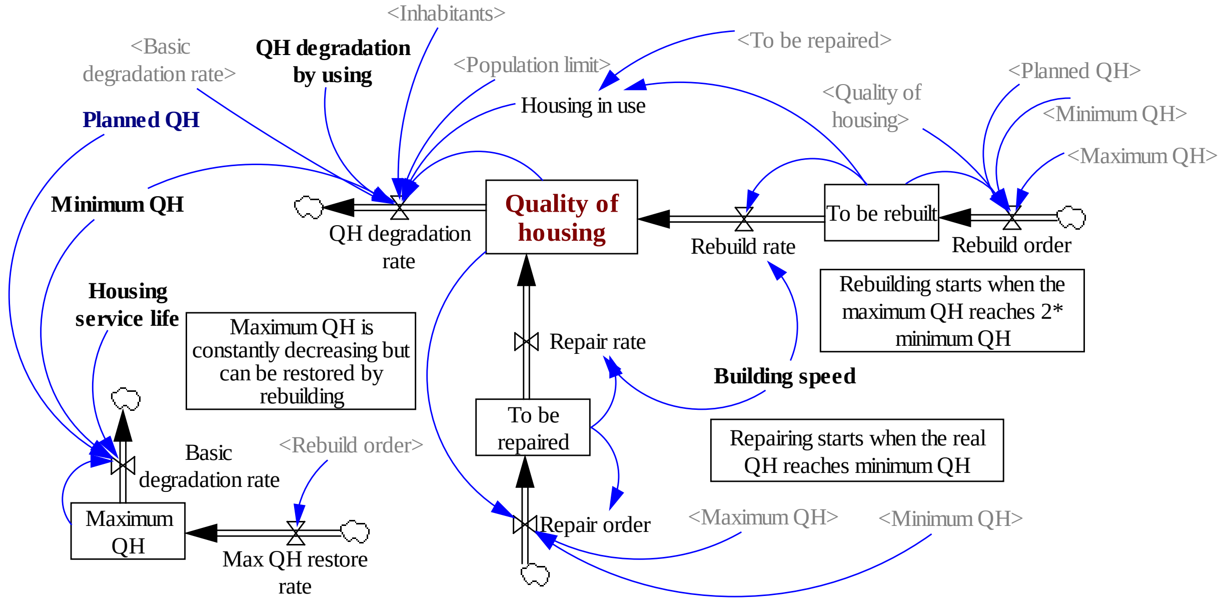


Figure 10. The dynamics of the quality of housing.

4.3 Quality of services

The sector is divided into private and public services. While the public services amount is constant, it is assumed that private services growth is governed by the total amount of inhabitants. However, it cannot exceed the physical limit (floor area) reserved for the private services and it may happen that some people will have to use private services outside the area.

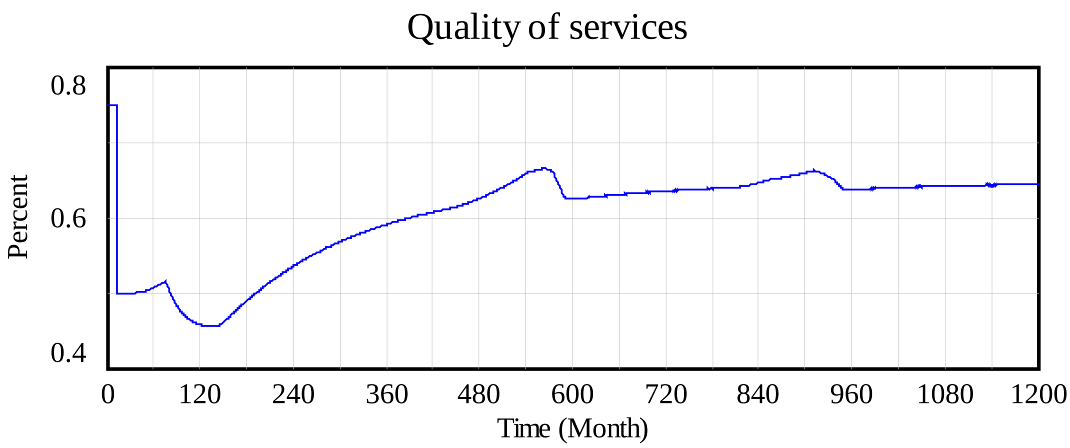


Figure 11. The graph describing the simulated development of the quality of services in the area in a theoretical test case.

The quality of services is calculated from the occupancy factor QS_{OC} and the attractiveness factor QS_{AT} and the weights l_1 and l_2 are set to ½.

$$QS = l_1 \cdot QS_{OC} + l_2 \cdot QS_{AT}$$

The occupancy factor QS_{OC} is based on the services capacity (*PUS* and *PRS*) and the number of inhabitants *I*.

$$QS_{OC} = \frac{PUS + PRS}{2 \cdot I}$$

The attractiveness factor QS_{AT} is calculated from the particular service attractiveness's for each of the population groups provided by [1].

$$QS_{AT} = \frac{Q_{S,A}I_A + Q_{S,B}I_B + Q_{S,C}I_C}{I}$$

Table 9. The constants of the quality of services.

Constant name	Units	Description	Initial setting	Comments
Required commercial space per inhabitant *(RCS)*	m^2	Required floor area of commercial space to provide private services to one inhabitant	25	Rough estimate
Required public space per inhabitant *(RPS)*	m^2	Required floor area of public space to provide public services to one inhabitant	10	Rough estimate
Private services growth per inhabitant *(GPS)*	People/ month	Speed (flexibility) of private services growth in response to population growth	0.005	Rough estimate

The **upper limits** of private (*MaxPRS*) and public (*MaxPUS*) services are set from the floor area of public buildings *FPB* and commercial buildings for private services *FCB*.

$$MaxPUS = FPB/RPS \text{ and } MaxPRS = FCB/RCS$$

While the public services *PUS* are all the time at the full capacity, private services *PRS* are growing.

$$PUS = MaxPUS$$

$PRS = \int GPRS\, dt$ with initial value 0 and upper limit of *MaxPRS*.

The **growth rate of private services** *GPRS* is calculated from the basic value *GPS* and the number of inhabitants *I* exceeding the private services *PRS*.

$$GPRS = \begin{cases} GPS(I - PRS)\ if\ \ PRS < MaxPRS \\ 0\ else \end{cases}$$

The *GPRS* value is limited to the maximum possible private services *MaxPRS* and delayed by 24 months.

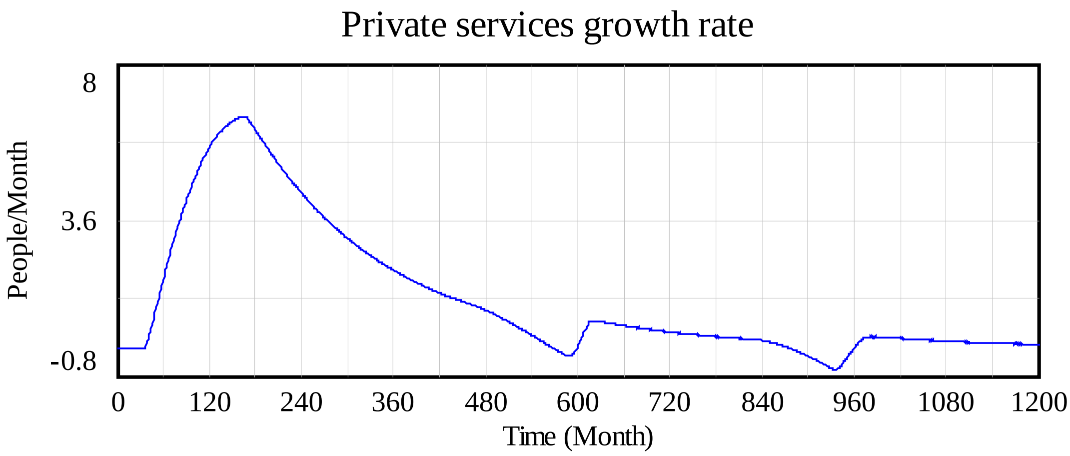


Figure 12. The graph describing the simulated development of the private services in the area in a theoretical test case.

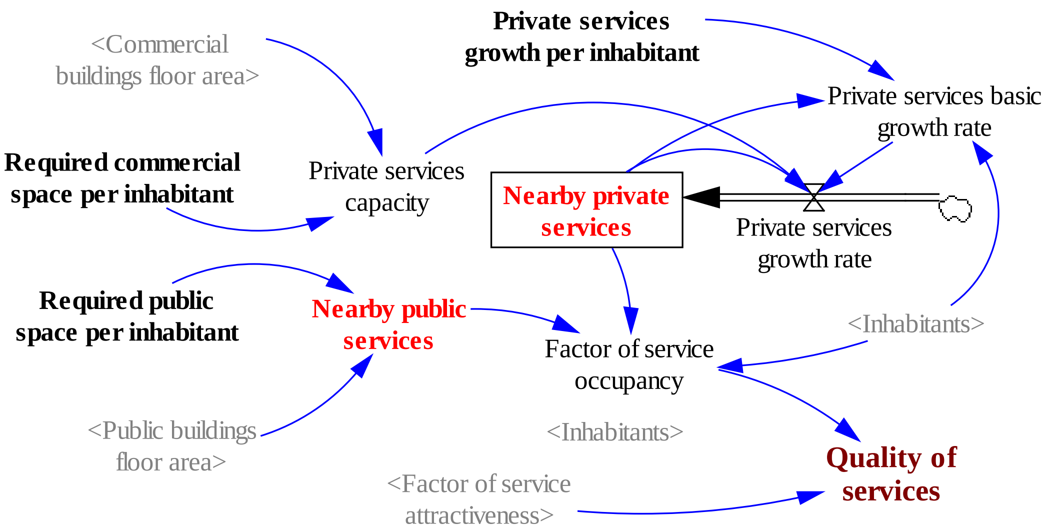


Figure 13. The dynamics of the private and public services.

4.4 Land use and area attractiveness

The **area attractiveness** *AQ* is a weighted average of three factors: greenness, urban vitality and variety of dwelling choices. They are measured by green area factor (*GAF* - describing the amount of green area per inhabitant), traffic density factor (*TDF* - describing the amount of walking/cycling/driving people per 1 m of street network) and free dwellings factor (*FDF* - describing the availability and variety of dwellings) together with the basic area attractiveness *BAQ* defined by factors provided [1]. All of them can have values from 0 (the worst case) to 1 (the best case).

$$AQ = b_1 \cdot BAQ + b_2 \cdot GAF + b_3 \cdot TDF + b_4 \cdot FDF$$

In this pilot phase, the constants b_1 to b_3 are set to equal values 1/4, but can be also weighted in a different way, like percentages from 0 to 100%.

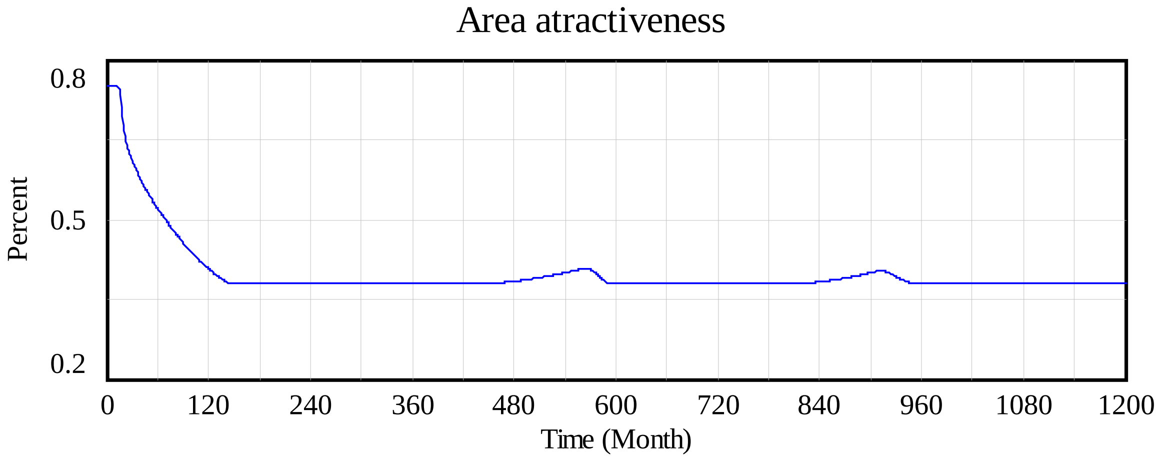


Figure 14. The graph describing the simulated development of the area attractiveness in the area in a theoretical test case.

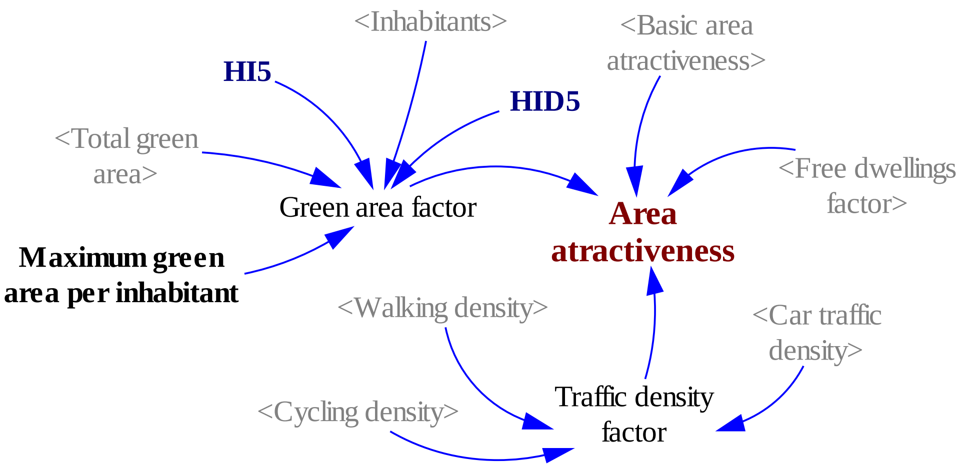


Figure 15. The dynamics of the area attractiveness.

The **basic area attractiveness** *BAQ* is calculated the same way as the attractiveness of services in the previous chapter.

$$BAQ = \frac{Q_{AR,A} I_A + Q_{AR,B} I_B + Q_{AR,C} I_C}{I}$$

Table 10. The constants of the land use and floor areas.

Constant name	Units	Description	Initial setting	Comments
Total land area *(TA)*	km^2	Total land area of the simulated region	1	Updated from HEKO
Floor area per km^2 *(REF)*	m^2/km^2	Floor area per km^2 of total land area	250 000	Has to be based on the real town plan
Share of built area *(SBA)*	*0 to 1*	The share of total area covered by buildings and infrastructure	0.4	Has to be based on the real town plan
Maximum green area per inhabitant *(MGA)*	km^2	The minimum green area that creates 100% satisfaction (per inhabitant)	0.01	Rough estimate
Public buildings *(SPB)*	*0 to 1*	The share of public buildings from the total floor area	0.05	Has to be based on the real town plan
Commercial buildings from the rest *(SCB)*	*0 to 1*	The share of commercial buildings from the floor area of non-public buildings	0.1	Has to be based on the real town plan
Average residential space per inh. *(RRF)*	m^2	The average residential space per inhabitant (determines the population limit)	50	Rough estimate

The **green area factor** *GAF* is calculated from the total green area *GA* and the maximum (to be exploited in practice) green area per inhabitant *MGA* and it is limited to the value obtained from the HEKO indicator no. 5 ("Local recreational areas and urban agriculture", see Attachment A: Issues and criteria of eco-efficiency assessment in HEKO tool) represented as HI_5 and HID_5.

$$GAF = \begin{cases} GA/(I \cdot MGA)\ if\ \ GA < I \cdot MGA \\ 1\ else \end{cases} \cdot \frac{100 + HID_5 - HI_5}{2 \cdot HID_5}$$

The **traffic density factor** *TDF* is the weighted average calculated from three different types of densities.

$$TDF = c_1 \cdot \min\left(1; \frac{d_1}{WD}\right) + c_2 \cdot \min\left(1; \frac{d_2}{CD}\right) + c_3 \cdot \min\left(1; \frac{d_3}{DD}\right), \text{ where}$$

WD, *CD*, and *DD* are walking, cycling and driving density respectively (in number of people/street-m), constants d_1 to d_3 represent the limits of dissatisfaction (e.g. for cycling: $d_2 = 5$ means that the factor is lower than 1 only if there is more than 1 cyclist per 5 meters of bicycle route network; respectively for walking $d_1 = 1$ means one pedestrian per walking route-m and for car driving $d_3 = 3$ means one car passengers per three street-m).

In this pilot phase, the constants c_1 to c_3 are set to equal values ⅓, but can be also weighted in a different way, like percentages from 0 to 100%.

The **free dwellings factor** *FDF* takes into account the number of inhabitants *I* and the population limit *PL*:

$$FDF = 1 - \frac{I}{PL}$$

The **total area** *TA* (in km^2) is divided into built area *BA* and green area *GA* according to share of built area *SBA* into following groups:

$$BA = TA \cdot SBA \text{ and } GA = TA \cdot (1 - SBA)$$

Then the **built area** *BA* (in km^2) is recalculated to floor area *TF* (in m^2) taking into account the average number of stories and other important parameters included in *REF*.

$$TF = TA \cdot REF$$

The **floor area** *TF* is divided into three groups: residential floor area *RF*, commercial floor area *CF* (for private services) and public floor area *PF* (for public services).

$$PF = TF \cdot SPB,\ CF = (TF - PF) \cdot SCB \text{ and } RF = TF - PF - CF$$

The **population limit** *PL* is calculated from the residential floor area *RF* and the minimum residential space per inhabitant *RRF*.

$$PL = RF \cdot RRF$$

The amount of people travelling outside the area is described by "the **need for travelling**" *NTR*. It is based on the amount of services *PRS, PUS* and the fraction of local job opportunities used by local people *J*LPJ*

$$NTR = e_1 \left[f_1 PRS + f_2 PUS \right] + e_2 JOB,$$

where the constants e_1 and e_2 describe the share of travelling time to access services and jobs, and constants f_1 and f_2 describe the share of travelling to private services or public services. Currently, they are set to 0.5.

The amount of **nearby job opportunities** *J* is calculated using the basic value *NSJ* increased by the jobs generated by services *PRS*, *PUS* with the rate *STJ*.

$$J = NSJ + (PRS + PUS) STJ$$

4.5 Quality of transport

Table 11. The constants of the quality of transport.

Constant name	Units	Description	Initial setting	Comments
Road capacity *(CapR)*	*People*	The maximum number of people that can use cars for everyday travels without risk of traffic congestion	500	Has to be based on the real town plan
Parking capacity *(CapP)*	*People*	The maximum number of people that are able to park their cars normally without need of looking for an alternative place	500	Has to be based on the real town plan
People using cars frequency *(PUC)*	*0 to 1*	The share of people willing to use cars (defines the lower limit of car usage)	0.2	Rough estimate
Quality of road infrastructure *(QRI)*	*0 to 1*	The quality of roads	0.8	Input comes probably from the road administration
Quality of public transport *(QPT)*	*0 to 1*	The quality of public transport	0.8	Input comes probably from the public transport provider
Public transport capacity *(CapPT)*	*People*	The maximum amount of people that can use public transport for they everyday travels	500	Input comes probably from the public transport provider
Non-service job opportunities *(NSJ)*	*People*	Number of job opportunities (excluding jobs generated by services)	100	Note: the number is fixed in this study
Local people using local jobs *(LPJ)*	*0 to 1*	Fraction of area inhabitants accessing local jobs without need for travelling outside	0.1	Rough estimate
Service-to-job rate *(STJ)*	*People*	Local job opportunities created by providing services to one inhabitant	0.05	Rough estimate

The amount of **people using public transport** *PPT* corresponds to the value of *NTR* decreased by the amount of people that would like to use their cars in all cases *I*PUC*. It can have values between 0 and the public transport capacity *CapPT*.

$$PPT = \min[\max(NTR - I \cdot PUC;\, 0);\, CapPT]$$

The amount of **people using cars** *PDC* is the basic value *I*PUC* which can be increased by the people that were not transported by public transport *NTR-I*PUC-CapPT*.

$$PDC = I * PUC + \max(NTR - I * PUC - CapPT;\, 0)$$

The number of **people walking/cycling** *PWC* is the rest of the population.

$$PWC = I - PDC - PPT$$

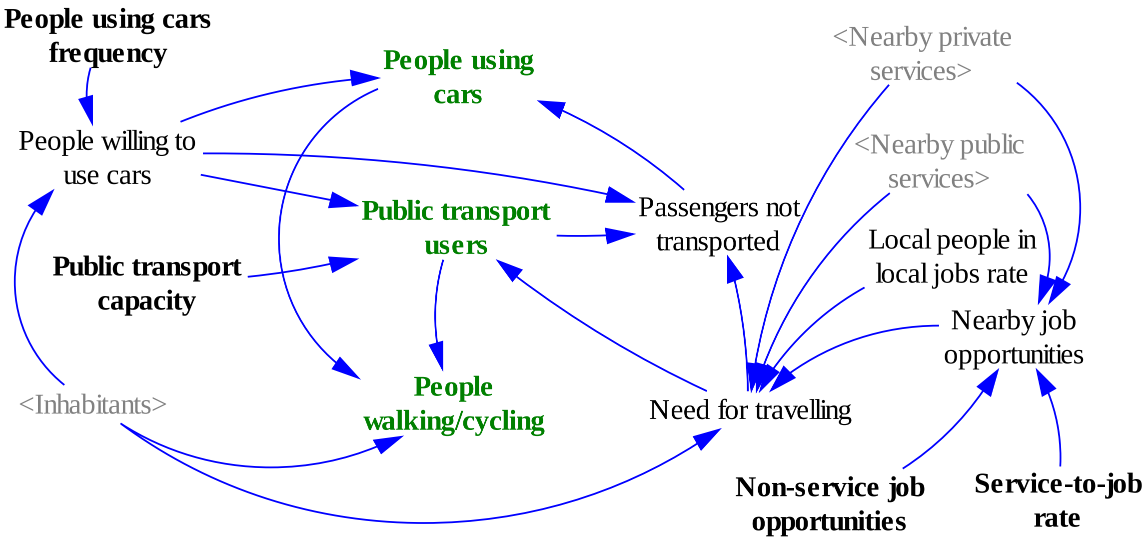


Figure 16. The dynamics of the choice of transport modes.

The **quality of transport** *QT* calculation is based on the satisfaction with driving cars *SDC*, with using public transport *SPT* and with walking/cycling *SWC*. All the values can be between 0 and 1.

$$QT = \frac{PDC}{I} SDC + \frac{PPT}{I} SPT + \frac{PWC}{I} SWC$$

The **driving satisfaction factor** *SDC* is based on the road infrastructure quality *QRI*, quality of parking *QPA*, road capacity *CapR* and parking capacity *CapP*.

$$SDC = m_1 \left[i_1 \cdot \min\left(\frac{CapR}{PDC};1\right) + i_2 \cdot \min\left(\frac{CapP}{PDC};1\right)\right] + m_2 \left(n_1 \cdot QRI + n_2 \cdot QPA\right)$$

The constants describing the importance of road and parking capacity are currently set to 0.5.

The **public transport satisfaction factor** *SPT* can be lower than the basic value of public transport quality *QPT* if the public transport capacity *CapPT* is not sufficient.

$$SPT = QPT \cdot \min\left[\frac{CapPT}{\max(NTR - I \cdot PUC;\, 0)};1\right]$$

The **walking/cycling satisfaction factor** *SWC* is addressed in the Chapter 4.6.

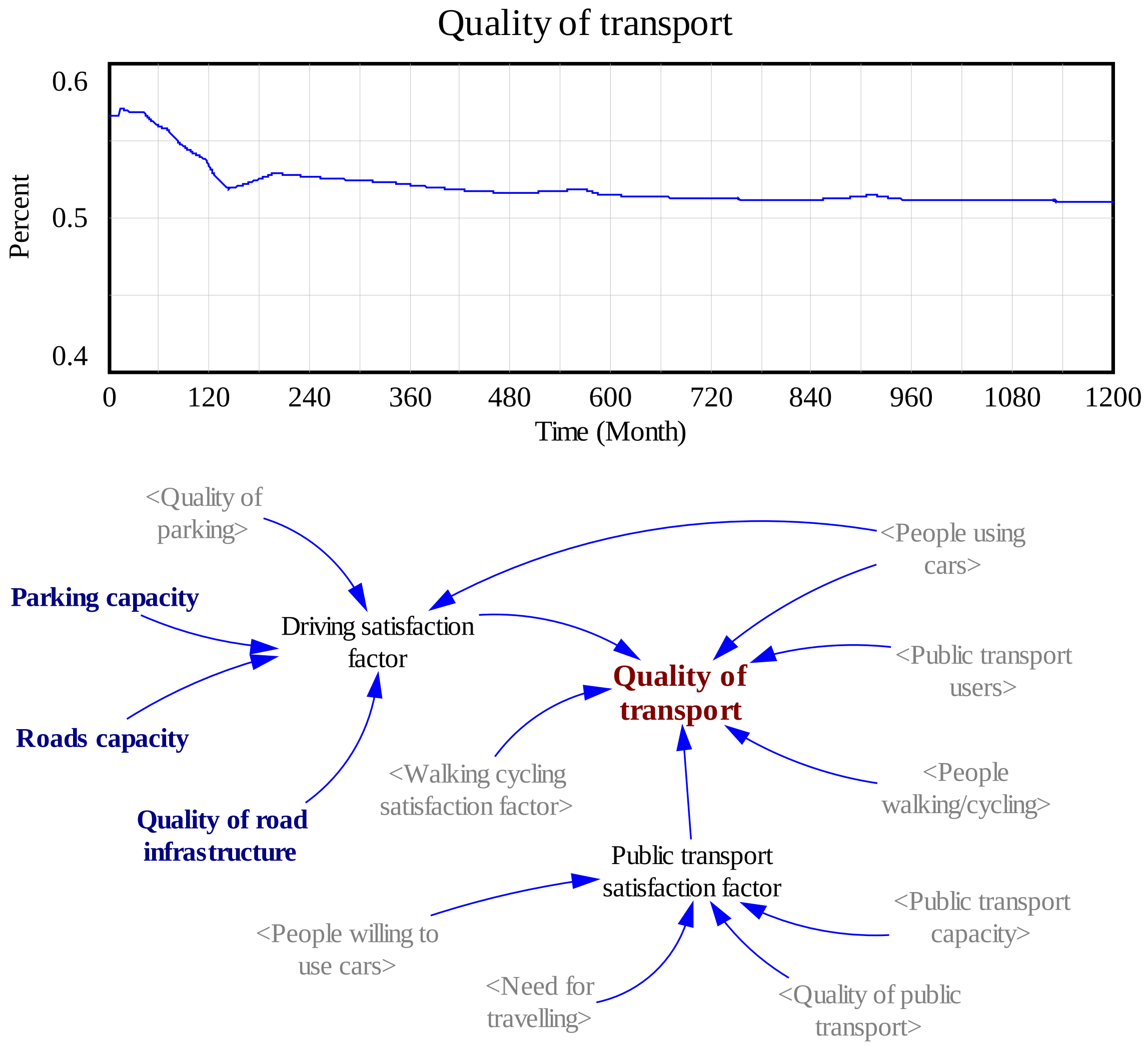


Figure 17. The dynamics of the quality of the transport (below) and the graph describing the simulated development of the quality of transport in the area in a theoretical test case.

The quality of public transport *QPT* and the quality of parking *QPA* are based on the data provided by [1].

$$QPT = \frac{Q_{PT,A}I_A + Q_{PT,B}I_B + Q_{PT,C}I_C}{I}$$

$$QPA = \frac{Q_{PA,A}I_A + Q_{PA,B}I_B + Q_{PA,C}I_C}{I}$$

4.6 Quality of walking/cycling

The calculation of **walking/cycling satisfaction factor** *SWC* is straightforward series of weighted averages starting from the satisfaction with walking *SW* and satisfaction with cycling *SC*:

$$SWC = \frac{PW}{PWC}SW + \frac{PC}{PWC}SC$$

where the number of people walking *PW* and cycling *PC* are calculated using "cycling ratio" *PCR* and the total number of people walking/cycling *PWC*:

$$PW = PWC(1 - PCR) \text{ and } PC = PWC \cdot PCR$$

Table 12. The constants of the quality of walking and cycling.

Constant name	Units	Description	Initial setting	Comments
Good walking routes *(WR_1)*	*0 to 1*	Share of routes qualified as "good"	0.2	Rough estimate, but can come from the building plan or HEKO tool
Average walking routes from the rest *(WR_2)*	*0 to 1*	Share of routes qualified as "average" from those which are not "good"	0.5	Rough estimate, but can come from the building plan or HEKO tool
Good cycling routes *(CR_1)*	*0 to 1*	Share of routes qualified as "good"	0.2	Rough estimate, but can come from the building plan or HEKO tool
Average cycling routes from the rest *(CR_2)*	*0 to 1*	Share of routes qualified as "average" from those which are not "good"	0.5	Rough estimate, but can come from the building plan or HEKO tool
Total length of street network *(L)*	*m*	Total length of street network	2 000	Updated from HEKO
Cycling ratio *(PCR)*	*0 to 1*	Share of "cycling" from "walking + cycling" people	0.5	Rough estimate
Bicycle parking capacity near houses *(BPH)*	*People*	Bicycle parking capacity near houses	500	Has to be based on the real town plan
Bicycle parking capacity in public areas *(BPP)*	*People*	Bicycle parking capacity in public areas	250	Has to be based on the real town plan

The **walking satisfaction factor** SW is based on the difference between walking routes assessed as "good" WR_1 and "bad" WR_3.

$$SW = 0.5(WR_1 - WR_3) + 0.5,$$

where $WR_3 = 1 - WR_1 - WR_2(1 - WR_1)$

The **cycling satisfaction factor** *SC* is, however, more complex since also the parking capacity is included:

$$SC = g_1[0.5(CR_1 - CR_3) + 0.5] + g_2 \cdot \min\left(h_1 \frac{BPH}{PC} + h_2 \frac{BPP}{PC}; 1\right),$$

where $CR_3 = 1 - CR_1 - CR_2(1 - CR_1)$

Constants g_1 and g_2 describe the importance of routes and parking places and constants h_1 and h_2 describe the role of parking near houses and near public places within the total parking places. All of them are currently set to 0.5.

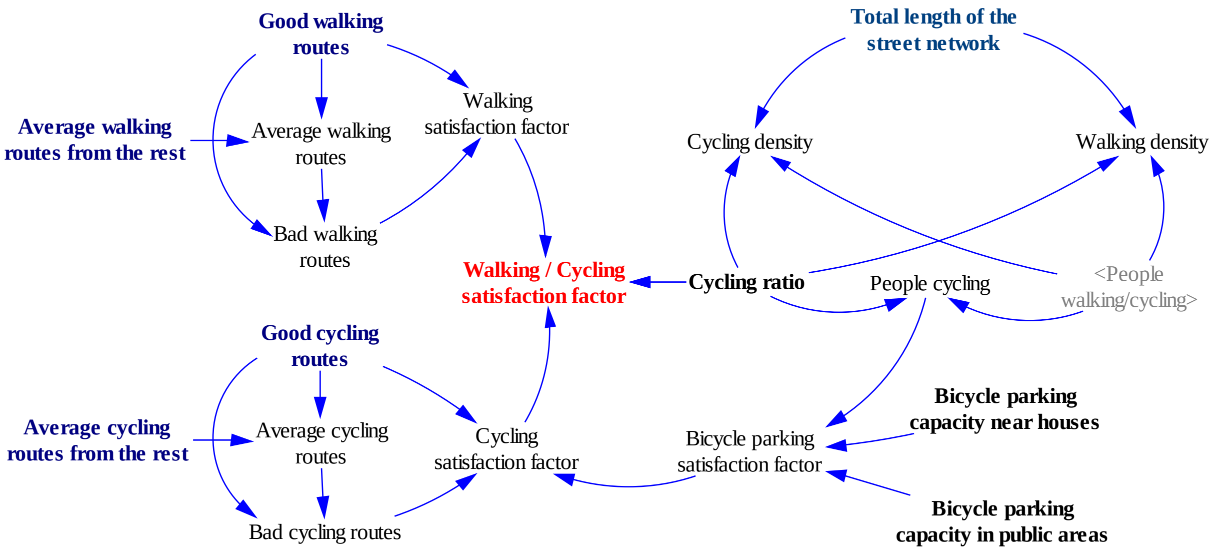


Figure 18. The dynamics of the satisfaction on walking and cycling conditions.

4.7 Costs and incomes

The last module calculates the budget balance of the simulated area. The monthly costs *MC* are the sum of different costs and incomes including other costs and incomes *OC* and *OI*:

$$MC = MaC + BuC + OC - TaI - RnI - OI$$

where *MaC* and *BuC* are maintenance and building (including reconstructions) costs respectively, *TaI* and *RnI* are tax and rent incomes respectively (Figure 20).

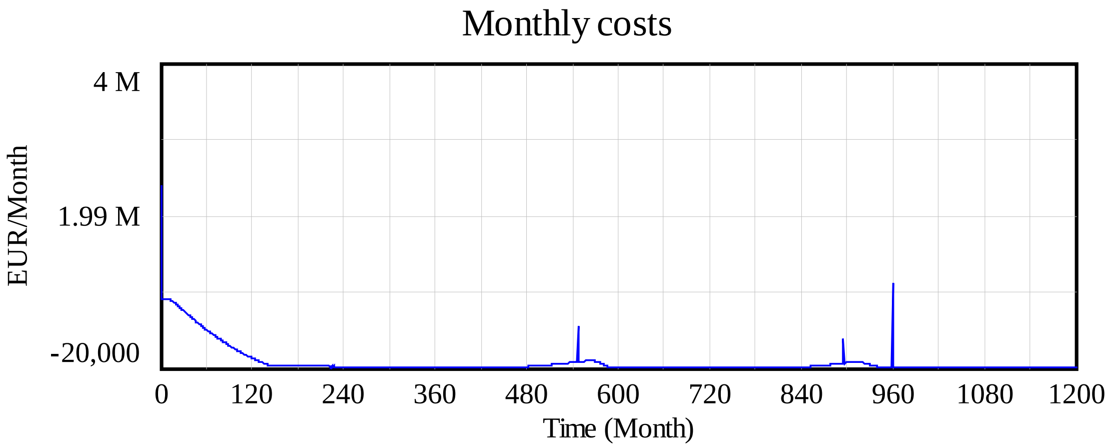


Figure 19. The development of monthly costs. Peak values indicate reconstruction/rebuilding actions.

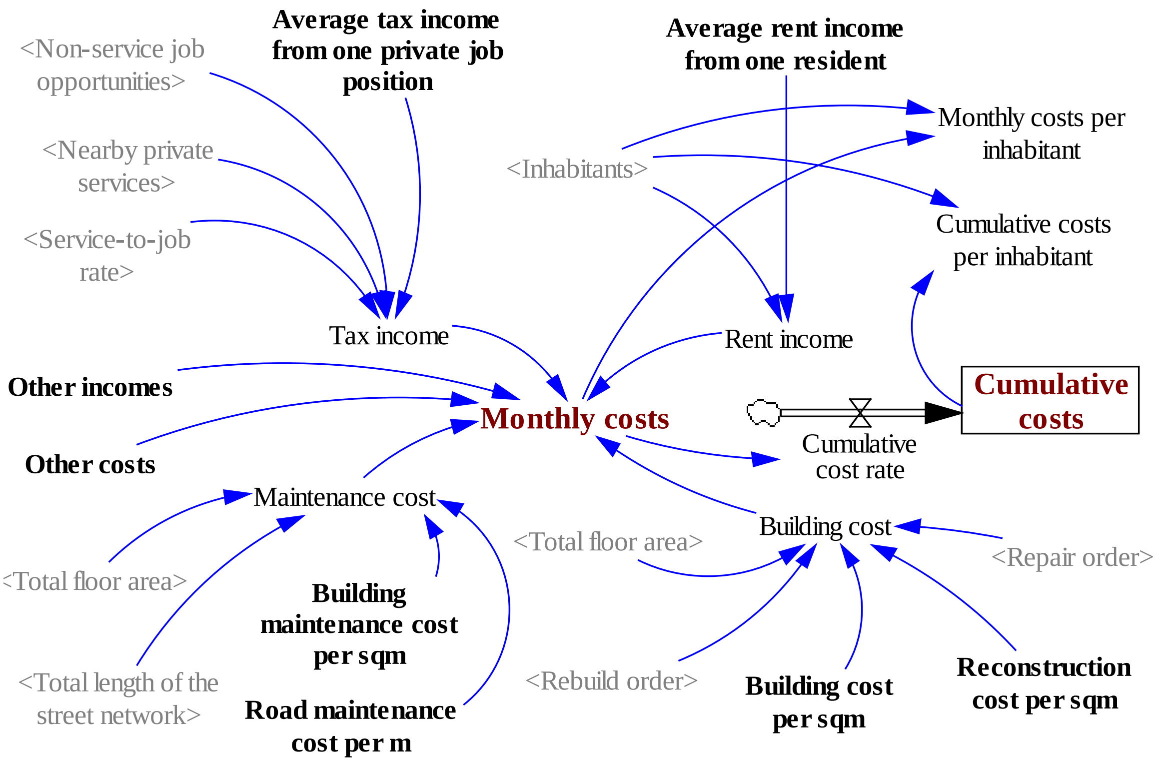


Figure 20. Calculation of monthly and cumulative costs.

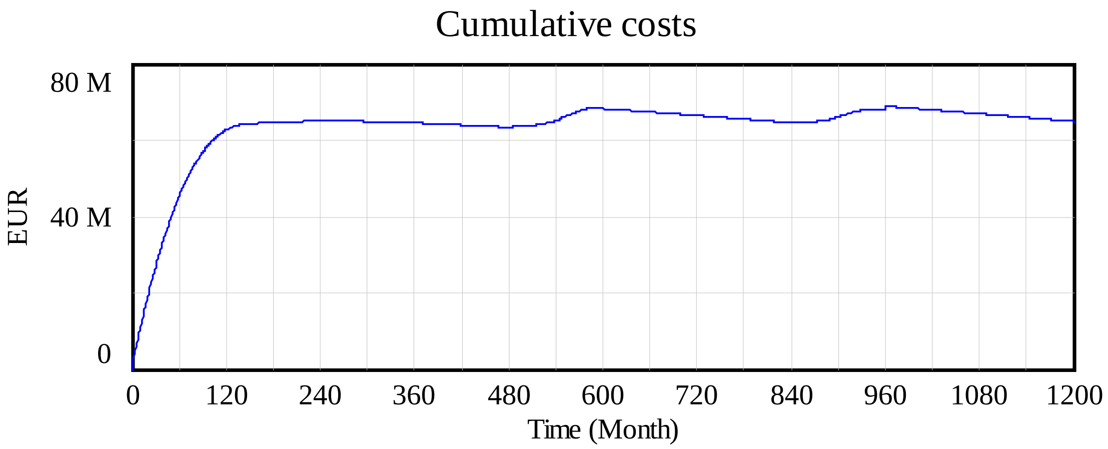


Figure 21. The development of cumulative costs.

5 Microsoft Excel interface

The presented Vensim (system dynamic) model is compiled into .vpm file and can be controlled by Microsoft Excel using the dynamic library “venDLM32.dll”. Both files have to be in the same folder as the excel document (Figure 22). Generally, using the dynamic data exchange (DDE) protocol, all constants and variables can be updated and model simulated from Excel workbook, however, the real-time simulation is only available when time periods of data transfer are relatively short.

Name	Size	Type
DynHEKO.xls	2 534 KB	Microsoft Office Excel 97-2003 Worksheet
UEE-SysDyn007.vpm	404 KB	Vensim PackagedModel
VenDLM32.dll	444 KB	Application Extension

Figure 22. The essential files for running the dynamic simulation in Excel.

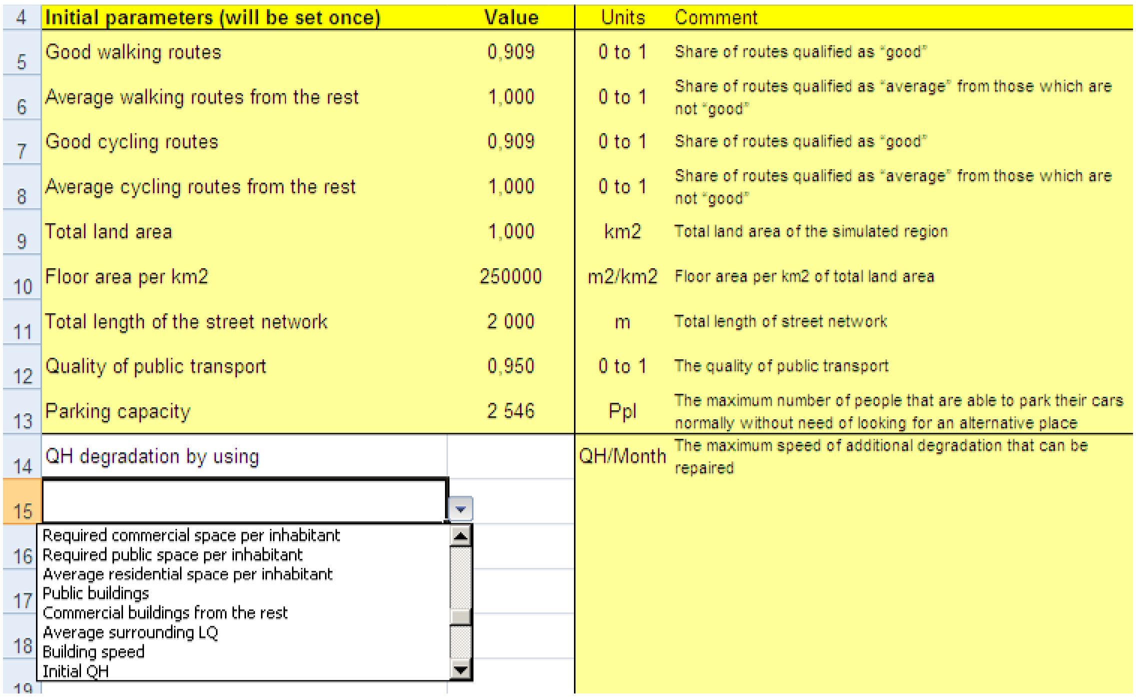
5.1 DynHEKO workbook

The HEKO tool was modified to be able to communicate with Vensim model and provide the basic data (indicated as *HI* and *HID* indexes). Dynamic data exchange (DDE) scripts are based on the SysDyn template developed in VTT and they are written in VBA as standard Excel macros. Therefore it is necessary to enable macros in the Excel document when opening.

5.1.1 Inputs

User settings of the dynamic simulation can be modified in “SD params” worksheet. They are divided into two groups:

a) **Initial parameters** will be set once before the simulation (Figure 23). Here, users can modify the model environment. Several parameters are already pre-defined and linked to the HEKO forms. More parameters can be added just by choosing from the drop-down menu in the first column. Proper units and parameter description will be displayed automatically.



	Initial parameters (will be set once)	Value	Units	Comment
5	Good walking routes	0,909	0 to 1	Share of routes qualified as "good"
6	Average walking routes from the rest	1,000	0 to 1	Share of routes qualified as "average" from those which are not "good"
7	Good cycling routes	0,909	0 to 1	Share of routes qualified as "good"
8	Average cycling routes from the rest	1,000	0 to 1	Share of routes qualified as "average" from those which are not "good"
9	Total land area	1,000	km2	Total land area of the simulated region
10	Floor area per km2	250000	m2/km2	Floor area per km2 of total land area
11	Total length of the street network	2 000	m	Total length of street network
12	Quality of public transport	0,950	0 to 1	The quality of public transport
13	Parking capacity	2 546	Ppl	The maximum number of people that are able to park their cars normally without need of looking for an alternative place
14	QH degradation by using		QH/Month	The maximum speed of additional degradation that can be repaired
15				

Figure 23. Setting the initial parameters. The yellow areas are already pre-defined and recommended not to be changed.

b) **Dynamic parameters** are updated in the simulation every time increment. Generally, the HEKO indicators can be changing in time and therefore they are already pre-defined in the table. Users can also add additional variables from the similar drop-down list as in case of the initial parameters.

5.1.2 Simulation control

The "DynHEKO" worksheet has a special toolbar for the dynamic data exchange with Vensim model. In Excel 2003 it appears as a new floating toolbar called "Simulation control" and in higher versions a new custom toolbar in "Add-ins" ribbon is displayed (Figure 24).

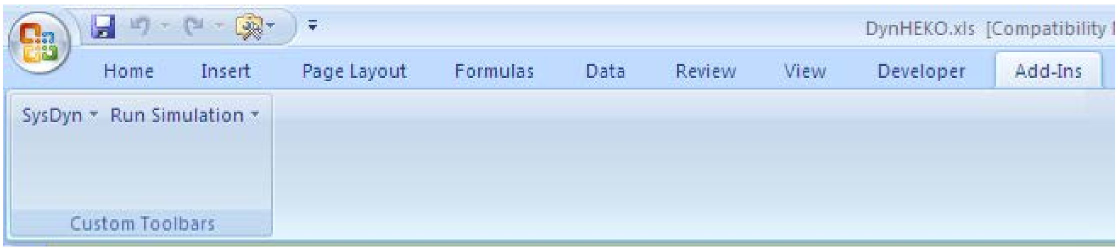


Figure 24. Simulation control in Excel 2007.

Every simulation should be started with "Start simulation" in "SysDyn" menu (Figure 25). The workbook will clear old simulation data (graphs from "SD Graphs" worksheet will disappear) and opens the connection with Vensim model.

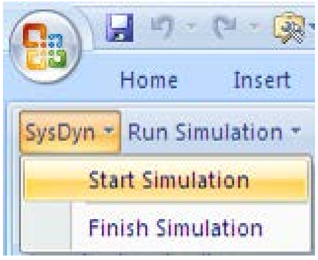


Figure 25. Start simulation.

Then the user can choose how long time period he wants to simulate in “Run Simulation” menu (Figure 26). By running the model in several steps it is possible to simulate mid-term decisions altering the model environment (e.g. increasing the parking capacity by 500 places in 20 years).

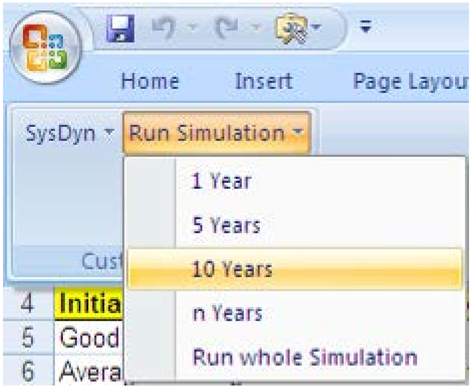


Figure 26. Run simulation period.

The total simulation time is 1 200 months (100 years). Selecting the “Run whole Simulation” will calculate remaining time steps until the end of this period. Note that during the simulation time the computer can stop responding. It is not recommended to try to shut-down the computer or kill the running processes.

5.1.3 Outputs

The simulation results are displayed as standard graphs (Figure 27) in “SD Graphs” worksheet.

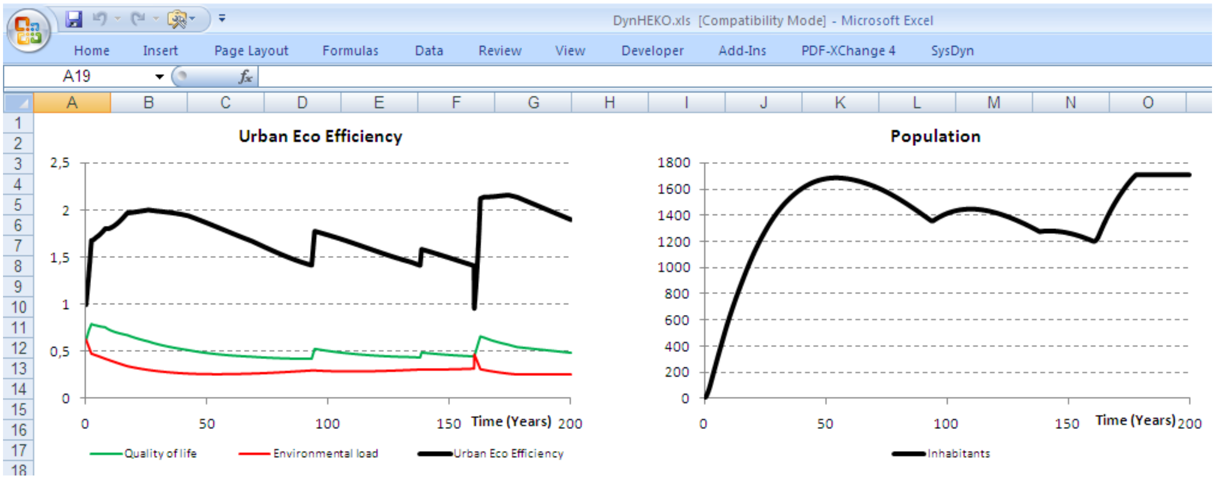


Figure 27. Examples of graph outputs in Microsoft Excel 2007 in a theoretical test case.

6 Conclusions

The experiment shows that there is a real potential for further development of dynamic modelling in urban eco-efficiency. The test bed case study covers only some of the wide variety of possible variables in both urban dynamics and urban eco-efficiency fields of knowledge. Even this rather limited experiment shows that the results could illuminate the possible choices in urban development both for urban planners and designers as well as decision makers in municipalities and developer companies. The results may reveal considerable potentials in improving urban eco-efficiency and reaching the climate change targets set in local and national levels.

The next development phase could be focused on the following three study lines:

1. in-depth analysis of the most relevant factors and variables of urban dynamics affecting eco-efficiency (requires some basic research, check of data availability, critical synthesis)
2. creating the first generation of the dynamic urban model able to produce relevant new and credible information of the development of urban eco-efficiency
3. the testing of urban dynamics model in real life cases (in an existing city with a real data set and user feedback).

It is also possible to make similar studies in other fields of urban dynamics modelling than the mathematical modelling refered in this report. The game theoretic approach could be one of these possibilities, as well as different combinations of GIS based cartographic simulations and organic or fractal growth models.

7 References

[1] Jantunen J, Penttinen M, Rämä P., *Eco-efficient Human Community*, Criteria results from expert workshop and interviews, VTT, 2011.

[2] Forrester, Jay W. *Industrial dynamics*, Cambridge, Mass. The MIT Press 1961. 464 p.

[3] Forrester, Jay W. *Urban dynamics*, Cambridge, Mass. The MIT Press 1969. 285 p.

[4] Forrester, Jay W. *World dynamics*, Waltham, MA, Pegasus Communications 1971 (1st ed.), 1973 (2nd ed.). 144 p.

[5] Forrester, Jay W. *Systems Analysis as a Tool for Urban Planning* (in: Readings in Urban dynamics. Volume I .1974, p. 13–28).

[6] Armah, F.A., Yawson, D.O, Pappoe, A.A.N.M A *Systems Dynamics Approach to Explore Traffic Congestion and Air Pollution Link in the City of Accra, Ghana*, in Sustainability 2010, 2, 252-265; ISSN 2071-1050, doi:10.3390/su2010252

[7] BREEAM Communities. *SD5065B Technical Manual*. BREEAM Communities Assessor Manual Development Planning Application Stage. BRE Global Ltd 2009.

[8] CASBEE for Urban Development. *Technical manual 2007 Edition*. Institute for Building Environment and Energy Conservation (IBEC). 2007.

[9] LEED 2009 for Neighborhood Development. The U.S. Green Building Council, Inc. 2009.

[10] Lahti, P., Nieminen J., Nikkanen A. & Puurunen E. Helsingin kaavoituksen ekotehokkuustyökalu (HEKO). Espoo 31.8.2010. Helsingin kaupunkisuunnitteluviraston yleissuunnitteluosaston selvityksiä 2011:1. VTT Tutkimusraportti VTT-R-06550-10. 95 s.

[11] Mass, Nathaniel J. (ed.) Readings in Urban dynamics. Volume I. Cambridge, Mass, Wright-Allen Press, Inc. 1974. 303 p.

[12] Meadows, Donella H., Dennis L. Meadows, Jørgen Randers, and William W. Behrens III. The Limits to Growth. Universe Books. New York 1972. 205 p. ISBN 0-87663-165-0

[13] Julien, A. 2009, Assessing the assessor, BREEAM vs. LEED, Sustain v09 i06, p. 30-33. http://www.breeam.org/filelibrary/BREEAM_v_LEED_Sustain_Magazine.pdf

[14] Kawakubo S. 2010. Assessment Framework of CASBEE-City: An Assessment Tool of the Built Environment of Cities. SB10 Finland

Conference Espoo 22-24.9.2010. Full Papers Proceedings. 978 p., pp. 93–96.

[15] Murakami S. 2010. Concept and framework of CASBEE-City. An Assessment Tool of the Built Environment of Cities. SB10 Finland Conference Espoo 22-24.9.2010. Full Papers Proceedings. 978 p. pp. 88–92.

Attachment A: Issues and criteria of eco-efficiency assessment in HEKO tool

Issues and criteria in urban planning and design projects where eco-efficiency is assessed with HEKO tool [10] are presented in the following tables.

Table 13. Eco-efficiency indicators used in HEKO tool.

Category	no of the issue	Issue to be assessed
LAND	1	land use for building purposes
	2	efficiency in land use and amount of infrastructure
	3	earthmoving
	4	contaminated soil
	5	local recreational areas and urban agriculture
	6	structural quality of soil for building purposes
WATER	7	management of storm water, drainage and ground water
	8	flood protection
	9	water consumption per inhabitant
ENERGY	10	energy consumption of buildings
	11	production of electricity
	12	production of heat
	13	utilisation of passive solar energy
	14	outdoor lighting
TRANSPORT AND SERVICES	15	mass transit
	16	walking and cycling
	17	use of passenger cars and parking
	18	location of services and mixed land use
CARBON AND MATERIAL CYCLES	19	carbon footprint and use of recycled materials
	20	waste management
	21	utilisation of existing building stock

Table 14. Eco-efficiency criteria used in HEKO tool.

assessment criteria with weights (subcategories of eco-efficiency, where the urban planning and design solution under consideration affects)					
MATERIALS	ENERGY	RENEWABLES	EMISSIONS	WASTE AND RECYCLING	ECO-SYSTEM
15	20	20	20	15	10
criterium: decreases material consumption (excl. fuels)	**critrerium**: decreases energy consumption	**criterium:** increases the share of renewables in energy production	**criterium:** decreases emissions, especially greenhouse gases	**criterium:** decreases wastes, increases recycling and reuse of materials, decreases dangerous waste and their impact	**criterium:** decreases harmful disturbances of eco-systems and negative change in biodiversity; increases flexibility and resilience, improves knowledge, management and participation in impact assessment

Attachment B: Model calibration variables

The following table summarizes the variables that have to be calibrated according to the particular location and urban parameters.

Table 15. Model calibration variables.

Var. name	Units	Description	Value	Comments
a_1	*0 to 1*	The importance of housing in quality of life	¼	The sum has to be 1.0
a_2		The importance of services in quality of life	¼	
a_3		The importance of area in quality of life	¼	
a_4		The importance of transport in quality of life	¼	
b_1	*0 to 1*	The importance of basic attractiveness in area attractiveness	¼	The sum has to be 1.0
b_2		The importance of green areas in area attractiveness	¼	
b_3		The importance of traffic density in area attractiveness	¼	
b_4		The importance of free dwellings in area attractiveness	¼	
c_1	*0 to 1*	The importance of walking in traffic density satisfaction	⅓	The sum has to be 1.0
c_2		The importance of cycling in traffic density satisfaction	⅓	
c_3		The importance of driving in traffic density satisfaction	⅓	
d_1	*m*	The minimum space between walking people	1 m	Normalized to the no. of lanes
d_2		The minimum space between cycling people	5 m	
d_3		The minimum space between driving people	3 m	
e_1	*0 to 1*	The share of travelling to access services	½	The sum has to be 1.0
e_2		The share of travelling to access jobs	½	
f_1	*0 to 1*	The share of travelling to services to access private services	½	The sum has to be 1.0
f_2		The share of travelling to services to access public services	½	
g_1	*0 to 1*	The importance of route quality in cycling satisfaction	½	The sum has to be 1.0
g_2		The importance of parking capacity in cycling satisfaction	½	
h_1	*0 to 1*	The importance of bicycle parking near houses in the overall bicycle parking quality	½	The sum has to be 1.0
h_2		The importance of bicycle parking near public areas in the overall bicycle parking quality	½	
i_1	*0 to 1*	The importance of route quality in driving satisfaction	½	The sum has to be 1.0
i_2		The importance of parking capacity in driving satisfaction	½	
j_1	*0 to 1*	The importance of energy load in environmental load	⅓	The sum has to be 1.0
j_2		The importance of emissions and waste in env. load	⅓	
j_3		The importance of building load in environmental load	⅓	
k_1	*0 to 1*	The share of residential environmental load per inhabitant	½	The sum has to be 1.0
k_2		The share of commercial/industrial env. load per worker	½	
l_1	*0 to 1*	The importance of occupancy in quality of services	½	The sum has to be 1.0
l_2		The importance of attractiveness in quality of services	½	
m_1	*0 to 1*	The importance of road and parking occupancy in driving satisfaction	½	The sum has to be 1.0
m_2		The importance of road and parking quality in driving satisfaction	½	
n_1	*0 to 1*	The importance of roads in road and parking quality	½	The sum has to be 1.0
n_2		The importance of parking in road and parking quality	½	

Attachment C: Comparison with Forrester model

The basic variable of the UEE-SysDyn model is the number of inhabitants who are attracted to move into the planned area or to move out. The focus is on the planning and design of rather small urban units within a city region and with integrated residential and service functions. The main output is the eco-efficiency of the area.

In the model proposed by Forrester [1][3][4][5], the basic variables are related to the business sector development in time (new, mature and declining phases) and the consequent land area and labour requirements. The focus is on simulating bigger urban units (e.g. cities or city regions) with integrated industry. The main output is the amount of collected taxes.

Enterprises:

Part of the "New enterprise sector" is simulated as "Private services growth" in UEE-SysDyn model.

Forrester pays more attention to assess also other aspects as mature business and declining industry.

Jobs and labour:

Jobs and labour sector is not considered as independent sub-models in the UEE-SysDyn model. It is assumed that inhabitants need to access their job either within the simulated area or outside. Relative impacts (environmental load) are recommended to be calculated for the sum of population and jobs.

Forrester uses complex labour model with systematic classification and job programs.

Land use:

The share of green areas and the land occupied by buildings is constant in the UEE-SysDyn model because it is assumed that the model serves mainly the evaluation of the built environment. The occupied land is divided into "commercial", "public" and "residential" areas.

Forrester uses dynamic changes of occupied/unoccupied area based on construction/demolition programs. The occupied land is divided into "housing" (premium, underemployment and worker) and "production units" (new enterprise, mature business, declining industry).

Taxes:

Taxes are not in the focus of UEE-SysDyn model but they are addressed in a very simple way in the costs and income calculation.

Forrester uses calculation based on the distribution of job/labour sector, housing and production units.