Sustainable Management of Building Stocks

Patrick Erik Bradley
Claudio Ferrara
Niklaus Kohler
Norbert Paul

Final Report of the
EIfER project:

SUB

(Sustainable Management of Building Stocks)

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Introduction

EDF R&D and EIfER commissioned the following report to ifib. The initial program fixed the objectives of the work:

> "Buildings stocks are defined in this study as groups of buildings with the same owner or the same manager-operator. Sustainable management of buildings stocks takes into account the ecological, economic, social and cultural dimensions of sustainable development. The objective of sustainable management is to maintain the complex value of the resource building stock, to minimise throughput and to maximise quality.
>
> Real Building Stocks (RS) are composed of buildings for which more or less detailed characteristics are known (or easily available). In practice however the knowledge is uncertain, incomplete and fuzzy. For managers of stocks it is inevitable to take decisions on this basis, which cannot be enlarged significantly in a short time (or with reasonable financial and personal resources). The hypotheses of this study is that it is possible to use default data from a well known stock (DF) of buildings (i.e. with detailed description of each building) to create a virtual stock (VS), which is a combination of the real stock, and the default stock (RS and DF). During the following operation period VS data will be gradually replaced by new real detailed data from the real stock. In the implementation of this proposition ifib will constitute a virtual stock of buildings and appropriate methods to apply the data to a real stock. The data of the real stock will be given by EDF R&D using available data in particular on frequencies, interventions and costs (investment, maintenance, operation, etc). This stock will only constitute a sample of the EDF R&D owned buildings. The management method should allow simulating several scenarios of the evolution of the RS in the next 20-40 years. The work can constitute the basis of future tools, which could be used for the management of EDF owned stocks as well as for other stocks. The results will also be partially useable in the common (EifER-ifib) project on sustainable neighbourhoods."

As it proved to be more complicated than expected to obtain data on the real EDF building stock prior and during the planned work period, it was decided between EDF R&D, EIfER and ifib to finish the theoretical work and use ifib stock data for illustration.

The authors wish to express their gratitude to Hatem Marzouk from EIfER who is in charge of the project for his understanding and support, to Mr. Alain Marti who has coordinated the efforts within EDF R&D to obtain data, to several persons in charge of building operation at EDF R&D who have given us useful insight, and to Mr. Devigne at Perigée S.A. for explaining the methods and data used in French facility management. The authors are further indebted to Julie Chouquet for helping out with her expertise on the ifib building stock database as well as her proficiency in the French language, to Regina Walder for her detailed knowledge about building elements and their effects, to Karsten Kremer, Li Zhang and Ting Tang for their programming skills, to Mehmet Aksözen for helpouts in retrieving data from a database, to Markus Peters as LEGEP expert, and to Martin Behnisch for suggesting to look into [**6**].

Karlsruhe, November 18, 2005.

Part 1

Management of building stocks

CHAPTER 1

Sustainable management of building stocks

1. Definition of buildings and building stocks

Building. According to international standards a building is a structure forming an open, partially enclosed, or enclosed space constructed by a planned process of combining materials and components to meet specific conditions of use.

Building stock. Set of buildings owned or managed by an economic actor with an explicit or implicit management strategy.

Building as a service. A building (and by extension a building stock) can be considered as providing a multitude of services to the users. The (direct) material services are:

- A surface as a support for use functions
- An indoor climate (heat, fresh air, light)
- Equipments for drinking water, warm water, elimination of used water, gas, electricity, lifts etc.
- Security and protection against intrusion, natural disasters etc.

A building can also provide indirect material and immaterial services like:

- Protection against wind (urban microclimate)
- Historic (bequest) value
- Social value
- Cultural (memorial) value

To provide these services (output) a building uses different resources (input) like materials, energy, capital, work time, knowledge, skills etc. Besides the desired service, buildings also produce non-desired output like emissions into water, air, soil as well as effects on nature and humans.

The inputs are generally services provided by other actors during the building life cycle:

- planers and builders in the construction phase, the refurbishment and transformation phases, and the deconstruction phases.
- managers and operators in the use phase.

The totality of services constitutes the value of a building at a certain moment. Due to ageing, a building looses a part of its initial value through physical, functional, formal and legal obsolescence. The amount of loss can be influenced by the initial quality, maintenance, refurbishment and transformation. Other values can however increase with age, e.g. social memory, historical value, bequest value. It is difficult to quantify these. Attempts have been made to monetarise them (e.g. through willingness to pay). Furthermore the problem of externalisation of costs has to be taken into account.

2. Definition of management of building stocks

We give objectives used in real estate management adapted from [**21**]. They represent the current management approach and can be considered as generally accepted.

(1) Adapt stock to user needs
(2) Adapt stock to the general objectives of the owner
(3) Assure the correct functioning of the buildings
(4) Create the necessary cash flow to cover operation, maintenance, and refurbishment fond.

Objectives (1) and (2) strongly depend on the time horizon. Some sustainability objectives are contained in (2) together with other quality criteria. Even if these criteria are generally not explicit they are of considerable importance. Figure 1 gives an overview of the management of building stocks.

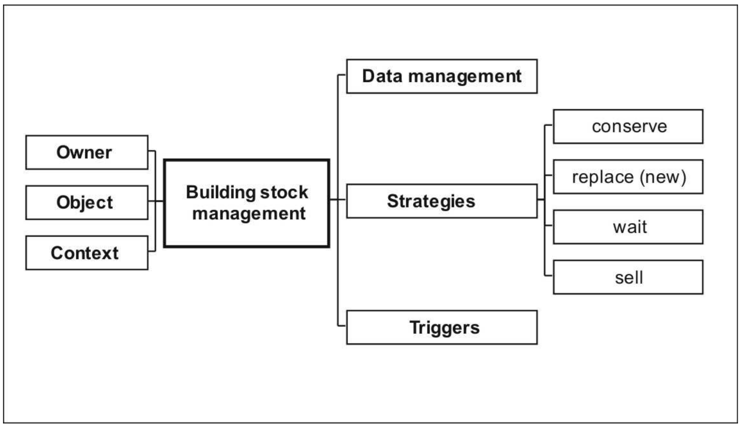


FIGURE 1. Overview of management of building stocks.

Description of the evolution of housing stock

The crucial parameters to describe the evolution of a building stock are:

(A) Size
(B) Composition (diversity of use)
(C) Value, which can be divided into
- physical
- economical
- social
- cultural

Physical value can be considered as the inverse of the sum of all impacts resulting from constructing and maintaining the stock.

Management measures

Management measures derive from a management strategy. At each moment the owner can decide on the type of measures, namely:

- increase value (e.g. modernisation, transformation, replacement)
- maintain value (e.g. optimal operation and maintenance)
- demolition
- sale

3. Definitions of sustainability

Sustainable development is generally considered as something positive but rather vague—which might be the reason why there seems to be no real opposition to the idea. The historical origin of the term varies from language to language. The English term "sustainability" was created in the 1970s; the French corresponding expression ("dévelopement durable") is also a recent construction. The German term ("Nachhaltigkeit") derives from a traditional notion used in 19th century wood administration that was marked by shortage [**3**]. The term meant "... not to cut more wood annually than the forest could give each year"; i.e. not to take more than nature could give over a longer period. In the following decades the economic interpretation in the sense of considering money as a universal equivalent for value became dominant. In the middle of the twentieth century the complex functions of the forest as a climatic regulator, a source of bio-diversity and as a space for recreation emerged and a new definition of the long-term value of forests and of sustainability was established. This definition includes four components:

(1) assure the desired effects in the long-term
(2) social concern: restriction of individual user rights in favour of the community
(3) economy: use of resources taking into account economic principles
(4) responsibility: towards a larger community and future generations

Nowadys, these aspects of sustainable development are generally recognised:

(1) ecological aspects linked to resource conservation and carrying capacity
(2) economic aspects taking into account the long-term conservation of natural and man-made capital
(3) social aspects taking into account social capital and intergenerational equity
(4) cultural aspects taking into account cultural diversity

Figure 2, based on [**3**], illustrates the various aspects of sustainable development.

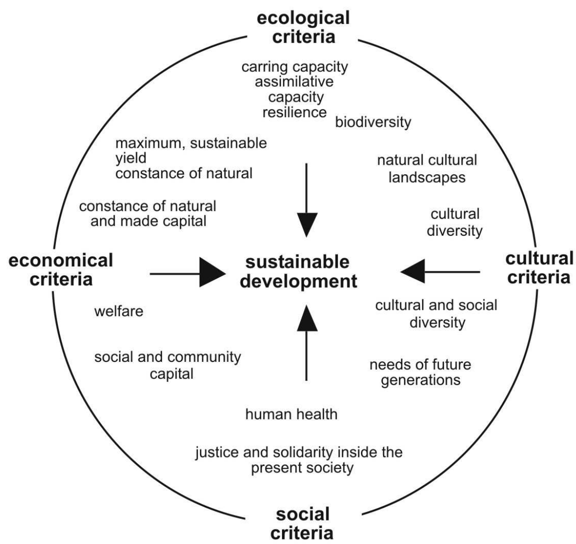


FIGURE 2. Different aspects of sustainable development, based on [**3**].

During the last 20 years, the approach to sustainability policies has changed significantly. Important steps such as the 1987 Brundtland Report [**11**] and the Rio Earth

Summit in 1992 marked the development towards a more comprehensive and integrated assessment of sustainability whereas the pre-Brundtland assessment methods were mainly based on environmental assessment techniques. Later Life Cycle Analysis [**22**] and Mass Flow Analysis [**2**] introduced the notions of resource conservation and of long time frames. Risk analysis and technology assessment revealed in turn social consequences. Critical distinctions were drawn between eco- and anthropocentric approaches. Finally the human settlement with its economic, social and institutional arrangements was considered as a system of its own that had to be respected. The Rio Conference did not only initiate the Commission on Sustainable Development (CSD) which prepared the Kyoto Conference (1997), but also turned the attention towards the capacity of the environment to support urbanisation processes. The realisation of the "city of tomorrow"[**17**] became a protection objective in Europe where the majority of the population lives in cities which often have a long history [**18**]. The broadened focus of assessment methods includes economic and social structures as well as cultural heritage, reflecting their close relation with the ecological dimension. Environmental assessment considers how the process of urbanisation consumes natural resources, why it produces emissions that pollute the ecosphere and which effect it has upon bio-diversity in general. It includes economic questions relating to the financing of infrastructure, transport and utilities, required to support urban structures. Social issues like human health, social capital, safety and security are also taken into consideration. Common to all these assessments is the long-term perspective. Long-term stable conditions are necessary to enable and maintain functioning human societies in a sustainable urban environment.

4. Sustainable Development of the Built Environment

In recent research as well as in government policies sustainability frameworks for the built environment are based on multiple protection goals [**16**]. Ecological goals concern the protection of resources and of the ecosystem. The common quantitative framework is given by the analysis of energy and mass flows in time and space, generally within a Life Cycle Analysis. Economic goals concern both investments, which in the case of buildings and buildings stocks should be considered as a long-term resource productivity problem and running costs. Instead of minimising the investment cost, it is preferable to find for a given investment a solution that has the highest durability and reusability. Low running costs are in itself a good indicator for low environmental impact (low energy consumption and high durability). The social aspects of sustainability include comfort, wellbeing and human health protection of the users and for the building workers. The protection of cultural resources, above all architectural heritage, historic urban systems and human made landscapes has become a fully recognized goal. Bio-diversity, social diversity and cultural diversity guarantee a long-term stable equilibrium [**17**]. Figure 3 shows the different dimensions of sustainability and goals for buildings associated to them.

Sustainable development is based on the conservation of regional resources and regional cultural diversity [**19**]. In industrialised countries with a large and highly developed building stock this means

(1) Management in a long term perspective of the architectural heritage (building stock) as the largest financial, physical and cultural capital of industrial societies
(2) Development of techniques to maintain, refurbish and adapt the existing buildings to new requirements; adaptation of new techniques to fit the existing buildings
(3) Creation of long term adaptable structures for new buildings

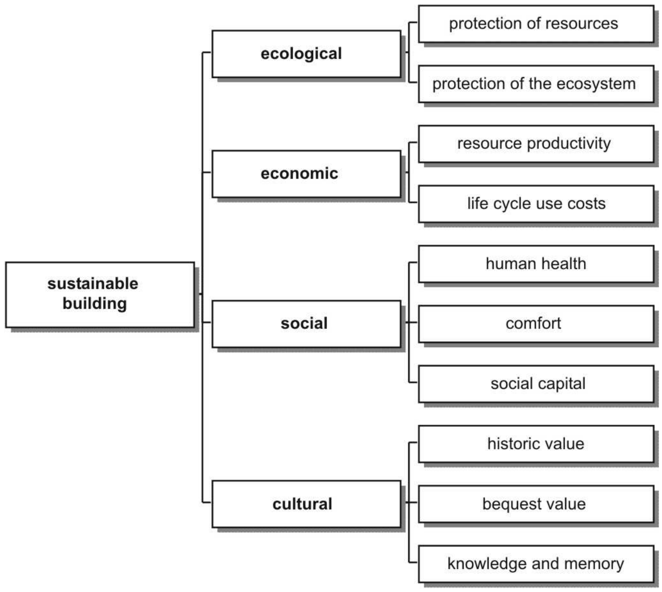


FIGURE 3. The different dimensions of sustainability and some associated goals for buildings.

The inequity between the North and the South is a central and common objective to sustainable development. In fact in societies with rapidly expanding populations and non-controlled urbanisation the objectives of sustainable development will be weighted differently [**29**].

5. Definition of sustainable management of building stocks

Cities are composed of buildings and infrastructure (e.g. roads, sewage plants). The building stocks are the largest financial, physical and cultural capital of European societies. Management of large building stocks includes decision making with comprehensive impact on the environment. Construction activities represent more than half the investments and the flow of materials and energy associated with these activities is dominant for the impact of mankind on nature. The choice between renovation, demolition and rebuilding or continuing with the available buildings has very different ecological, economic and socio-cultural impacts.

- *The medium and long-term management of building stocks is the principal control position for resource consumption, environmental impact, and investment and social equilibrium.*

Managers of building stocks determine the future of at least 60 % of the European building stock. They have for the time being very few and insufficient tools to evaluate environmental impacts of their decisions. In research, there is theoretical knowledge about the present and future mass flows and environmental burdens and about the dynamics of building stocks. Although Life Cycle Assessment (LCA) methods and tools relating mass flow, energy and costs of individual buildings and infrastructure exist, they have not been applied to large sets of buildings even if the need is identified in all European countries.

- *The development of management strategies (methods, tools, reference data) can only result from the combination of research (on sustainability objectives,* *Life cycle analysis and building stock modelling) and the complex every day management practice of building stockowners.*

Traditional intergenerational maintenance strategies of building stocks have often been abandoned and have not been replaced by new methods yet. Experience shows that only strategies based on the natural refurbishment intervals of buildings stocks are realistic. Short-term strategies ($<$ 10 years) are necessary, but they do not allow substantial change. To avoid undesired long-term effects they must be integrated with longer-term (approximatively 25-40 year) strategies. The owners or managers of stocks have concentrated in the last decades on the extension of the stocks (i.e. new constructions). For the decades to come, maintenance, refurbishment and transformation of buildings will be predominant. For the long-term management, the basic data on stocks are often insufficient or partial. The costs to establish these data for all buildings of a stock are enormous and cannot be justified economically; the time needed to establish them is long thus making the data obsolete before they can be used.

- *The development of scaleable methods will allow implementing strategies immediately without a detailed description of building stocks. The dissemination of these techniques will allow the professional managers and owners of building stocks to initiate immediately comprehensive medium and long-term management strategies.*

6. State-of the art of management of building stocks, potentials and risks

On the side of the stakeholders, the state of the art of professional practice and management tools for building stocks is diffuse. In most countries there are universities with curricula on real estate management, housing estate management and facility management. Facility management systems are current for individual, highly equipped buildings, however, they are neither necessary nor useful for large sets of technically relatively simple buildings (e.g. housing). Furthermore there are professional organisations proposing communication standards and normalised formats for real estate and housing estate management. The existing accounting systems deal generally with purely financial aspects reducing maintenance and refurbishment to ratios or functions of stock inventories or cash flows. They sometimes have rough physical ageing functions for the prediction of future periodic refurbishment needs. There are still no bidirectional links between the existing accounting systems and the domains of long-term sustainable management as well on the level of physical, quantifiable data as on the level of qualitative criteria. Table 1 gives examples of problems in this field and the state of the art in the task of trying to solve these.

7. Existing approaches

Facility Management Systems

FM systems support the management of surfaces, operation, maintenance and accounting of individual buildings. There are many commercially available systems based either on databases with graphic front ends or on CAD systems with an FM database. Of course these FM systems allow managing a large number of objects and some are already available on the internet as multi-user platforms. The amount of work to get the necessary data for such systems is considerable, both as an initial input effort and as continuous data maintenance. The costs to obtain the data per m^2 of use surface vary between 2.5 and 3.2 EURO/m^2 when documents (plans) are available and 8 and 11 EURO/m^2 when no data are available [**27**].

Problems	State of the art	Innovation	Implementation
Long-term, intergenerational time constants of building stocks	Generally not taken into account by stakeholders, little research knowledge	Comprehensive definition of sustainability and long-term development	Establishment and discussion of scenarios, Long-term Guidelines,
Ageing of the building stock, Growing needs for refurbishment	Identified by stakeholders, but not quantitatively nor qualitatively dominated	Linking management tools to Life Cycle Models	Interfacing Basic model (tool) with specific management tools
Social problems linked to physical decay of buildings	Identified by stakeholders, basic research exists, implementation knowledge missing	Integration social aspects into a sustainable development framework through specific risk indicators	Application of checklists with indicators, Guidelines, Examples
Limited economic resources	Existing management systems indicate the tendencies without giving long-term solutions	Identification of long-term economic strategies	Scenario calculation with different strategies, boundary conditions and calculation models
Appreciation of the physical state of the stocks	Existing management systems do generally not integrate the physical state. Basic research knowledge exists.	Scaleable, physical model of the state of the stocks and their transformation	Application of scaleable models, and data through interfaces for specific management tools
Cultural significance of the architectural heritage	Not identified by stakeholders. No comprehensive research knowledge	Identification of cultural aspects, integration in a comprehensive framework	Application of checklists with indicators, Guidelines, Examples
Importance of a sustainable development	Growing awareness, but no solutions. Large basic research exists	A comprehensive framework of sustainability indicators	Definitions, Quantification, Interrelation-schemas, Guidelines, Rules
Long-term, comprehensive strategies	Problem identified but no solution neither in practice nor in research.	Formulation of strategies and development of scenario techniques	Strategies formulated as scenarios with boundary conditions and reference values. Application guidelines
Need of comprehensive models	Identified by stakeholders, but problem too important for national stakeholders. Basic research exists	Development of a common basic European model	Open common models (tools), basic data, reference values in scaleable form
Information about successful strategies and tools	Large interest, but difficulty to access information.	Data base of best practice cases	Database on www, implementation examples with application comments

TABLE 1. Some problems and state of the art in their resolutions.

Portfolio Management

Commercial real estate companies have their own definition of portfolio management. Some companies focus mainly on the acquisition and disposition of properties, others handle property management and collections, and still others are largely concerned with the long range forecasting of value for invested capital. In all cases the objective is to increase the asset value of the portfolio, which means increasing the cash flow while decreasing costs. There are four major information workflows:

- *Asset valuation.* The determining of the accurate market value of an individual property or an entire portfolio is a highly specialised activity partially supported by software tools
- *Budgeting and Forecasting* consists in matching a detailed view of the next 12 month's expectations and performance with a 10-year strategic forecast. It can be greatly simplified through better data access and establishing a single process across the portfolio.
- *Cash flow.* Rent collection, billings and invoice processing are basic activities supported by large software solutions relating real estate owners, tenants, operators, contractors and banks.
- *Operations accounting, leasing and reporting* are the fourth important activity.

The tools for portfolio management are often sub-products of financial and PPP software like SAP. The financial aspects are dominating. Problems of sustainable development are not in the realm of the real-estate industry.

Investment decision support systems for housing stocks

Although financial considerations have gained importance in the housing sector during the last decade, additional criteria are also determinant in the first stages of decision making about strategic housing management. Essentially, these are

(1) the housing market and the housing demand,
(2) the technical quality of the building, including its upgrading potential,
(3) the environmental impact of building maintenance and refurbishment.

The INVESTIMMO European project [**20**], developed under the "Competitive and Sustainable Growth Programme", encompasses all these criteria to provide long-term efficient investment strategies in housing maintenance and refurbishment. A model for predicting the future deterioration of all building elements was developed, based both on a European database on building element deterioration, on literature and expert knowledge. The model can be used to predict the evolution of refurbishment costs of building elements in the next 10-15 years for different building maintenance scenarios.

INVESTIMMO has been completed by SUREURO [**28**] which has also a simulation model that is used to demonstrate, by simulation, that possible targets can be met using the knowledge and tools developed in the SUREURO project. It is a game, based on a realistic case and various strategies and focusing on the housing companies business process and decisions. The INVESTIMMO and SUREURO tools use the building diagnostic method EPIQr. The quality of aging and economic basic data is uncertain. The environmental impact part is mainly related to energy consumption calculation.

The programme TOBUS for administrative buildings concentrates mainly on deterioration energy aspects and has not been followed by a commercial software development.

8. Modelling of buildings

Most of the research on the life cycle of individual buildings takes place in the LCA research and development of design tools. Buildings are generally decomposed into elements, which in turn can be decomposed up to basic resources (raw materials from nature, energy). Different elements have different life cycles, which are partly interrelated.

According to the intention buildings are decomposed to certain levels as given in Table 2.

Level	Number	Type	Application
Whole building	1	Current building attributes (age, function etc.)	Management of stocks
Macro-elements	5- 7	Structure, Staircases, Facade, Roof, Interior Walls, Coatings, HVAC e.g.	Management of stocks. Annual diagnosis possible
Elements	25-35	Cost elements are composed of process and exist for new construction, operation, refurbishment, deconstruction	Design, Construction, Facility Management. Usual level of diagnosis. Possibility energy calculation. Diagnosis every 10 to 15 years
Process	150 -250	Construction process	Tender, Construction

Table 2. Levels of Decomposition of buildings.

Methods for building stock management can be established at the levels of whole buildings, macro-elements or elements. As mentioned before the effort to get the necessary data is very different. If there are no detailed data existing and the stock is large (> 100 buildings) there are no available methods. The development of methods to handle this problem is an objective of this report. At the level of macro-elements it is possible to use diagnostic codes on a regular basis. This has been done by [**26**] for the building stock of the canton of Zürich (several thousand buildings). Each year the operation personnel had to fill in a diagnosis form for each building (macro-elements). This was the basis for a multi-annual investment plan and for rapid intervention if the state of building had deteriorated massively since the last diagnosis. The method has proved to be operational. The disadvantages were that they led to relatively high maintenance costs because elements were changed at the first signs of deterioration. Furthermore the method needed a relatively expensive operational staff. At the level of elements, diagnosis methods for refurbishment have been developed for the last 20 years at least. The first French MER methode (méthode d'évaluation rapide) was followed by the Swiss MER method and above all the Swiss "Grobdiagnose" method which works quite well. This method has been completed with energy consumption and indoor air aspects and with a long-term estimation part in EPIQr. The same methods are used by LEGEP, in a completely scaleable way from whole buildings to detailed building process [**23**]. A stock of 250 buildings which are analysed in detail on the process level and simulated over the whole span using LEGEP is the basis for the simplified method with very little information developed in this present project.

9. Scaleable management methods

Building stockowners generally do often not dispose of the data needed for an efficient comprehensive sustainable management. The costs for getting complete data on all buildings are in general far too high. Interventions are therefore based on ad-hoc methods for different objectives (economic, ecological, social etc). These ad-hoc methods are not compatible and do not consider the mutual interdependencies. They do not allow the definition of comprehensive realistic strategies.

One way to overcome this dilemma is to use default values in scaleable methods. As there is always insufficient data, very few exact data will be available in the beginning. Most of the data used will be default values (i.e. average reference values). When the process advances and new evidence appears through current maintenance, the default values will be gradually replaced by real measured values. At the end, only measured values will be used allowing continuous improvement of the model for further applications. The proposed method has a stochastic character and relies heavily on basic research both in statistical methods and structural knowledge about buildings (i.e. geometric interrelations which can be derived from building product models).

10. Sustainable management

According to Daly [**15**], strategies in sustainable management consist of:

- Minimising the throughput (e.g. resource consumption, waste, emissions)
- Maximise the quality (e.g. value)

This can be reached through a long life span of the artefacts combined with low emissions of the building operation.

More precisely, some kind of optimisation problem has to be posed and solved. A different approach is the use of constraint satisfaction methods: For each objective an upper limit value is given. The lower limit is generally 0. This defines a "solution space" for the quantities in concern. If all objectives are reached the solution is accepted from a sustainability point of view. The graphic representation as a spider gives a good idea of the solution space.

Evolution over time

In many cases the objectives as described in the previous paragraph evolve over time. This can be graphically represented as a corridor when adding the time dimension. This is illustrated in Figure 4.

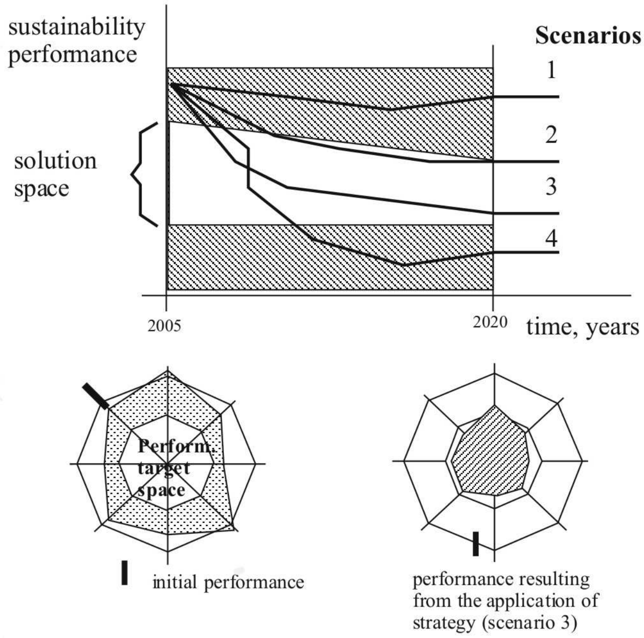


FIGURE 4. Multidimensional criteria and solution corridor.

Part 2

Modelling building stocks with few data

CHAPTER 2

Modelling the building stock

1. Building and building stocks

1.1. Stock analysis. Detailed knowledge about a building stock is rarely easy to obtain. A first detailed investigation of a large building stock is explained in [**5**], [**8**] or [**10**].

The data for the first analysis of a known building stock come from Ettlingen, a small city near Karlsruhe [**9**]. Analysing the data yields estimators for the survival probability of the building stock depending on the function class (residential building (RB) or non residential building (NRB)) [**7**] and their medium life span.

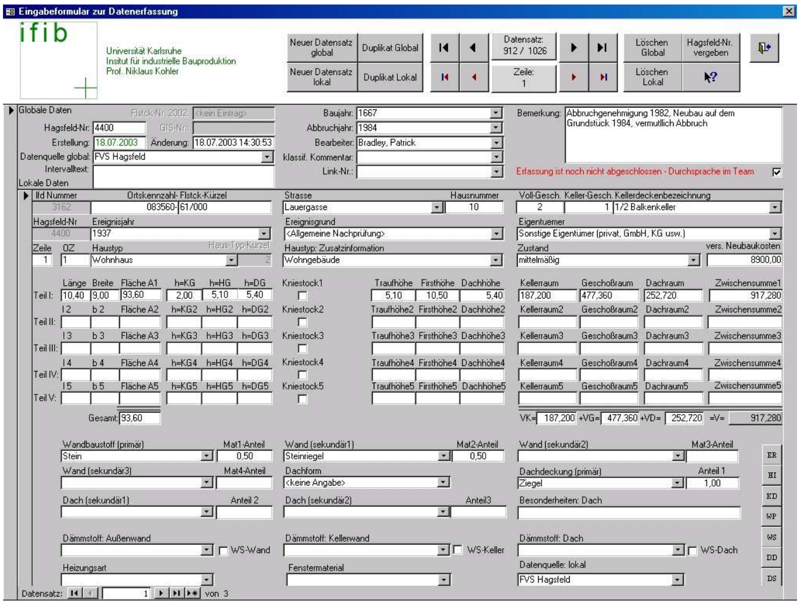


Figure 1. Mask of building stock database

The survival was observed to be seemingly different for residential and non residential buildings, and the lifespans seem to increase with age. However, sound statistical tests have to be performed yet in order to confirm these observations (or to reject them). In any case, we adopt the age/function classification of [**9**], as shown in Table 1.

age class	1	2	3	4	5	6	7	8	9
begin	-	1835	1871	1919	1934	1950	1965	1977	1995
end	1834	1870	1918	1933	1949	1964	1976	1994	today

Table 1. The age class definitions.

1.2. Sample buildings. Economic data on buildings in general and also on NRB are easy to find. There are standardised methods to calculate them, for example [**1**].

The calculation of economic and ecological data of a known sample of buildings is performed by entering the data into LEGEP [**23**]. The results produced by LEGEP are normally presented as single data or as summarised diagrams (see Figure 2).

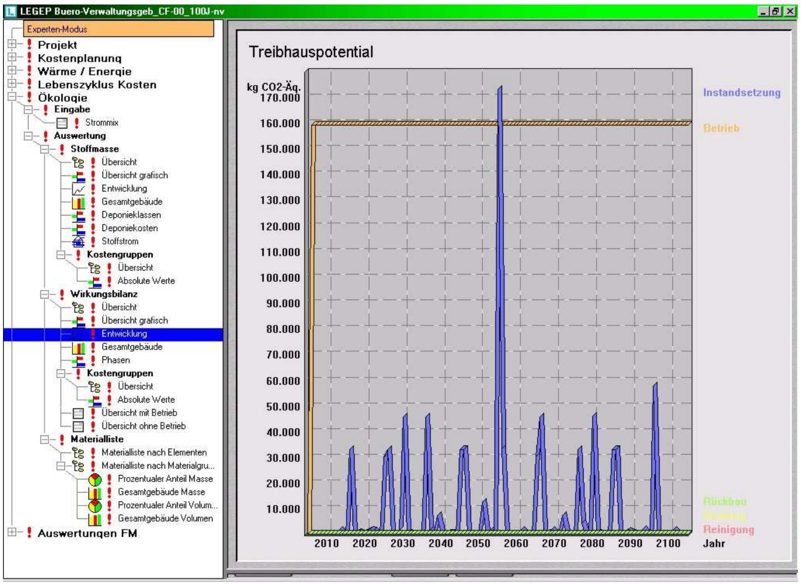


FIGURE 2. LEGEP. Impact assessment, Treibhauspotential = global warming potential (GWP).

In order to analyse the complex data output of LEGEP a small program was written to extract the data from the project database. The results are the massflows and costs triggered by the different processes of the building. There are six different processes during the life span of a building provided by LEGEP:

(1) New construction
(2) Cleaning
(3) Servicing
(4) Operation
(5) Maintenance
(6) Demolition

For each process LEGEP produces either continuously or for selected time points the values of the 19 evaluation criteria from Table 1 in Appendix A. So, for each component we get a 6×19 data matrix. By calculating the sum over all components the result will be a 6×19 matrix for the whole building. These data can be analysed in different ways and with different views and will be the basis for the modeling of the building stock.

2. Incomplete information

2.1. Primary building model. In order to handle the question of incomplete information a so called primary building model is developed. By using ratios, correlations and interdependencies extracted from the literature and by expert knowledge the number of necessary data is reduced and the remaining required data are identified. This approach is exemplified for the class of office buildings. A simple scheme of the primary building model is shown in Figure 3. The upper part of the left column in the figure consists of the so called *free variables*. These are variables, which have no linear relation to the other ones. The variables on the lower part of the left column are connected with a *strong relation* among each other, meaning that they are linearly correlated. A *weak relation* is a linear correlation based on a number of assumptions. For example, a weak relation connects the construction year with the four variables of the lower frame in Figure 3. This is explained in more detail in Chapters C and D.

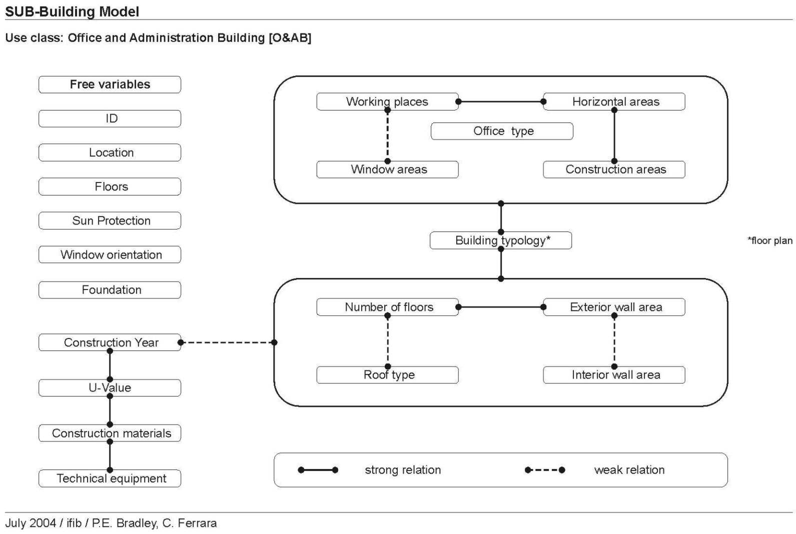


FIGURE 3. Scheme of the primary building model.

The starting point of the related variables in the model core is the number of working places. For a more generalised model these are the functional units, like beds in a hotel, students in a school, etc. There is, depending on the office type, related to every workplace a mean gross floor area (horizontal area, cf. Appendix B.1). The gross floor area is also related with a ratio to the construction area. The building typology based on the simplified floor plan of the building connects the upper part of the model with the lower part.

Details about numbers and ratios to the different variables are listed in the Appendix B through Appendix D. The first idea of this type of model is to reconstruct a real building from a minimum quantity of information. The second idea is to replace the default data step by step by known data. So the real building gets more precise over time.

CHAPTER 3

Management of building stocks

Among the goals of the management of building stocks should be the overcoming of the impact which the ageing process has on the buildings involved.

The ageing of single materials, e.g. metals, paintings etc. are well investigated. But on the component level under real conditions there are only a few publications about ageing and life spans which also show a great variance in results. This means that the data underlying this project are not as accurate as in other engineering sciences. However, the methods used in this project can *in principle* lead to exact results, once exact values for the parameters used are determined[1].

Age functions for the essential components of buildings are defined by first taking a normalised age function and then dilating it to the absolute age function with the component's mean lifetime. Strategies are discussed upon which a simulation of construction and refurbishment is built.

1. Age functions

Even if in the momentary stage of applying the project's methods to a (non-EDF) building stock, the level of building components has not been attained yet, the ageing of building components is described here in some detail, as it will eventually become the pre-dominant approach for a building stock with gradual increase of detailed knowledge on individual buildings.

1.1. Age functions for building components. The definition and properties of age functions in this section are not restricted to building components. In fact the term *age function* is defined in an entirely abstract way in order to make it applicable to very many instances, e.g. to buildings themselves.

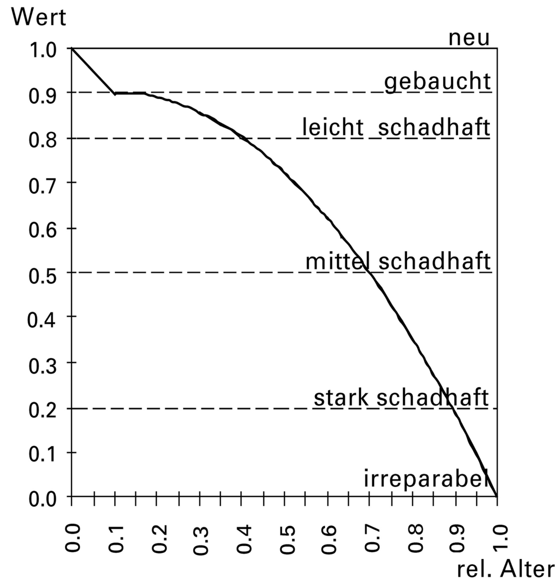
Definition 1.1. *An* age function *is a (not necessarily continuous) map* $V\colon \mathbb{R}_{\geq 0} \to \mathbb{R}_{\geq 0}$ *which is monotonic decreasing (not necessarily strictly), and such that there exists* $r \in \mathbb{R}_{\geq 0}$ *with* $V(r) = 0$*. The infimum of all non-negative numbers* t *such that* $V(t) = 0$ *is called the* life span or lifetime *of* V *(or of the object to which* f *is assigned).*

Figure 1 yields an example of an age function together with an exemplified interpretation of some of its values.

Remark 1.2. The notion of age function as in Definition 1.1 has a great computational advantage. Namely, the monotonicity of V allows to compute by a simple binary search the infimum of all times t such that $V(t) < y$ or, equivalently the supremum of all times t such that $V(t) \geq y$, where y is any given positive value of V. This is effected in Algorithm 1.4.

The following definition captures the possible times of, say, a refurbishment: assume that one wishes to refurbish at a certain value y of the age function V. Then the *critical time* for V at that given value is roughly the latest possible time point at which V has value y, i.e. if the time is infinitesimally larger, then V decreases below the value y.

[1]For example through a huge number of field studies.



Translation:

1.0 = new
0.9 = used (fully serviceable)
0.8 = slightly damaged (functionable)
0.5 = fairly damaged (functionable)
0.2 = strongly damaged
0.0 = irreparably damaged

FIGURE 1. Evaluation scale on an age function.

DEFINITION 1.3. *Let V be an age functions and $y \leq V(0)$ a possible value of $V(t)$. The number*

$$t_{\text{crit}} = \begin{cases} \sup\{t \mid V(t) \geq y\}, & y > 0 \\ \text{lifetime}, & y = 0 \end{cases}$$

is called the critical time *for V at value y.*

ALGORITHM 1.4. Computation of the critical time of an age function V with $V(0) > 0$ at value y.

(1) INPUT: age function V, threshold value y, precision $\varepsilon > 0$.
(2) Set lower time $t_\ell := 0$, upper time $t_u := 1$.
(3) Set upper value $V_u := V(t_u)$.
(4) If $V_u = 0$, then goto (7).
(5) Set $t_u := 2 \cdot t_u$.
(6) Goto (3).
(7) Set mean time $t_m := \frac{t_\ell + t_u}{2}$.
(8) If $V(t_m) \geq y$, then set $t_\ell := t_m$, else set $t_u := t_m$.
(9) If $t_u - t_\ell \geq \varepsilon$, then goto (7).
(10) RESULT: $t_{\text{crit}} := t_\ell$.

Age functions play an important rôle in the study and simulation of building stocks, as the shape of V has an impact on the issue of optimal refurbishment or replacement times for buildings or building components. Table 1 gives an example of mean lifetimes for building components.

In Table 1, *Interior finishings 1* means the substance without kitchen/bathroom and *Interior finishings 2* means the surfaces. The meaning of the variables γ, t_c and T_c will be explained below.

no.	name	weight [%]	mean lifetime [yrs.]	γ	t_c	T_c [yrs.]
1	window	8	20	2	0.1	2
2	structure	35	150	2	0.1	15
3	façade	8	40	2	0.08	4
4	heat generation	1	20	2	0.4	8
5	interior finishings 1	16	60	2	0.1	6
6	electro	6	25	5	0.05	1
7	sanitary	6	25	2	0.1	3
8	roof	4	50	2	0.1	5
9	heat distribution	2	25	2	0.4	5
10	interior finishings 2	6	20	2	0.1	2
11	other technical	3	20	-	1	20
12	other	5	35	-	1	35

TABLE 1. Parameter values.

DEFINITION 1.5. *A* normalised *age function is an age function v such that $v(0) = 1$ and whose lifetime equals 1.*

The age function of Figure 1 is in fact a normalised age function.

REMARK 1.6. Note that for any non-zero age function V one can define

$$v(t) := \frac{1}{V(0)} \cdot V(\text{lifetime} \cdot t). \tag{1}$$

The minuscule t has then the meaning of normalised time, whereas the absolute time is

$$T = \text{lifetime} \cdot t.$$

However, not in all cases, $v(t)$ is in fact an age function. E.g. The function

$$V(t) = \begin{cases} 1, & t = 0 \\ 0, & \text{otherwise} \end{cases}$$

yields the constant function $v(t) = 1$, which is not an age function.

Remark 1.6 leads to the notion of normalisable age functions.

DEFINITION 1.7. *An age function V is called* normalisable*, if $v(t)$, as defined in (1) is an age function. In any case, $v(t)$ is called the* normalisation *of V.*

The example of a non-normalisable age function from Remark 1.6 is rather exotic, as the following lemma shows:

LEMMA 1.8. *Let V be an age function with positive life span. Then its normalisation is a normalised age function.*

PROOF. If the life span of V is not zero, then from (1) we see that $v(0) = 1$ and the life span of v equals 1. In order to prove that the normalisation v is in fact an age function, let r be such that $V(r) = 0$. Setting

$$\rho := \frac{r}{\text{lifetime}}$$

now yields $v(\rho) = 0$. □

Normalisation allows us to define the notion of *equivalent* age functions.

DEFINITION 1.9. *Let $\mathbb{A}$ be the set of all normalisable age functions. Age functions $V, W \in \mathbb{A}$ are said to be* equivalent*, if their corresponding normalised age functions v and w (as constructed in Remark 1.6) are equal.*

Assume now that we have, say, a building with various components each of which are subject to ageing. Thus we have a family of age functions. If certain components have equivalent age functions, then we say that these components are *age equivalent*. All this is formalised in the following definition:

DEFINITION 1.10. *Let X be a set and $F\colon X \to \mathbb{A}$ be a map associating to each $x \in X$ an age function V_x. Then we say that X is* subject to ageing*, and F is an* ageing map*. Further, $x, y \in X$ are said to be* age-equivalent *for (X, F), if V_x and V_y are equivalent age functions.*

LEMMA 1.11. *Equivalence of age functions is an equivalence relation. Each equivalence class is represented by a unique normalised age function.*

PROOF. This follows immediately from the definition. □

The importance of this trivial observation lies in its powerful use for simulations using a database of building components: if these are classified by their normalised age functions, the actual age function for the component can then be determined by extracting its lifetime from a table.

The next definition is useful for determining the relevance of certain classes of age functions of a given object X subject to ageing.

DEFINITION 1.12. *Let X be subject to aging. An age-equivalence class consisting only of one element is called* singular*, the other age-equivalence classes are called* generic*.*

A very important subset of age functions is given by the following definition, as it turns out to describe the ageing of actual building components.

DEFINITION 1.13. *An age function $V\colon \mathbb{R}_{\geq 0} \to \mathbb{R}_{\geq 0}$ is called* standard*, if V is continuous and if there is a $t_c \geq 0$ such that its restriction $V|_{[0,t_c]}$ to the interval $[0, t_c]$ is linear and the restriction $V|_{[0,\infty)}$ is polynomial. The degree of the polynomial $V|_{[0,\infty)}$ is called the* type *of V.*

According to [**14**] building components have as empirical normalised age functions of the form

$$v(t) = \begin{cases} 1 - t, & t \leq t_c \\ v_c\left(1 - \left[\frac{t-t_c}{v_c}\right]^{\gamma}\right), & t > t_c \end{cases}$$

for some value $v_c = v(t_c)$ at some change-point time t_c with parameters given as in Table 1 (the sources for the entries in Table 1 are given in Table 2). In other words, the corresponding empirical age functions are all found to be standard.

Table 1 gives both normalised and absolute change-point times t_c and T_c. From this table, the absolute age function $V(T)$ can be calculated for each building part.

The partitioning of a building into the 12 components of Table 1 follows [**4**]. Table 3 visualises the different normalised age functions.

DEFINITION 1.14. *The components as in Table 1 are named the* stratus components*.*

As building components are subject to ageing, the quest is to explicitly determine the map $X \to \mathbb{A}$ for a given set of building components.

variable	source
weight	[**4**]
mean lifetime	[**12**, Tabelle 6.3]
γ	[**14**]
t_c	[**14**]

TABLE 2. The underlying sources for Table 1.

LAW 1. *The set* $\mathcal{S}$ *of (unweighted) stratus components of a building has exactly one generic age equivalence class* $\mathcal{S}_{\text{gen}}$. *It consists of standard age functions of quadratic type. The singular age equivalence classes are also standard.*

For brevity, we can state the law as

The stratus components are generically standard of quadratic type.

EMPIRICAL PROOF. This is a mere restatement of the results from [**14**] discussed above. □

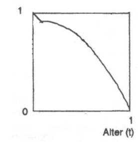
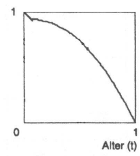
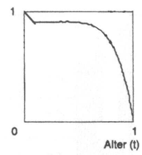
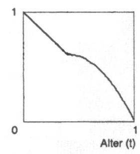
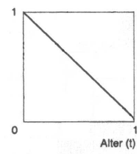
	Normal case	**Special cases**			
	window, roof texture, interior finishings, sanitary (without kitchens), façade	structure	electronic devices	heating	other, other technical
					
γ	2	2	5	2	-
t_c	0.1	0.08	0.05	0,4	1
ω	0.48	0.35	0.06	0.03	0.08

TABLE 3. Parameters for normalised age functions and their weights ω in buildings [**14**] and [**4**].

1.2. Service lives and life spans. Every material and every component has a finite life. But this fact does not allow to determine the exact point of time at which the service life ends.

In the mid 90s a first empirical investigation of the life cycle of components (status, age, replacement time) with 80 buildings from the University of Zürich [**21**] was executed. One result this study showed is that the component age is only one of many factors leading to repair actions or replacements.

A diploma thesis [**13**] carried out at the ifib reveals enormous differences in the existing literature on the life spans of the same component (cf. Figure 2).

In order to narrow down the huge variance in empirical lifetimes of building components, more factors have to be taken into consideration.

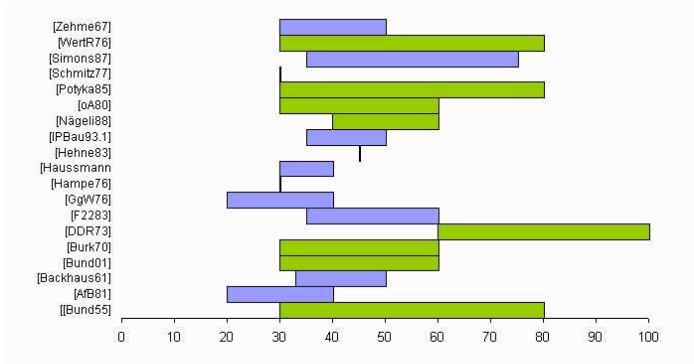


Figure 2. Different life spans of windows in existing literature ([**13**]).

For example, for the lifespan of whole buildings, one would be tempted to take the mean lifetime of the structure from Table 1. However, this does not take into consideration the year of construction or the function of the building. As an attempt in finding the age and functional dependence of a building's lifetime, a model township building stock was studied[**9**]. It was observed that the mean lifespans of buildings is lower for non-residential buildings than for residential buildings and is higher for older buildings than for younger ones (Figure 3). However, it has further to be taken into account that older buildings are refurbished more often than younger ones, and also that the observed lifespan of very young buildings is necessarily very much lower than the actual lifespan, because not enough time has elapsed since their construction.

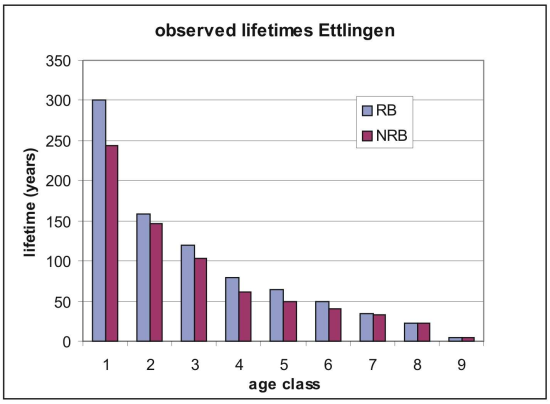


Figure 3. Observed mean lifetimes for Ettlingen buildings.

We therefore propose the mean lifetime distribution from Table 4 with somewhat lesser variation and with a similar shape as the distribution of Figure 3.

age class	1	2	3	4	5	6	7	8	9
residential	150	120	100	90	85	80	75	70	60
non-residential	120	100	90	75	70	70	65	60	50

Table 4. Assigned lifetimes to age and function classes of buildings in years.

1.3. Age functions for buildings. Age functions for buildings are a weighted sum of component age functions. Here, we use the decomposition into stratus components whose age functions are empirically known.

Theoretical approach.

In this subsection, we assign to each building an age function. In this project this approach is only of theoretical value so far, as in the practical implementation in the prototype, we proceed in a simpler manner, as described below. Nevertheless, the theoretical approach can also be practically implemented without much more effort and become important in a situation where the data is more accurate, as for example in a real-time field study using the hybrid approach.

LEMMA 1.15. *Any convex linear combination*

$$v = \sum_{i=1}^{n} \alpha_i v_i$$

of normalised age functions $v_1, \dots, v_n$, i.e. such that $\alpha_1, \dots, \alpha_n$ are non-negative real numbers with

$$\alpha_1, + \dots, + \alpha_n = 1$$

is again a normalised age function.

PROOF. This is a straightforward calculation. □

Lemma 1.15 means that the normalised age functions are a convex subset of $\mathbb{A}$. This makes sure that the following definition yields a well-defined age function.

DEFINITION 1.16. *Let X be a finite set subject to ageing with ageing map $F\colon X \to \mathbb{A}$, and let $v_1, \dots, v_n$ be the normalised representatives of the age equivalence classes $[x_1], \dots, [x_n]$ of (X, F). Then the* normalised age function for X *is defined as*

$$V_X = \sum_{x \in X} \frac{1}{\#[x_i]} \cdot v_i.$$

Practically, for a building which is not described in great detail, one would replace the coefficients $\frac{1}{\#[x_i]}$ in V_X by the weights from Table 1, and use the resulting normalised age function instead of V_X. However, the results from Section 1.1 suggest an even simpler approach for the prototype, described in what follows.

Simplified Approach.

Law 1 says that buildings have a unique generic age function of standard quadratic type, if weights are not considered. The weights shown in Table 3 reveal that there is a singular age equivalence class (structure) whose weight is very large. However, as the relative change point time t_c is close to the generic change point time 0.1, we can merge the generic and that singular class to one class of weight 84%. Neglecting the other singular classes, we adopt the

ASSUMPTION. *The normalised age function of a building is assumed to be*

$$v(t) = \begin{cases} 1 - t, & t \leq t_c \\ (1 - t_c)\left(1 - \left[\frac{t - t_c}{1 - t_c}\right]^2\right), & t > t_c \end{cases} \tag{2}$$

For the concrete change-point time $t_c = \frac{1}{10}$, this yields

$$v(t) = \begin{cases} 1-t, & t \le \frac{1}{10} \\ \frac{9}{10}\left(1-\left[\frac{t-\frac{1}{10}}{\frac{9}{10}}\right]^2\right), & t > \frac{1}{10} \end{cases} \tag{3}$$

Remark 1.17. It should be noted that the simplified age function (2) is *not* the normalisation of a weighted sum of the (unnormalised) component age functions for the generic class $\mathcal{S}_{\text{gen}}$ because of the high variance in the mean lifetimes of the components within $\mathcal{S}_{\text{gen}}$. Therefore, the Assumption can only serve as a first approximation towards building age functions in the case of little prior information.

In a practical performance of our hybrid approach where more and more buildings become known in sufficient detail, one would at the same time gradually adopt the theoretical approach in each step, as the exact weights for determining the building age function are then known.

2. Maintenance and maintenance strategies

The goal of this section is to describe methods of calculating times at which events are to be triggered. Each such event replaces the current age function by another. The central concept here is that of a threshold strategy.

Definition. A *threshold strategy* (or short: *T-strategy*) is a pair $\sigma = (r, c) \in \mathbb{R}_+^{\mathbb{N}} \times \mathbb{R}_+^{\mathbb{N}}$ such that $c_0 = 1$ and $r < c$. The components $r = (r_n)$ and $c = (c_n)$ are sequences of real numbers, where r_n is the *threshold* and c_n the *improvement level*.

The chosen T-strategy has a direct impact on the refurbishment time t_R of a building part. Namely, the strategy gives a threshold value r_0 for $v^{(0)}(t) = v(t)$ at which a refurbishment is triggered. After the refurbishment a new function

$$v'(t) = c_1 \cdot v^{(0)}(t - t_R)$$

is assigned to the building part in concern. The factor c_1 depends on the chosen strategy. In absolute time, the refurbishment is triggered at time T_R, when $V(T_R) = r \cdot V(0)$. After refurbishment, the new absolute function is set to

$$V'(T) = c \cdot V(T - T_R).$$

By iterating this process, we get a sequence $\mathfrak{v}_\sigma(t) = (v_n(t))$ of age functions which depends on the chosen strategy σ.

Example 2.1 (**The partial-total refurbishment scenario**). In the scenario described here, we assume an age function $f(t)$ with $f(0) = 1$, and a partial refurbishment (PR) after k years and a total refurbishment (TR) after ℓ years. Further, we assume that the first refurbishment after construction is PR, followed by an alternating sequence of TR and PR. This is called the *partial-total refurbishment scenario.*

The threshold r_n is calculated thus:

$$r_n = \begin{cases} f(k)^n, & n \text{ even} \\ f(\ell)^n, & n \text{ odd} \end{cases}$$

The value function, in terms of k and ℓ is

$$F(t) = \alpha \cdot f(t - t_n), \qquad \text{if} \quad t \in [t_n, t_{n+1}), \quad n \in \mathbb{N},$$

where the interval boundaries are given by

$$t_n = \begin{cases} \frac{n}{2}(k+\ell), & n \text{ even} \\ \frac{n+1}{2}k + \frac{n-1}{2}\ell, & n \text{ odd} \end{cases}$$

and

$$\alpha_n = \begin{cases} f(k) + s_n \cdot (1 - f(k)), & n \text{ even} \\ f(\ell) + s_n \cdot (1 - f(\ell)), & n \text{ odd} \end{cases}$$

for $n > 0$ and with $\alpha_0 := 1$. The numbers s_n are assumed to be positive and determine the initial value of the next run of the ageing process after refurbishment. Thus the corresponding T-strategy is

$$\sigma = ((r_n), (\alpha_n)),$$

and the resulting sequence $\mathfrak{f}_\sigma(t) = (f_n(t))$ of age functions is such that

$$f_{n+1}(0) \quad \text{is} \quad \begin{cases} \text{larger than } f_n(0), & \text{if } s_n > 1. \\ \text{equal to } f_n(0), & \text{if } s_n = 1. \\ \text{smaller than } f_n(0), & \text{if } s_n < 1. \end{cases}$$

Example 2.2 (**3 Strategies**). In this example one differentiates between three main strategies:

- Obsolescence strategy (OB)
- Value concervation strategy (VC)
- Value enhancement strategy (VE)

The OB strategy maintains no more than what is absolutely necessary and when damages occur. There is no planning needed to execute this strategy. Building elements are not maintained or renovated, and exchanged only when they do not function any more. So the original building elements are replaced when the value of their age function is about 20 - 30 %.

The VC aims at conservation of the use and comfort level of a building or a whole building stock. To reach this aim the building elements are inspected and maintained regularly. They are renovated or replaced when the value of their age function is about 50 %.

The VE keeps the builing on a high functional and comfort level. The building elements are inspected and maintained very often. They are renovated and replaced when the value of their age function is about 70 %.

	threshold	improvement level (PR)	improvement level (TR)
VE	0.8	1.0	1.1
VC	0.6	0.8	1.0
OB	0.5	0.7	0.9

Table 5. The chosen strategy parameters. PR = partial refurbishment. TR = total refurbishment.

The strategy parameters used in the first simulation run are given in Table 5. They are chosen in order to yield partial refurbishment between 20 and 35 years after construction, and total refurbishment after 40-60 years after construction.

3. The Simulator

The simulator is an adaption of StratSim, a strategy simulator programmed by Norbert Paul. A detailed description of StratSim can be found in [**25**].
The concept of the simulator is described in the following.

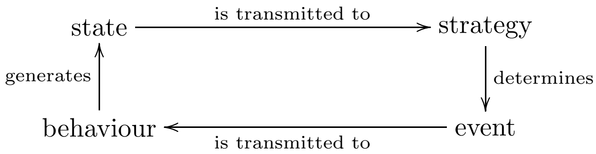
The ingredients are

- buildings

- events
- strategies
- behaviours
- states
- simulations

whose essential properties are explained below.

The simulator connects for each simulation the items above according to the cyclic scheme



We now describe the essential properties of all ingredients in the way in which the simulator makes use of them.

Definition 3.1. *We define the following sets*

- $\mathbb{T}$ *is the open unit interval* $(0,1)$*, meaning the relative* threshold *values for age functions.*
- EventClass, AgeClass, FunctionClass, StateClass *are finite sets whose meaning (referring to buildings) is given by their names.*
- *phase* $=$ EventClass $\cup$ StateClass*.*
- $\mathbb{E}$ *is the set of all* events*.*
- $\mathbb{S}$ *is the set of all* states*.*
- $\mathbb{I} = \mathbb{R}_{\geq 0} \times \mathbb{R}_{>0}$ *is the set of* initial conditions *of age functions*
- Σ *is the set of all* strategies*.*
- $\mathbb{A}$ *is the set of all* age functions
- ConstructionYear $= \mathbb{N}_0$.
- Date $= \mathbb{N}_0$.
- Size $= \mathbb{R}_{>0}$.

where we define by their essential properties:

(1) *A* building b *has: a year of construction* $y \in$ ConstructionYear*, an age class* $ac \in$ AgeClass*, a function class* $fc \in$ FunctionClass*, a size* $v \in$ Size*.*
(2) *An* event *has: a date* $d \in$ Date*, an event class* $ec \in$ EventClass*, a building* b*, a simulation* S*, a state* $s \in \mathbb{S}$*.*
(3) *A* state *has: a phase* $p \in$ Phase*, an age function* $f \in \mathbb{A}$*, preageing, an event* $e \in \mathbb{E}$*.*

Definition 3.2. *A* behaviour *is a map*

$$\beta \colon \text{AgeClass} \times \text{FunctionClass} \times \mathbb{S} \times \mathbb{E} \to \mathbb{S} \times \mathbb{A}$$

Definition 3.3. *A* strategy *is a finite family* $\mathfrak{S} = \{S_i\}_{i \in I}$ *of maps*

$$S_i \colon \mathbb{S} \times \mathbb{T} \to \mathbb{E} \times \mathbb{I},$$

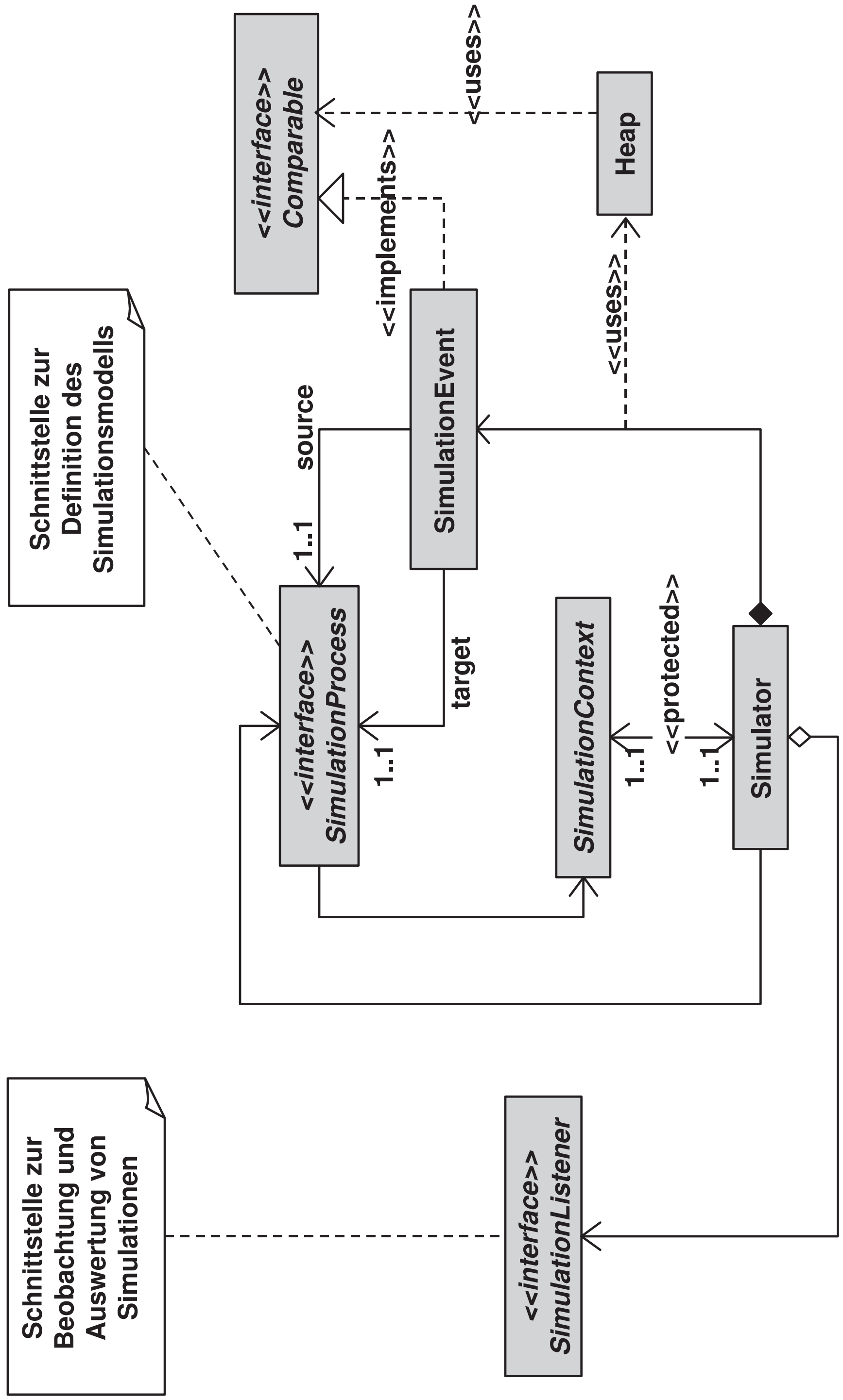
where $I = \{obs, cons, enh\}$ *has the meaning of* obsolescence, value conservation, value enhancement*, respectively.*

Definition 3.4. *A* simulation s *has:*

INPUT. begin, end $\in$ Date*, a default strategy* $\mathfrak{S}_{\text{def}} \in \Sigma$*, a set* X_s *of buildings, a map* $\text{strat}_s \colon X_s \to \Sigma$*, a behaviour* β*, an initial sequence of states and events.*

OUTPUT. An alternating sequence of states and events.

The UML-diagram shows the functionality of StratSim:



Essentially, a simulation setup contains all simulations, and one simulation is marked as history. This simulation is protected. To each building is associated a strategy. The building simulation is then initiated by giving a simulation setup and a set of buildings.

4. Using the simulator

In order to run the simulator, it has to be fed with building and simulation data. This is achieved through a data base, masks for which are shown in Figures 4, 5 and 6. Input of simulations with start year, end year and connection to other simulations is illustrated in the top of Figure 4. The default value is a default history. The bottom picture in the same figure shows how to associate simulations to *scenarios* which associate to each building a sequence of simulations, possibly including history.

Figure 5 visualises the start of simulation runs. And Figure 6 shows how to see for each single building the strategy and start year chosen for a given simulation.

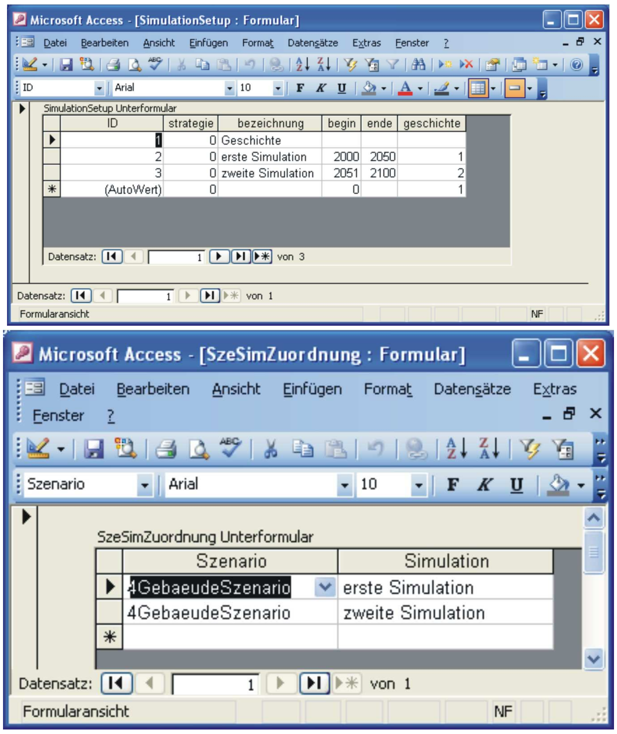


FIGURE 4. Masks for data input (buildings and scenarios).

5. A first simulation run

In a first simulation run we considered one example office building constructed in the year 1980.

The effect we consider is the global warming potential (GWP) in the unit of kg CO_2 equivalent for the three strategies discussed in Example 2.2 of Section 2. To be precise, a combination of Examples 2.1 and 2.2 is performed.

Namely, the scenario is a sequence PR–TR–PR– . . . after new construction, where the refurbishment times are determined by the the strategies obsolescence (OB), value conservation (VC) and value enhancement (VE).

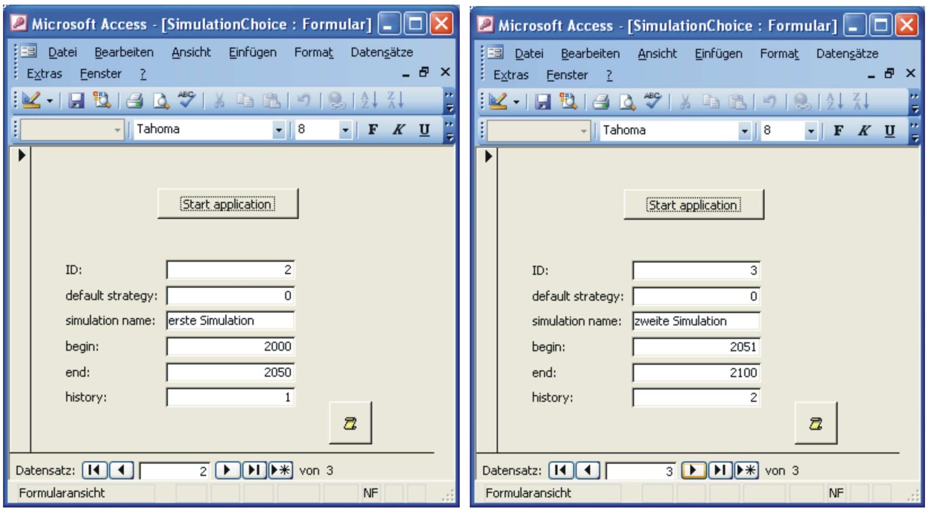


FIGURE 5. Start simulations.

FIGURE 6. A stock containing a building with a certain strategy.

The effect GWP is given as

$$\mathrm{gwp}(t) = a_0 + a_1 t \tag{4}$$

with positive coefficients a_0 and a_1. The value of a_0 is the sum of the effect due to new construction and the effects of partial and total refurbishment taken place up to time $t > 0$. The number a_1 is the operational coefficient where the effect due to operating the building is assumed to be linear in time.

The actual values of a_0 and a_1 is taken from the database underlying [**23**]. Figure 7 shows the values of $\mathrm{gwp}(t)$ for the three strategies in a simulation run of 100 years together with the effect of new construction and each partial or total refurbishment taking place within this time.

It can be noticed that the simulated strategy dependent functions gwp_i are in the expected order

$$\mathrm{gwp}_{\mathrm{VE}} \leq \mathrm{gwp}_{\mathrm{VC}} \leq \mathrm{gwp}_{\mathrm{OB}}$$

with the exception of short intervals of time. However, the differences would be, after one hundred years, only within experimental error!

The problem to this undesired first result lies in the model assumptions. In fact, the effect $\mathrm{gwp}(t)$ depends on the refurbishment times t_r induced by the strategy but not

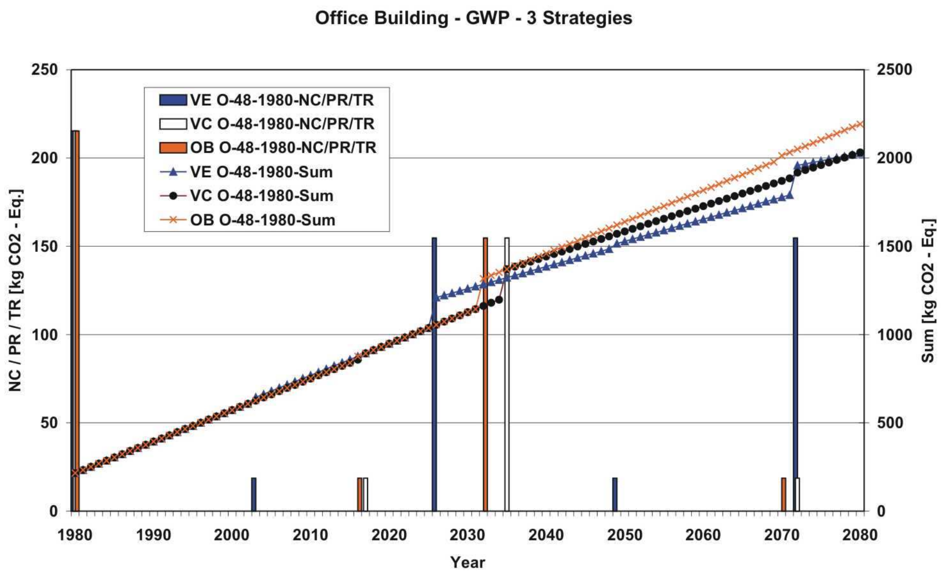


FIGURE 7. Three strategies for one building.

on the values of the age functions involved at time t_r. In other words, the difference Δv between the initial value of the new age function and the value of the old age function immediately before a refurbishment ought to be considered in a more realistic model.

6. An example having an optimal strategy

We illustrate the previous methods by an example model for which an optimal strategy can in fact be calculated.

Let us assume an age function of type (2) from Section 1.3, and assume that a certain effect is of interest.

To be more precise, assume that at a certain time $t > 0$ a refurbishment takes place yielding again the same new age function beginning from the value 1. In other words, we assume the T-strategy

$$\sigma = ((r_n), (c_n)) \qquad \text{with } c_n = 1 \text{ for all } n \in \mathbb{N}.$$

with *jumps* of *height* $\Delta v := 1 - v(t_n)$ at the refurbishment times t_n depending on the thresholds r_n, and we are considering, say, $t_1 = t > 0$.

Now assume that we have the following constant effect factors c_0, c_1, c_2:

c_0 : refurbishment factor
c_1 : operational factor
c_2 : improvement factor for Δv

which are all assumed to be strictly positive with $c_0 < c_2$. Taking c_1 to be constant is in contrast to the previous section. However, this keeps the model simple.

The factors are assumed to amount to an effect Eff(t) due to refurbishment at time t:

$$\text{Eff}(t) := c_0 + c_1 t + c_2 \Delta v.$$

An *optimal strategy* would then minimise the mean effect up to the time point t:

$$\begin{aligned}\mathrm{eff}(t) &:= \frac{\mathrm{Eff}(t)}{t} = \frac{c_0}{t} + c_1 + c_2 \frac{\Delta v}{t} \\ &= \frac{c_0}{t} + c_1 + c_2 \cdot \begin{cases} 1, & t \le t_c \\ \frac{1}{t}\left(t_c + \left(\frac{t-t_c}{1-t_c}\right)^2\right), & t > t_c. \end{cases}\end{aligned}$$

As the function $\mathrm{Eff}(t)$ is continuous, consisting of a positive linear part and a positive quadratic polynomial, the mean effect $\mathrm{eff}(t)$ has no inflexion points. Therefore, the minimum occurs at the unique critical point

$$t_{\min} = \sqrt{(1-t_c)^2 \cdot \left(\frac{c_0}{c_2} + t_c\right) + t_c^2} \tag{5}$$

which lies indeed in the unit interval, as $c_0 < c_2$. In fact, we have

$$t_c < t_{\min} < 1,$$

so the minimum occurs during the quadratic part of the ageing process. We also see that in this case the operational effect factor c_1 has no influence at all.

As a result, we get in this example for the simplified age function (3) from Section 1.3 an optimal strategy depending only on the ratio of the two effect factors c_0 and c_2:

$$t_{\min} = \sqrt{\frac{9^2}{10^2} \cdot \left(\frac{c_0}{c_2} + \frac{1}{10}\right) + \frac{1}{10^2}}.$$

Determining this ratio then becomes the actual task in this approach. This, however, requires some data.

Figure 8 shows a family of effect functions $\mathrm{eff}_{c_0}(t)$ for $t \in [0.05, 1]$ where c_0 varies over the unit interval $[0,1]$, and $c_1 = 0$, $c_2 = 10$ are fixed. Note that due to the fact that

$$\lim_{t \to 0^+} \mathrm{eff}_{c_0}(t) = \infty$$

the plot actually shows the function $\min\{100, \mathrm{eff}_{c_0}(t)\}$. One can see in the figure that each effect function $\mathrm{eff}_{c_0}(t)$ indeed has a local minimum within the unit interval. The lines of equal effect show where the minimum of each effect function lies.

Remark 6.1. Note that if we view the model here as a partial generalisation of the model from the previous section, then we get $\mathrm{gwp}(t)$ from equation (4) by letting $c_2 \to 0$. In this case, the global minimum for the corresponding $\mathrm{eff}(t)$ occurs at $t = 1$, and different strategies have a significant difference only if the refurbishment times are sufficiently distinct, thus leading to relatively long simulation runs.

Example 6.2. In the situation where $v(t)$ is of the concrete form (3) we have for $c_0 = 1$, $c_2 = 4$ a minimum of the corresponding $\mathrm{eff}(t)$ at

$$t_{\min} = \sqrt{\frac{1094}{4000}} \approx 0.52$$

which gives an optimal threshold value of

$$v(t_{\min}) \approx 0.65.$$

Figure 9 shows the values of $\mathrm{eff}(t)$ at some time before and after $t_{\min}$ amounting to thresholds of 0.5 and 0.8. The effect is calculated by the simulator, and one sees that indeed the effect is the lowest at $t_{\min}$.

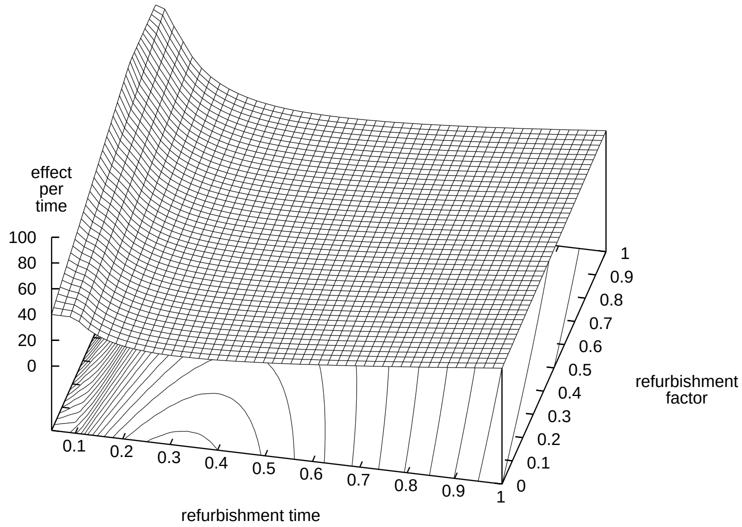


Figure 8. A family of effects and lines of equal effect.

Gesamtergebnis : Auswahlabfrage

simulationSetup	SimulationsPhasen.gebaeude	bezeichnung	wirkung
optimal	normhaus100	AEFF	1.04210526316
optimal+epsilon	normhaus100	AEFF	1.04615384615
optimal-epsilon	normhaus100	AEFF	1.04285714286

Datensatz: 1 von 3

Figure 9. Simulation results for an abstract effect.

7. One building—three strategies

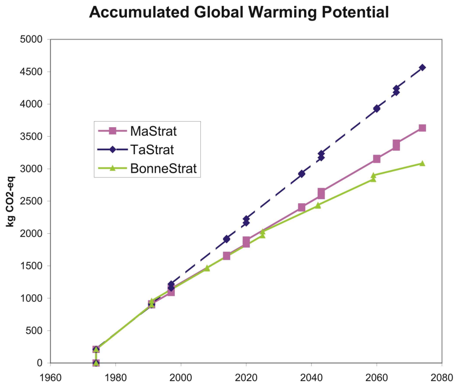
In this section we compare three strategies for one and the same building using a more general model within the partial-total refurbishment scenario.

The strategies are given according to Table 6. Note that the column "improvement level" indicates the value of tbe age function after the measure has taken place. The strategy TaStrat does not alter the energy consumption during the operational phase, while MaStrat lowers it down to 90% of the consumption before the first partial refurbishment. BonneStrat has as first measure after new construction (NC) a total refurbishment (TR) and lowers energy consumption after every total refurbishment according to Table 7. As the slope of the accumulated effects are assumed, similarly to the previous models, proportional to the energy consumption during operational phase, the middle column has been given the name "slope".

The corresponding accumulated global warming potential and costs are shown in Figure 10. Note that for BonneStrat only the slopes B_0 to B_3 are shown, and that after each total refurbishment the relative performance of BonneStrat grows in comparison with the other two strategies.

As a first interpretation, we observe that

(1) for some effects (e.g. gwp) the refurbishment effects are negligible in comparison to the effects of energy consumption during operational phase.



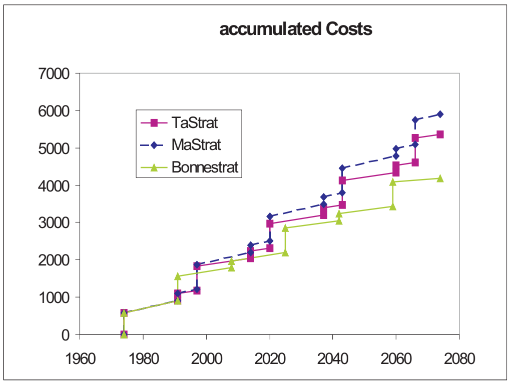


FIGURE 10. Comparing the effects of three strategies (per square meter floor space).

(2) The effects of BonneStrat are significantly lower than the other two strategies only after a long time of application.
(3) BonneStrat has higher effects at the first measure due to skipping the first partial refurbishment.

Figure 11 shows the accumulated differences after one hundred years for more effects. Observe that BonneStrat yields an improvement of at least 10% in comparison with TaStrat, while MaStrat does this in most cases. However, only for the effects radioctivity, acidification potential and costs is there a noticeable long-term improvement as compared with MaStrat.

strategy	measure	improvement level	next threshold	energy consumption after
TaStrat	NC	1	0.5	1
	PR	0.7	0.5	1
	TR	1	0.5	1
MaStrat	NC	1	0.5	1
	PR	0.7	0.5	0.9
	TR	1	0.5	0.9
BonneStrat	NC	1	0.5	1
	PR	1	0.5	same as before
	TR	1	0.5	$B_1 - B_5$

TABLE 6. Simulation run of 3 different strategies.

	slope	standard
B_0	1	average
B_1	0.90	1985
B_2	0.72	1995
B_3	0.58	2002
B_4	0.30	low emission
B_5	0.12	passive house

TABLE 7. Improvements in energy consumption.

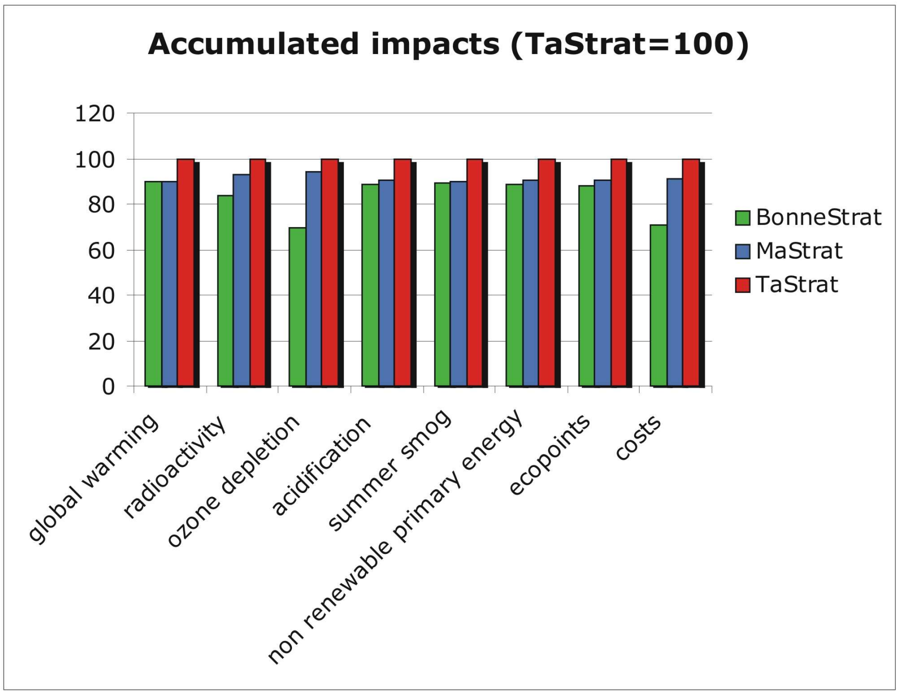


FIGURE 11. Effects of three strategies after 100 years.

Part 3

Using a reference building stock

CHAPTER 4

Similarities between buildings

The theory of similarity is treated e.g. in [**6**] which we use as a general reference for the theoretical discussions of this chapter.

1. Similarity matrices and distance functions

1.1. Definitions. Given a set $\mathbb{O}$ of N different objects $\mathcal{O}_1, \ldots, \mathcal{O}_N$, one assigns to each pair of objects $\mathcal{O}_j$, $\mathcal{O}_k$ a real number s_{ij} ranging from 0 (least similarity) to 1 (greatest similarity) satisfying the following axioms:

$$s_{kj} = s_{jk} \qquad 1 \le j,k \le N \tag{6}$$

$$s_{kj} \ge 0 \qquad 1 \le j,k \le N \tag{7}$$

$$s_{kj} \le s_{kk} \qquad 1 \le j,k \le N \tag{8}$$

$$s_{kk} = 1 \qquad 1 \le k \le N \tag{9}$$

Definition 1.1. *Any function* $s\colon \mathbb{O} \times \mathbb{O} \to \mathbb{R}$ *satisfying the axioms* (1)–(4) *above is called a* similarity matrix *or a* similarity measure *on* $\mathbb{O}$*.*

Closely related to similarity is the concept of *distance* on $\mathbb{O}$.

Definition 1.2. *A* distance matrix *on* $\mathbb{O}$ *is a function*

$$d\colon \mathbb{O} \times \mathbb{O} \to \mathbb{R}, \quad (\mathcal{O}_j, \mathcal{O}_k) \mapsto d_{jk},$$

satisfying the following properties

$$d_{jk} = d_{kj} \qquad 1 \le j,k \le N \tag{10}$$

$$d_{kj} \ge 0 \qquad 1 \le j,k \le N \tag{11}$$

$$d_{kk} = 0 \qquad 1 \le k \le N \tag{12}$$

d *is also called a* distance measure *on* $\mathbb{O}$.

If d *satisfies further the property*

$$d_{jk} \le d_{ji} + d_{ik} \qquad 1 \le i,j,k \le N, \tag{13}$$

then the distance matrix d *is called* metric*.*

Remark 1.3. Note that for a distance matrix d there can exist objects $\mathcal{O}_j \neq \mathcal{O}_k$ but $d_{jk} = 0$. This is usually the case, if for example two different objects have identical attributes.

In mathematical terms, a metric distance matrix is nothing but a semimetric on $\mathbb{O}$.

Remark 1.4. According to [**6**, Kapitel 1.§2.a)], all practically relevant distance matrices satisfy

$$d_{jk} = 0 \implies d_{ij} = d_{ik} \quad \text{for all } \mathcal{O}_i \in \mathbb{O}. \tag{14}$$

This means that if two objects $\mathcal{O}_j$, $\mathcal{O}_k$ have distance zero, then their distances to all other objects of $\mathbb{O}$ coincide.

1.2. Invariance for quantitative data. It is quite common to have information about the given set $\mathbb{O}$ of objects in form of a real $p \times N$-datamatrix $X = (x_{ki})$. As a distance matrix one then takes in fact a distance matrix on the column set $\{x_1, \dots, x_N\} \subseteq \mathbb{R}^p$ of the matrix X.

An important property of a distance matrix on *quantitative* data is that it should not depend on the units of measurement used. This property is reflected in the following definition

DEFINITION 1.5. *Assume that X consist entirely of quantitative data. A distance matrix d on X is called* scale invariant*, if for any real diagonal matrix $S = \operatorname{diag}(s_1, \dots, s_p)$ and for any two columns x_j, x_k holds true*

$$d(x_j, x_k) = d(Sx_j, Sx_k) \tag{15}$$

In other words, rescaling the data columns as

$$x_k = \begin{pmatrix} x_{k1} \\ \vdots \\ x_{kp} \end{pmatrix} \mapsto Sx_k = \begin{pmatrix} s_1 x_{k1} \\ \vdots \\ s_p x_{kp} \end{pmatrix}$$

does not alter the distances regardless of the values of the parameters $s_1, \dots, s_p$.

DEFINITION 1.6. *A distance matrix d on quantitative data X is said to be* translation invariant*, if for any vector $b \in \mathbb{R}^p$ holds true*

$$d(x_j, x_k) = d(T_b(x_j), T_b(x_k)), \tag{16}$$

where

$$T_b \colon \mathbb{R}^p \to \mathbb{R}^p, \quad x \mapsto x + b$$

is translation by b.

In [**6**, Kapitel 1.§3.] many examples of similarity and distance matrices and their properties are discussed.

1.3. Data containing non-quantitative variables. For data not consisting entirely of quantitative variables, it is also possible to define a similarity matrix. Various approaches are discussed in [**6**, Kapitel 1]. Of particular interest in our case is the existence of both quantitative as well as qualitative data (mixed variables).

In the presence of mixed variables, we will adopt the procedure as described in [**6**, Kapitel 1.§6.a) 4.]. First of all decompose the variable matrix X into its non-quantitative part X_{nqu} and quantitative part X_{qu}:

$$X = X_{\mathrm{nqu}} \sqcup X_{\mathrm{qu}},$$

where X_{nqu} consists of the non-quantitative columns and X_{qu} of the quantitative columns of X, and $\sqcup$ denotes here concatenation of the two matrices. Now, define similarity matrices s_{nqu} on X_{nqu} and s_{qu} on X_{qu}. Then

$$s = w_{\mathrm{nqu}} s_{\mathrm{nqu}} + w_{\mathrm{qu}} s_{\mathrm{qu}} \tag{17}$$

is a similarity matrix on X, if the weights w_{nqu} and w_{qu} are non-negative with

$$w_{\mathrm{nqu}} + w_{\mathrm{qu}} = 1.$$

This will be made more explicit in (18) of Section 2.1.

2. Similarities of building stocks

2.1. Generalities. In this subsection we assume we are given a building stock $\mathbb{X}$ consisting of N buildings $\mathcal{X}_1, \dots, \mathcal{X}_N$. To $\mathbb{X}$ is associated a vector-valued function

$$X = \begin{pmatrix} X_1 \\ \vdots \\ X_p \end{pmatrix} : \mathbb{X} \to A, \qquad \mathcal{X}_k \mapsto x_k = \begin{pmatrix} x_{k1} \\ \vdots \\ x_{kp} \end{pmatrix},$$

assigning to each building a vector of length p from some set A. The components of the vectors from A are the attributes corresponding to the given building. As we are dealing with quantitative as well as with qualitative variables, it will in general not be the case that A is a subset of $\mathbb{R}^p$.

As in Section 1.3, we decompose the attribute vectors into their non-quantitative parts and their quantitative parts. Let $p = m + n$ such that there are m non-quantitative and n quantitative attributes for each building. For notational convenience, we assume that each $x_k \in A$ is of the form

$$x_k = \begin{pmatrix} y_k \\ z_k \end{pmatrix}, \quad y_k = \begin{pmatrix} y_{k1} \\ \vdots \\ y_{km} \end{pmatrix}, \quad z_k = \begin{pmatrix} z_{k1} \\ \vdots \\ z_{kn} \end{pmatrix},$$

where y_k is the vector consisting of the m non-quantitative components of x_k and z_k the vector of the quantitative components of x_k.

From [**6**, Kapitel 1.§6.a)] we can take a similarity matrix as follows

$$s_{ij} := \underbrace{\frac{1}{p} \cdot (\#\text{concurring components of } y_i \text{ and } y_j)}_{=:\sigma_{\text{nqu}}} + \underbrace{\frac{1}{p} \sum_{i=1}^{n} \left(1 - \frac{|z_{ji} - z_{ki}|}{r_i}\right)}_{=:\sigma_{\text{qu}}}, \tag{18}$$

where $r_i = \max\{z_{\ell i} \mid 1 \le \ell \le N\} - \min\{z_{\ell i} \mid 1 \le \ell \le N\}$ is the spread of the values of the i-th attribute over the whole building stock $\mathbb{X}$.

2.2. Distances obtained from similarity. If s_{ij} is a similarity matrix, then

$$d_{ij} := 1 - s_{ij} \tag{19}$$

is easily seen to define a distance matrix. Let now $p = m + n$ be such that X consists of m non-quantitative and n quantitative variables. Then, using the notation of (18), we have similarity matrices

$$s_{\text{nqu}} := \frac{p}{m}\, \sigma_{\text{nqu}}, \quad \text{resp.} \quad s_{\text{qu}} := \frac{p}{n}\, \sigma_{\text{qu}}$$

induced on X_{nqu} resp. X_{qu}, which in turn induce distances

$$d_{\text{nqu}} := 1 - s_{\text{nqu}}, \quad \text{resp.} \quad d_{\text{qu}} := 1 - s_{\text{qu}}.$$

LEMMA 2.1. *If s is a similarity matrix as defined in (18), then d_{qu} is invariant under scaling and translation. Further, $d = 1 - s$ is metric and satisfies (14), if viewed as a distance matrix on the building stock $\mathbb{X}$.*

PROOF. This follows easily from the definitions. □

2.3. Similarity of EDF-buildings and the LEGEP-building stock. The goal of the project is to simulate sustainable management of a given EDF-building stock $\mathfrak{E}$ by running a simulation on a reference building stock $\mathfrak{R}$ held by ifib in LEGEP format. The idea is to associate to each EDF-building from $\mathfrak{E}$ all LEGEP-buildings from the reference building stock $\mathfrak{R}$ with minimal distance. The distance we use will be of the type (18) from Section 2.1.

As EDF has not provided any data yet, we assume that a certain minimal set of variables describing buildings from $\mathfrak{E}$ are known or at least known for a subset of $\mathfrak{E}$. They are chosen to be variables known for the buildings from the reference stock $\mathfrak{R}$ and are assumed to be easily provided for $\mathfrak{E}$, at least for most buildings of $\mathfrak{E}$.

The minimal set of building related variables we consider, as described above, consists of

- construction year, indexed by c;
- function, indexed by f;
- gross area, indexed by a;
- main construction material, indexed by m;

for each building. Thus, if $\mathcal{X}$ is a given building, its attributes will be denoted by the vector

$$X = \begin{pmatrix} X_c \\ X_f \\ X_a \\ X_m \end{pmatrix},$$

where X_c denotes the construction year, X_f the function, X_a the gross area and X_m the main construction material of building $\mathcal{X}$.

Remark 2.2. For a given building $\mathcal{X}$ of the EDF building stock $\mathfrak{E}$, we expect to know at least the values of X_c, X_f and X_a. The latter could also be deduced using the methods from Section 2 in Chapter 2, but only at the expense of obtaining inaccurate values of X_a.

We shall assume that the two building stocks $\mathfrak{E}$ and $\mathfrak{R}$ are disjoint, and set

$$\mathfrak{X} = \mathfrak{E} \cup \mathfrak{R}.$$

First we assume further that the vector of variables X is completely known for all buildings $\mathcal{X} \in \mathfrak{X}$. The case of missing values for the material variable X_m will be treated in Section 2.4.

Under the assumption above, we can write down the similarity matrix from Section 2.1 for two buildings $\mathcal{X}, \mathcal{Y} \in \mathfrak{X}$ explicitly as

$$s_{XY} = \frac{1}{4}\left(\delta_{X_f,Y_f} + \delta_{X_m,Y_m} + \frac{|X_c - Y_c|}{R_c} + \frac{|X_a - Y_a|}{R_a}\right), \tag{20}$$

where

$$d_{xy} := \begin{cases} 1, & \text{if } x = y \\ 0, & \text{otherwise} \end{cases}$$

is the *Kronecker-delta*, and

$$R_c := \max_{\mathcal{X}\in\mathfrak{E}}\{X_c\} - \min_{\mathcal{X}\in\mathfrak{X}}\{X_c\}, \quad R_a := \max_{\mathcal{X}\in\mathfrak{E}}\{X_c\} - \min_{\mathcal{X}\in\mathfrak{X}}\{X_c\}$$

denote the variations of the values of X_c, resp. X_a.

Remark 2.3. By Lemma 2.1, the similarity matrix defined above is invariant under scaling and translation.

With the similarity matrix as defined in (20), we proceed as in the previous section, where a distance matrix was defined as (19). Thus, we define the corresponding distance matrix for buildings $\mathcal{X}, \mathcal{Y} \in \mathfrak{X}$ as

$$d_{XY} = 1 - s_{XY}, \tag{21}$$

where s_{XY} is the similarity matrix from (20).

2.4. The case of missing material data. It may be that the EDF-building stock $\mathfrak{E}$ contains buildings with unknown value of X_m, that is, whose main construction material is unknown. In this case, we proceed accordingly as described in [**6**, Kapitel1.§6.b)].

The similarity matrix has to be modified in such a way that it considers only the known components, where the weights are adjusted accordingly. To be precise, if $\mathcal{X} \in \mathfrak{X}$ is a building with unknown main construction material X_m, then for any building $\mathcal{Y} \in \mathfrak{X}$ the XY-element s_{XY} of the similarity matrix is replaced by

$$\sigma_{XY} := \frac{1}{3}\left(\delta_{X_f,Y_f} + \frac{|X_c - Y_c|}{R_c} + \frac{|X_a - Y_a|}{R_a}\right), \tag{22}$$

using the same notations as in (20). However, we do assume that for all buildings, the values of X_c, X_f and X_a are known[1].

In the case of missing X_m for building $\mathcal{X}$, we define the adjusted distance matrix element to be

$$\Delta_{XY} := 1 - \sigma_{XY}.$$

This gives us the general definition of the similarity resp. distance matrices for the building stock $\mathfrak{X}$:

$$S_{XY} := \begin{cases} s_{XY}, & \text{if } X_m \text{ and } Y_m \text{ are known} \\ \sigma_{XY}, & \text{otherwise} \end{cases} \tag{23}$$

$$D_{XY} := 1 - S_{XY}. \tag{24}$$

3. Distances within a relational database

Assuming that we have the data on the EDF building stock $\mathfrak{E}$ (cf. previous section), we can proceed by defining queries yielding the list of LEGEP buildings from the reference stock $\mathfrak{R}$ with minimal distance to each building from $\mathfrak{E}$.

The two building stocks $\mathfrak{E}$ and $\mathfrak{R}$ originate certainly from two different databases, but we can assume that both datasets can be integrated into a common database in which the stock $\mathfrak{E}$ is represented by a table `BATIMENT` and the stock $\mathfrak{R}$ is given by the table `BUILDINGS`. This simplifies the formulation of queries.

For convenience, we assume further that `BATIMENT` does not contain missing data. This allows us to use the distance

$$d_{XY} = 1 - \frac{1}{4}\left(\delta_{X_f,Y_f} + \delta_{X_m,Y_m} + \frac{|X_c - Y_c|}{R_c} + \frac{|X_a - Y_a|}{R_a}\right), \tag{25}$$

given by combining equations (20) and (21) from Section 2.3.

The query

[1] If this is not the case, (22) can easily be adjusted in a similar manner.

$$
\begin{array}{ll}
\texttt{Select} & * \\
\texttt{From} & \texttt{BATIMENT, BUILDING} \\
\texttt{Where} & d(\texttt{BATIMENT}, \texttt{BUILDING}) \\
& = (\texttt{Select}\, \min(d(\texttt{BATIMENT}, \texttt{BLD})) \\
& \texttt{From BUILDING as BLD});
\end{array}
$$

associates to each building $\mathcal{X}$ of BATIMENT the list of all buildings $\mathcal{Y}$ from BUILDING with minimal distance $d(\mathcal{X}, \mathcal{Y}) = d_{XY}$.

Note that in a practical implementation of the query, the formula (25) for the distance $d(\texttt{BATIMENT}, \texttt{BUILDING})$ has to be given explicitly.

CHAPTER 5

The hybrid approach

1. Diagnostic methods of management

The aim of a building diagnosis is to determine the value of the age function $v(t)$ associated to a building X at a given time t after new construction. The result of such a dignosis is usually an indicator concerning the state or usability of the building in concern.

1.1. Indirect diagnosis. The building *state* can be determined indirectly by indicators as

- time since last intervention
- type of last intervention
- evolution of maintenance costs

The *usability* of a building can be determined for example by

- frequencey of previous interventions
- evolution of rent

It is noted that the usability itself is a weak indicator of the state. However, these methods yield only a very rough value of $v(t)$.

For unrefurbished buildings there is also the indicator

- time t since new construction of X

which gives a more accurate value of $v(t)$ the smaller t is, i.e. the newer the building is. Practically, this applies to many buildings of at most around 25 years.

1.2. Component based direct diagnosis. In [**26**] a component based method for building diagnosis is described. It can be summarised as follows.

For each component a diagnosis code is given together with a recommendation.

Example 1.1 (A diagnosis code). Often a diagnosis code of the following kind is used

A. good (maintenance only)
B. slight degradation (repair)
C. significant degradation (repair and partial replacement)
D. end of life (replacement)

where perhaps a further code D* is given for end of life inducing consecutive costs on other elements.

After estimating the value of the component age functions one can construct from these a building age function.

2. Using a reference building stock

Our methods so far yield a further possible diagnosis method:

- the value of the age function $v'(t)$ associated to a building X' which is most similar to X, where X' is taken from a stock $\mathfrak{S}$ of known buildings

In this case, one would define

$$v(t) = v'(t).$$

This method can be generalised to allowing $\mathfrak{S}$ to be a stock of virtual buildings in a simulation. In this way, one creates for all stock buildings with little information a virtual age function which can be used in order to run simulations. The known buildings yield age functions by the previous methods.

3. Determining priorities

The full strength of the hybrid approach lies in the possibility of gradually obtaining more detailed knowledge of a building stock $\mathcal{X}$ and at the same time making reasonably good strategy decisions. We now sketch such an approach where we suppose some fixed strategy.

(1) Use a virtual stock and available priori information in order to determine a subset $\mathcal{Y} \subseteq \mathcal{X}$ of relatively high risk and of reasonable size (depending on the abilities of dealing with the following step) by using the virtual age functions.
(2) Perform a component based diagnosis of all buildings from $\mathcal{Y}$ and identify the subset $\mathcal{Z} \subseteq \mathcal{Y}$ all buildings to be refurbished immediately. Replace for each building from $\mathcal{Y}$ the virtual age function by the age function $v(t)$ through diagnosis.
(3) Establish refurbishment times for the non-refurbished buildings $\mathcal{Y} \setminus \mathcal{Z}$ using the given strategy and $v(t)$.
(4) Repeat step (1) with $\mathcal{X}_1 := \mathcal{X} \setminus \mathcal{Y}$, and so on.

Assuming that for each iteration $\mathcal{Z} \neq \emptyset$ (and $\mathcal{X}$ finite), all buildings from $\mathcal{X}$ are known after finitely many iterations, as then the sequence

$$\mathcal{X}_0 := \mathcal{X} \supseteq \mathcal{X}_1 \supseteq \mathcal{X}_2 \dots$$

is strictly decreasing.

Example 3.1. Let $\mathcal{X}$ be a stock in which every year around 4-5% of the buildings from $\mathcal{X}$ have to be refurbished. However, we assume little a priori knowledge about the stock. Let each iteration, assumed to be completed every year, yield about 10% of $\mathcal{X}_0 = \mathcal{X}$ as identified for immediate diagnosis. It is quite clear that the chance of missing a building in need of immediate refurbishment decreases every year. In this example, after at most 10 years sufficient knowledge about $\mathcal{X}$ has been accumulated in order to make refurbishment decisions without reference to the virtual stock.

Part 4

Application to small building stocks

CHAPTER 6

Modified simulator for building components

The simulator StratSim can handle building stocks only on the level of whole buildings. However, in reality, refurbishment measures are taken on the level of building components. Therefore, it became necessary to modify the simulator. The following sections describe the theory and implementation of the modified simulator which we call StratSim$^+$

1. T*-strategy

Definition 1.1. *A* T*-strategy *is a pair* $\sigma^* = (\sigma, a)$, *where* $\sigma = (r, c)$ *is a T-strategy and* $a = (a_n)$ *is a sequence with* $a_n \in (r_n, 1]$.

Let us introduce some notation: for a given T*-strategy σ^* as in Definition 1.1, let

$$t_i := \min\{t \mid v_{i-1}(t) = r_i\} \tag{26}$$

$$t_i' := \min\{t \mid v_{i-1}(t) = a_i\} \tag{27}$$

$$\Delta t_i := t_i - t_i', \tag{28}$$

where v_i is recursively defined as

$$v_i(t) = c_i \cdot v_{i-1}(t + \Delta t_i). \tag{29}$$

Note that $v_i\colon \mathbb{R}_{\geq 0} \to \mathbb{R}_{\geq 0}$ is a well defined age function, as Δt_i is non-negative.

Definition 1.2. *A* value progression *is a sequence of age functions*

$$\mathfrak{v}_{\sigma^*}(t) = (v_n(t)),$$

if there exists a T*-strategy $\sigma^* = (\sigma, a)$ such that each $v_n(t)$ satisfies conditon (29).

The general idea of the T*-strategy is to allow a value progression $v^{(n)}(t)$ where, say $v'(t)$ occurs at refurbishment time t_R, but does not necessarily run through the whole age function $v(t)$, but only the part of $v(t)$ from $a_1 < 1$ on.

An example of a T*-strategy is illustrated in Figure 1, where we consider N components: The first component age function to reach its specific MustValue m (red horizontal line) is assumed to be component N, and each component whose age function is below its specific ScheduledValue s (blue horizontal line) are refurbished together with component N. In Figure 1, at least component 1 is refurbished at the same time as component N. An implementation of this idea is described in Section 2.1

2. The simulator StratSim$^+$

2.1. General description. The further developped simulator StratSim$^+$ consists of two components:

(1) Abstract simulator.
(2) Implementated simulator.

The abstract simulator is the unchanged abstract simulator underlying StratSim . The implementated simulator can now simulate on the level of building components, i.e. events now take place on elements.

The hierarchy within a given set of building stocks is now as follows:

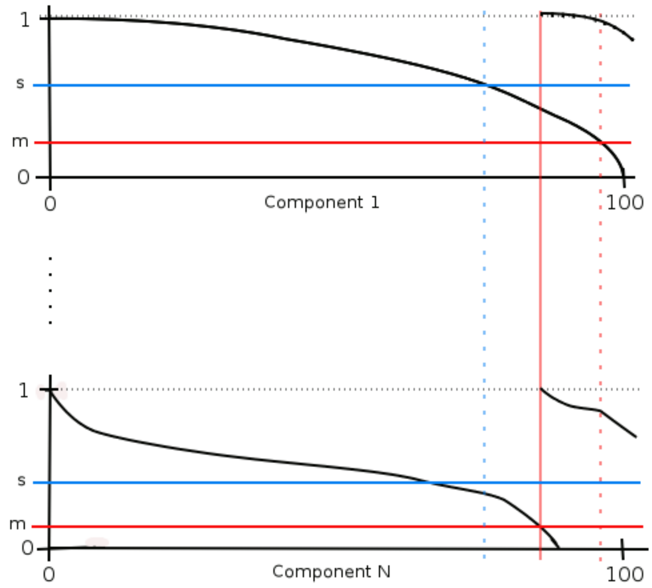


FIGURE 1. An example of a T*-strategy.

- A *building stock* consists of buildings.
- A *building* consists of components.
- Each *component* has a unique construction type.
- Each *construction type* has a unique age function.

In this way, a building stock is a union of buildings, and a building is a union of components. Also, there are maps between the sets

$$\begin{aligned} \{\text{components}\} &\rightarrow \{\text{construction types}\} \\ \{\text{construction types}\} &\rightarrow \{\text{age functions}\} \end{aligned}$$

and the component type can be viewed as the strongest characterisation of a given component.

The implementation of the simulator uses only the standard age functions from Definition 1.13 of Part 2, Chapter 3.1, and is completely based on databases for reasons of variability. In particular, the event queue is incorporated in a database, thus allowing it to be arbitrarily long.

As compared to the previous implementation, the descriptions of strategy and behaviour have been simplified.

A *strategy description* contains

- ScheduledValue
- MustValue
- NewValue

In the case that the age function reaches ScheduledValue, the corresponding element is prebooked into a RepairList. When the age function of some component in a given building reaches MustValue, all entries of RepairList are repaired, and each corresponding component age function is assigned NewValue.

An important requirement is that

$$\text{MustValue} \leq \text{ScheduledValue}$$

Namely, from the monotonicity of age function, we infer that any component, whose age function is below MustValue, is automatically on RepairList.

The *event description* is simply the assignment of NewValue after repair. This has the advantage that a more differentiated behaviour becomes possible by subclassing.

2.2. Events. In order to allow different components to be repaired at the same time, StratSim$^+$uses five different kinds of *events*:

- Init
- Schedule
- Repair
- RepairAll
- Terminate

The last three events have the objective of setting flags when ScheduledValue is reached and to effect simultaneous repairs when a first component reaches MustValue.

Init. The event Init causes for each component an entry into EventQueue the following items:

(1) Clear RepairList.
(2) At ScheduleTime do Schedule.
(3) At RepairTime do RepairAll.

Schedule. The event Schedule causes a given component to be registered into RepairList.

Repair. The event Repair causes the effect of the following:

(1) Set RepairDate to CurrentDate.
(2) Set InitialValue to NewValue.
(3) Remove component from RepairList.

RepairAll. The event RepairAll causes for all components the effect of:

(1) Check, whether component is in need of repair at RepairTime (or if component has already been repaired).
(2) If component is not in need of repair, remove component from RepairList, otherwise do Repair of component.

Terminate. The event Terminate marks the end of a simulation.

2.3. History. For StratSim$^+$, there exist two types of scenarios. Namely,

- Simulation
- History

StratSim$^+$assigns to each component a history, consisting of a list of events and states. In particular, the time and effect of the latest repair before a given historical time can be extracted from the history: either it is contained in the database or it is assumed that the component was new at time of building construction. The latter is also contained in the database.

History is required by StratSim$^+$in order to initialise all components to be simulated at the beginning of each simulation run.

2.4. RepairStrategy. StratSim$^+$uses RepairStrategy in order to govern the events, states and behaviours of all components in question. Its main objective is to either calculate for each component the next ScheduleTime/RepairTime and to insert events into EventQueue, or to do nothing. In the first case, we say that RepairStrategy *acts* or takes an *action*, in the latter case, we say that RepairStrategy remains *idle*. The decision of RepairStrategy on taking action or remaining idle relies on the state of a component after an event has occurred.

The idea of RepairStrategy is an implementation of a generalisation of the T*-strategy which can handle the problem of possible simultaneous repairs of components whose times of scheduled repairs are close to each other.

The occurrence of an event induces a behaviour which places a component into a new state. This state is represented by RepairTime, NewValue and the boolean variable ShouldBeRepaired. To be more precise, when a component age function reaches ScheduledValue, then ShouldBeRepaired = TRUE. The default value of ShouldBeRepaired is FALSE.

This, of course, does not apply to the Terminate event.

Definition 2.1. *A* state *of a component is the triple*

$$\text{State} = (\text{RepairTime}, \text{NewValue}, \text{ShouldBeRepaired}).$$

The pair (RepairTime, NewValue) *will be referred to as the* RepairState *of the component.*

Upon initialising, each component is assigned a value of State by finding the latest event in History.

Table 1 lists the measures taken in all cases.

Event	Behaviour	RepairStrategy
Init	seek last event RepairState unchanged set ShouldBeRepaired = FALSE	act
Schedule	RepairState unchanged set ShouldBeRepaired = TRUE	idle
RepairAll	update State of components on RepairList	idle
Repair	update RepairState set ShouldBeRepaired = FALSE	act

Table 1. Behaviour, state and strategy.

2.5. Event priorities. In order to break ties and to avoid unwanted multiplicities of events, priorities are given to the events according to Table 2.

Event	Priority
Schedule	most urgent
Init	urgent
Repair	urgent
RepairAll	least urgent

Table 2. Event priorities.

The procedure for breaking ties in the case of simultaneous events is first by EventTime, then by priority, and finally by the order of entry into EventQueue. That is, if E and F are two events which are supposed to occur at exactly the same EventTime and have equal priority, then event E occurs before F if and only if E has been entered into EventQueue before event F.

3. Diagnosing

For reasons of flexibility, diagnosing is performed via the help of a database.

DEFINITION 3.1. *A* (discrete) *diagnosis* $\mathfrak{A} = \{A_1, \dots, A_m\}$ *of a valuation progression* $\mathfrak{v}$ *is a finite partition*

$$A_1 \cup \dots \cup A_m = U,$$

where the $A_i = (a_i, b_i]$ *are all disjoint non-empty intervals, and*

$$U = (0, v_0(0)].$$

The intervals A_i *are called the* diagnosis classes *of* $\mathfrak{A}$.

REMARK 3.2. In case there exists for $\mathfrak{v} = (v_i)$ at some time a value greater than $v_0(0)$, then we extend the unique diagnosis class $A = (a, v_0(0)]$ to

$$A^* := (a, \sup\{v_i(t) \mid i \in \mathbb{N}\}].$$

Then we call the set $\mathfrak{A}^*$ obtained from $\mathfrak{A}$ by replacing A by A^* the *extended diagnosis*, and A^* the *extended diagnosis class*.

When diagnosing, either the simulator or an external person determines the diagnosis class of a given component at a given time t at a given status s. It is the unique $A_s = (a_s, b_s] \in \mathfrak{A}$ which contains the value $v_s(t)$, where v_s is the age function of the component in status s.

Now, it may happen that the real value $v_s(t)$ is not explicitly known. In this case, STRATSIM$^+$will pragmatically use the mean value

$$x_s := \frac{a_s + b_s}{2}$$

as an approximation of $v_s(t)$.

The latter case can be interpreted as follows: the component ageing is given by the function v_s. However, it may happen that in reality, the values of v_s are run through at a different velocity than suggested by the actual choice of v_s. This means that the true value $v_\tau(t)$ of the component at a given time is not exactly known. In particular, the true age function v_τ is unknown. It is hoped, however, that the determined diagnosis class contains the value of the component's true age function at time of diagnosis making.

CHAPTER 7

Simulation output

1. The output scheme

1.1. Repair plan. After a simulation has run, a table listing all events at their event times is given out. The first thing to do is to filter out all Repair events, leading to a table with headers

- COMPONENT. Meaning an ID for the building component in concern.
- EVENTTIME. The time at which a Repair event occurs.
- PREVALUE. Value of component age function an instant before Repair event occurs.
- POSTVALUE. Value of component age function an instant after Repair event occurs.
- ENERGYIMPROVEMENT. An number indicating the choice of energy improvement type effected by Repair event.

This table can be interpreted as a repair plan of the simulation. However, in order to be able to compair simulations, a further column is introduced:

- REPAIRCOST. The cost of the component Repair event.

The RepairCost is calculated as

$$\text{RepairCost} = \text{UnitCost} \times \text{ComponentSize} \times \Delta v,$$

where

$$\Delta v := \text{PostValue} - \text{PreValue},$$
$$\text{UnitCost} := \text{Costs per ComponentUnit},$$

and ComponentSize is given in the dimension of ComponentUnit. The values of all these variables are taken from a table in the database.

1.2. Operational costs and energy consumption. For reasons of simplicity, operational costs are defined to be precisely the energy consumption costs. These are defined per component unit.

In addition, for certain components, an energy consumption level is defined which allows to have "identical" components with differing energy consumption. To be more precise, at each Repair event, the strategy can decide on how much to improve the energy performance relative to the previous performance. The contribution of energy improvement to the costs is given by

$$\text{EnergyImprovementCost} = c_E \times \text{UnitCost} \times \text{ComponentSize} \times \text{EnergyImprovement},$$

where EnergyImprovement is the relative improvement in energy consumption, and $c_E \in [0, 1]$ is a constant factor depending on the component in concern.

The components concerned are:

- heat generation
- roof
- façade
- windows

- other technical devices.

The costs of energy consumption are thus calculated as follows:

$$\text{EnergyCost} = \text{EnergyLoss} \times \text{Costs per EnergyUnit} \times \text{ComponentSize} \times \text{Duration},$$

where

$$\text{EnergyLoss} = \text{previous EnergyLoss} \times (1 - \text{EnergyImprovement}).$$

The latter makes necessary an initial value of EnergyLoss. That, however, is defined by the user.

In order to pervent discrepancies between the sum of all initial component energy losses and a building energy loss, the component energy losses are merely used in order to obtain the relative energy losses of the components with respect to the overall building energy loss.

1.3. Comparison of simulations. The scope of comparing simulations is assumed to be the comparison of different strategies. This means that two identical building stocks with identical history, components and initial values of component age functions but with differing strategies are supposed to be compared.

The output tables of such simulations are summaries consisting of

(1) Number of Repair events.
(2) Total costs.
(3) Total operational costs.
(4) Total Repair costs.
(5) Building value previous to and after simulation.

The building value at a given point t in time is given in the following definition:

DEFINITION 1.1. *The* value $v_X(t)$ *of a building* X *at time* t *is defined as the superposition of all value progressions in* t *of the components of* X *according to their weights in* X*.*

In Definition 1.1, it is assumed that at initial time time $t = 0$, i.e. at time of new construction, all component value progressions are at the top value of the very first age function for each component. Thus, $v_X(0)$ represents roughly the new value of the building X just before the begin of its service life.

2. Implementation of StratSim$^+$

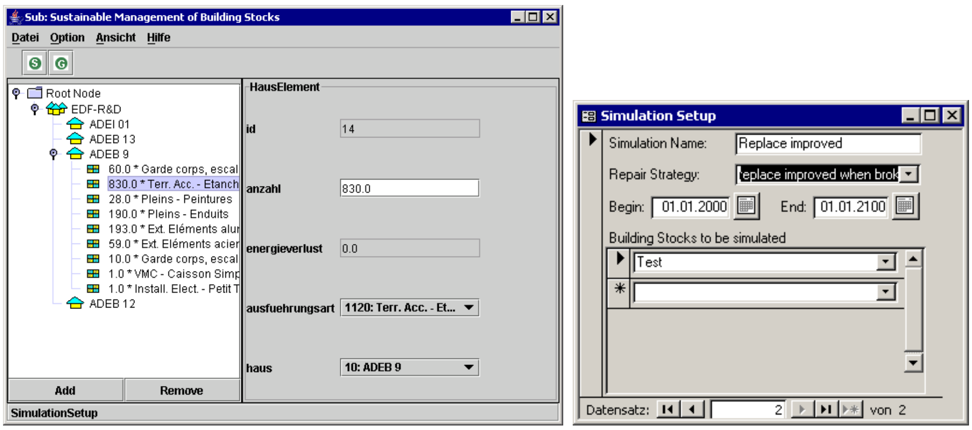


FIGURE 1. Left: Defining a building stock (JAVA frontend); right: simulation setup (Access frontend).

The actual implementation of StratSim+ was effected in JAVA. The frontend was programmed in Access. However, for reasons of platform independence, also a JAVA frontend was programmed.

There, building stocks and a simulation setup can be defined. The level of detail is the building component. Figure 1 (left) illustrates the building stock definition with the JAVA frontend. The level of detail is given by a vertex in a tree. Figure 1 (right) shows also the definition of a simulation setup with the Access frontend.

The definition of the various building components and stocks at the various level of granularity is realised in the Access frontend through a menue (Figure 2). Also, from the menue, the simulation runs are started as well as the results are shown.

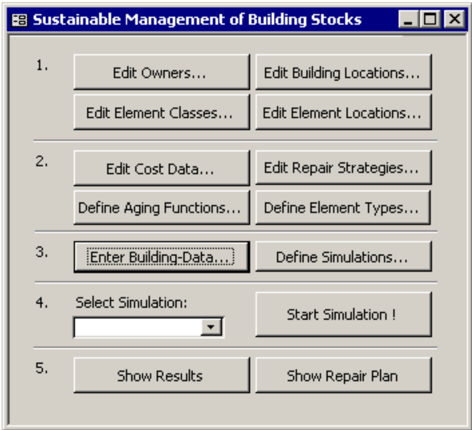
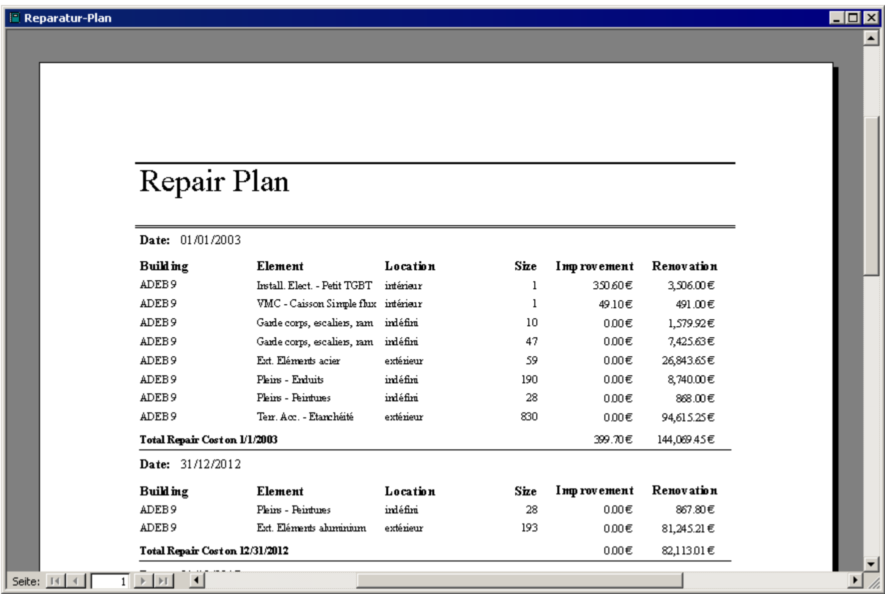


FIGURE 2. Menue (Access frontend).

The results are summarised via the button "Show Results". The summary contains a list of costs for repairs, energy consumption and improvement.



Reparatur-Plan

Repair Plan

Date: 01/01/2003

Building	Element	Location	Size	Improvement	Renovation
ADEB 9	Install. Elect. - Petit TGBT	intérieur	1	350.60€	3,506.00€
ADEB 9	VMC - Caisson Simple flux	intérieur	1	49.10€	491.00€
ADEB 9	Garde corps, escaliers, ram	indéfini	10	0.00€	1,579.92€
ADEB 9	Garde corps, escaliers, ram	indéfini	47	0.00€	7,425.63€
ADEB 9	Ext. Eléments acier	extérieur	59	0.00€	26,843.65€
ADEB 9	Pleins - Enduits	indéfini	190	0.00€	8,740.00€
ADEB 9	Pleins - Peintures	indéfini	28	0.00€	868.00€
ADEB 9	Terr. Acc. - Etanchéité	extérieur	830	0.00€	94,615.25€
Total Repair Cost on 1/1/2003				399.70€	144,069.45€

Date: 31/12/2012

Building	Element	Location	Size	Improvement	Renovation
ADEB 9	Pleins - Peintures	indéfini	28	0.00€	867.80€
ADEB 9	Ext. Eléments aluminium	extérieur	193	0.00€	81,245.21€
Total Repair Cost on 12/31/2012				0.00€	82,113.01€

Seite: 1

FIGURE 3. Repair plan (from Access frontend).

The button “Show Repair Plan” has as output a detailed repair plan for each component, sorted by date. An example is given in Figure 3. Of course, this is to be treated as a suggestion from the chosen strategy. It is clear that the actual dates do not take into consideration the spreading one has in reality, i.e. the lifetimes are used in the calculations as exact lifetimes.

Appendix E contains more screenshots of the implementations in JAVA and Access and of a simulation run of a test example.

In future research, it should be desireable to validate the suggested repair plan (affecting here a particular EDF building) as well as the resulting costs and consumptions in a field study with real buidlings.

Conclusion and perspectives

The project *Sustainable Management of Building Stocks* deals with the problem of sustainably managing a given building stock when little prior information on the stock is available.

The initial objectives from the introduction were limited to the definitions of sustainability objectives in the management of building stocks and in the elaboration of a method allowing to define and evaluate sustainable management strategies for large building stocks when disposing of little information. Little information is de facto the normal situation for the management level even if at the operational level a lot of partial information exists. This information is however not complete, not in the appropriate form or not available in the desired formats (i.e. electronically). There were no doubts about the possibility of the development of a method, the problem was how much basic information on the building stocks of EDF would be available at the beginning of the project and whether it would be in an appropriate form.

The data problem inside EDF was much more difficult to solve for a multitude of reasons, even if all (and the authors want to stress this) participants from EDF R&D and from PERIGEE were extremely helpful and willing to produce the data in a short time. There are many reasons why the data could not be obtained and it would be too long to enumerate them here.

As it can be assumed that also for an EDF building stock the knowledge of each building is not of great detail, the generation of missing geometric and other information relevant for mass and energy flow calculation was of first concern. It is shown in this project how to estimate these through typologies and via ratios from the literature.

The use of age functions allows to simulate the behaviour of a building stock under a given strategy. For this, age functions are conceptually defined, as they can have a large variety of shapes. This approach incorporates for example both continuous functions which are empirically described in the literature, and the discrete age functions which are intended for practical implementation in future work. Its full strength lies in its applicability in the simulator StratSim, where the general definition of age function is used for a consistency check. StratSim can simulate events which generate effects on the basis of any kind of age function whatsoever, thus making it a tool useful for general purpose. StratSim is applied to different models of effect and different strategies are compared.

If at the building level there is not much information on the building stock, a reference building stock turns out to be useful, especially when the stock is large. Through similarity matrices the most similar buildings in the reference stock are identified and simulated. The calculated effects can be adopted to the original stock, thus yielding a coarse estimation of a performance of a given strategy.

On the component level, we propose a hybrid approach where the momentary values of the component age functions are obtained through a diagnosis of some buildings.

From the component age functions, the building age functions of the diagnosed buildings are created and are used together with the reference building age functions in a simulation. Whenever a building is refurbished or diagnosed, the reference age function is replaced by the actual one. In this way, the reference buildings are gradually replaced by the actual buildings and at the same time more and more detailed information on the stock is gained in each step with very little extra effort. This approach seems applicable and could be validated with an EDF building stock in practice, e.g. in combination with existing diagnostic methods already used within EDF.

An implementation at the level of building components is realised in the prototype simulator StratSim^{+}. It considers age functions for each component and allows the simultaneous repair of components which are due or nearly due for a scheduled repair, where the scheduling times are estimated from component diagnoses.

As to insights obtained from this project, we can say that it is in fact theoretically possible to manage building stocks with little information by using a reference stock. The combined mass-energy and financial flow approach can be transferred to the management of building stocks. However, the different strategies proposed or used in this report must be validated in a field study. Component age functions make possible the management of building stocks with detailed a priori information.

It is remarked, however, that the effects of different strategies on the cost or consumption performance of a building stock could only be partially simulated, as the available data did not contain sufficient information on energy consumption and maintenance cost.

The perspectives are of two different natures, depending on the priorities of interest. A priority can be one of the following:

- (large) building stocks with little information
- (small) building stocks with detailed information.

In the first case, data on a large building stock has to be collected and processed and a reference building stock needs to be constituted. The protoptype StratSim should be adapted and enlarged in order to handle the actual data used. The methods described in this report should be evaluated in a field experiment.

In the second case, a collection of complete building data on some small EDF R&D building stock can be undertaken. This might also be done gradually. Further is needed complete data on costs and energy consumption of the chosen building stock. Also in this case, the prototype needs an adaptation and enlargement for handling the actual data used. Of great importance is the establishment of cost tables on which the comparison of strategies would rely. Finally, the methods from this report should again be evaluated in a field experiment.

APPENDIX A

Evaluation Criteria

Criterion	Abbreviation	type	Equivalent [Unit]
`Global warming potential`	GWP	cml	CO_2-Eq. [kg]
`Ozone depletion potential`	ODP	cml	CFC-11-Eq. [kg]
`Acidification potential`	AP	cml	SO_x-Eq. [kg]
`Nutrification potential`	NP	cml	PO_4-Eq. [kg]
`Abiotic depletion`	Abiotic	cml	Sb-Eq. [kg]
`Summer smog`	POCP	cml	C_2H_4-Eq. [kg]
`Primary energy renewable`	PER	cml	– [MJ]
`Primary energy not renewable`	PENR	cml	– [MJ]
`Ecopoints95`	ECO	cml	– [-]
`Mass flow (input)`	STM	cml	– [kg]
`Mono-landfill*`	MOD	other	– [kg]
`Hazardous waste landfill*`	SAD	other	– [kg]
`Hazardous waste combustion*`	SAV	other	– [kg]
`Domestic waste combustion*`	HMV	other	– [kg]
`Domestic waste landfill*`	HMD	other	– [kg]
`Compost*`	KOM	other	– [kg]
`Underground landfill*`	UTD	other	– [kg]
`Radioactivity`	Radio	other	– [kBq]
`Costs`	Costs	other	– [Euro]

TABLE 1. LEGEP criteria

*Landfill and combustion are output mass flows. The sum of input (+, STM) and output (-) flows has to be zero.

APPENDIX B

Identification variables

These are essential variables for the description of a building, and are as such its basic invariants throughout all times.

- ID number `ID`
- data origin `Origin`
- location `Location`
- year of construction `Constyear`

1. The variables — office buildings

The SUB-model describes a building quite coarsely. Here are its variables

- number of working places `Workplace`

The office type `Officetype` can take the values

- standard cell office `standard`
- combi office `combi`
- session room `group`
- open plan office `openplan`
- comfort cell office `comfortcell`

So, for an office building, the vector variable

$$\texttt{Office} = a \cdot \texttt{standard} + b \cdot \texttt{combi} + c \cdot \texttt{group} + d \cdot \texttt{openplan} + e \cdot \texttt{comfortcell}$$

is of interest.

Horizontal Areas.

- gross floor area `BGF`
- net floor are `NGF`
- main function area `HNF`
- traffic area `VF`
- function area `FF`
- construction area `KGF`

Typology `Typology` can take values

- square `square`
- rectangle `rect`
- L-shape `L`
- U-shape `U`
- comb shape `comb`
- (m, n)-atrium `atrium`
- T-shape `T`
- cross shape `cross`

geometric variables

- floor number `FloorNum`
- perimeter `Perim`
- exterior wall area `ExtwallArea`

- interior wall area `IntwallArea`
- exterior wall thickness `ExtwallThick`
- interior wall thickness `IntwallThick`

Roof type `RoofType`

Orientation `Orient`.

Other areas

- foundation area `FoundArea`
- floor area `FloorArea`

In any case, we get the list of variables as in Table 1

Variable	Suffix					Description
`Found`	`Thick`	`Area`	`Type`	`Mat`		foundation
`Floor`	`Num`	`Thick`	`Area`	`Type`	`Mat`	floors
`Extwall`	`Thick`	`Area`	`Type`	`Mat`	`Orient`	exterior walls
`Extwind`	`Area`	`Type`	`Mat`	`Orient`		exterior windows
`Extdoor`	`Area`	`Type`	`Mat`	`Orient`		exterior doors
`Sunprot`	`Area`	`Type`	`Mat`			sun protection
`Intwall`	`Thick`	`Area`	`Mat`			interior walls
`Intdoor`	`Area`	`Mat`				interior doors
`Ceil`	`Thick`	`Area`	`Type`	`Mat`		ceilings
`Roof`	`Thick`	`Area`	`Type`	`Mat`		roofs
`heating`	`Constyr`	`Type`				heating system
`gas`	`Constyr`	`Type`				gas system
`water`	`Constyr`	`Type`				water supply
`cooling`	`Constyr`	`Type`				cooling system
`electricity`	`Constyr`	`Type`				power supply
`telecom`	`Constyr`	`Type`				telecommunication
`transport`	`Constyr`	`Type`				transport system

TABLE 1. Variables (`Thick` = thickness, `Mat` = material, `Num` = number, `Orient` = orientation, `Constyr` = construction year).

Strictly speaking, the suffixes `Type`, `Mat` and `Orient` represent distributions.

2. The types

We now give in Table 2 the values of all variables with suffix `Type`.
The meaning of the suffix `Orient` is a distribution

$$a \cdot N + b \cdot NE + c \cdot E + d \cdot SE + \ldots,$$

where N, NE etc. denote the directions North, North-East etc.

3. The materials

Table 3 gives the values of all variables with suffix `Mat` which itself can take values from the set

$$\{\text{mineral, timber, metal, synthetic}\}.$$

Prefix	-Type
Found	point, srip, plate
Extwall	massive, double, skeleton, timber frame
Extwind	simple, box, bound, double façade
Extdoor	single, double, revolving
Sunprot	inside, outside fixd, outside moveable
Roof	flat, non-flat
heating	single room, single storey, central, community, local, none
gas	central, decentral, none
water	yes, no
cooling	single room, single storey, central, community, local, none
telecom	local net, single link, none
transport	escalator, lift, stairs, ramps, none

TABLE 2. The types.

prefix
Found
Floor
Extwall
Extdoor
Sunprot
Intwall
Intdoor
Ceil
Roof

TABLE 3. The materials.

APPENDIX C

Typology of office buildings and derived perimeters

In this chapter we give typology dependent relations between geometric variables for office buildings.

The value of `Area` can be taken approximatively as the quotient of `BGF` and `FloorNum`:

$$\texttt{Area} = \frac{\texttt{BGF}}{\texttt{FloorNum}}.$$

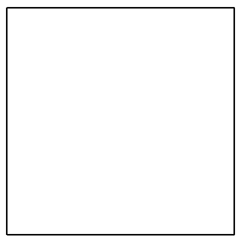
The following sections treat the calculation of `Perim` from the area `Area` and the typology `Typology`. The building typologies are taken from [**24**].

1. Some constants

cell depth	$z = 6m$
aisle width	$g = 3m$
light well width	$\ell = 6m$
inner courtyard width	$y = 30m$
b	$b = 2 \cdot z + g = 15m$
length of wing	$w_l = \begin{cases} 2 \cdot b = 30m & \text{(U-form)} \\ \frac{3}{2}b = 22.5m & \text{(comb form)} \end{cases}$

2. Square

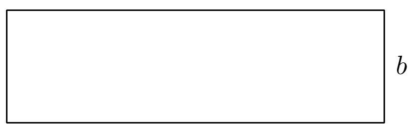
Here the perimeter is obtained from the value of `Area` simply by taking the square root.



The equation is

$$\texttt{Perim} = 4 \cdot \sqrt{\texttt{Area}}.$$

3. Rectangle



In this case, we have $\texttt{length} = \frac{\texttt{Area}}{b}$ which gives

$$\texttt{Perim} = 2 \cdot b + 2 \cdot \texttt{length} = 30m + \frac{2 \cdot \texttt{Area}}{15m}.$$

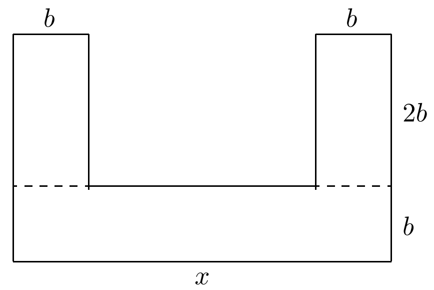
4. L-shape

L-shaped office buildings are approximated by rectangular buildings of the same area.

5. U-shape

Each wing in the U-shaped typology is taken of length $w_l = 2 \cdot b$ as described in Subsection 1 and has thus an area of $w_A = b \cdot w_l = 2\ b^2 = 225\ m^2$. This gives

$$\texttt{Perim} = 2 \cdot x + 10 \cdot b, \quad \text{where} \quad x = \frac{\texttt{Area} - 2 \cdot w_A}{b}.$$

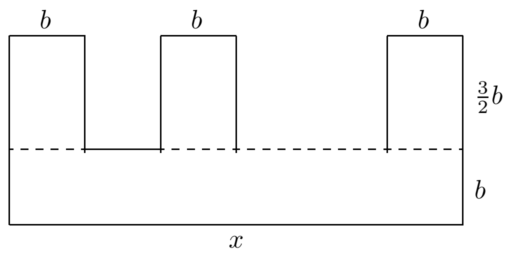


6. Comb shape

The comb is of a similar shape as the U-form, but is defined to have at least three wings, each of them having a length of $w_l = \frac{3}{2}b$ (Subsection 1) which gives an area of $w_A = \frac{3}{2}b^2$.

Together with the number WingNum of wings, the is readily calculated as

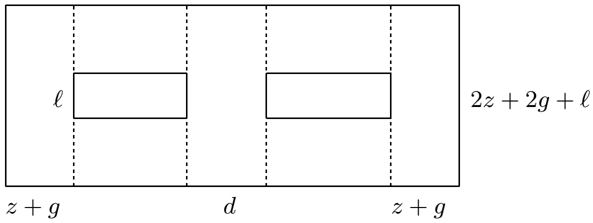
$$\texttt{Perim} = 2x + (2 + 3 \cdot \texttt{WingNum}) \cdot b, \quad \text{where} \quad x = \frac{\texttt{Area} - \texttt{WingNum} \cdot w_A}{b}.$$



7. The (m, n)-atrium

For the typology (m, n)-atrium the first parametre m denotes the number of inner courtyards and the second, n, the number of light wells. We assume a distance of $d = 10m$ between inner courtyards or light wells.

7.1. The case $m = 0$. In the case that there are only light wells in the atrium, the floor plan is assumed something like this (with possibly a different number of light wells):



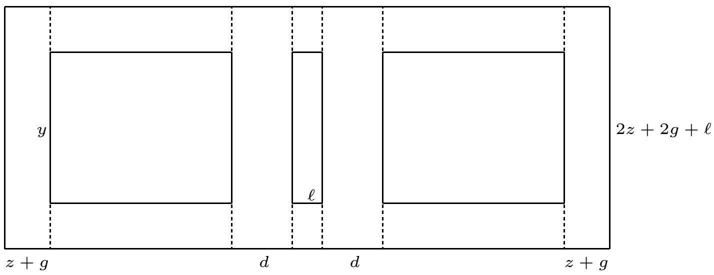
And we get

$$\texttt{Perim} = 2 \cdot (2z + 2g + \ell) + 4 \cdot (z + g) + 2(n - 1) \cdot d + 4\ell_x + 2n \cdot \ell,$$
$$\text{where} \quad \ell_x = \frac{\texttt{Area} - (\ell_e + (n - 1) \cdot \ell_d)}{2z + 2g},$$
$$\text{and} \quad \ell_e = (2z + 2g + \ell) \cdot (z + g) \quad \text{and} \quad \ell_d = (2z + 2g + \ell) \cdot d.$$

The latter quantities ℓ_e resp. ℓ_d are the areas of the rectangles separating the light wells from the exterior walls resp. other light wells.

8. The case $m > 0$

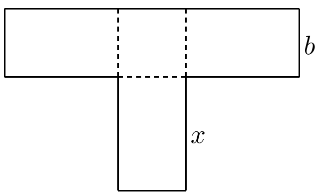
The existence of inner courtyards gives an arrangement of light wells differring from the case without inner courtyards.



This time we get

$$\texttt{Perim} = 2 \cdot (2z + 2g + y) + 4 \cdot (z + g) + 2(m + n - 1) \cdot d + 4\ell_y + 4n \cdot \ell + 2(m + n) \cdot y,$$
$$\text{where} \quad \ell_y = \frac{\texttt{Area} - (\ell_{e'} + (m + n - 1) \cdot \ell_{d'} + 2m \cdot \ell y)}{2z + 2g},$$
$$\text{and} \quad \ell_{e'} = (2z + 2g + y) \cdot (z + g) \quad \text{and} \quad \ell_{d'} = (2z + 2g + y) \cdot d.$$

9. The T-shape

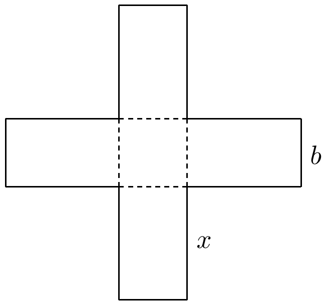


We assume a regular T-shaped typology as in the picture above. Then

$$\texttt{Perim} = 4 \cdot b + 6 \cdot x, \quad \text{where} \quad x = \frac{\texttt{Area} - b^2}{3b}.$$

10. The cross shape

Here we assume a regular cross of this type



This gives

$$\texttt{Perim} = 4 \cdot b + 8 \cdot x, \quad \text{with} \quad x = \frac{\texttt{Area} - b^2}{4b}.$$

APPENDIX D

The office building model

We need following variables from which others can be estimated: `Officetype`, `Workplace`, `Typology`, `Constyear`.

Relations from which the horizontal areas can be obtained are given by equations (30) to (37). Note that the dependency on `Typology` is through `Perim` which depends on the typology and area (cf. Appendix C). The meaning of the variables are explained in Appendix B.1.

$$\texttt{ExtwallArea} = 3\,\mathrm{m} \cdot \texttt{Perim} \cdot \texttt{FloorNum} \tag{30}$$

$$\texttt{BGF} = c(\texttt{Officetype}) \cdot \texttt{Workplace} \tag{31}$$

$$\texttt{NGF} = .87 \cdot \texttt{BGF} \tag{32}$$

$$\texttt{NF} = .61 \cdot \texttt{BGF} \tag{33}$$

$$\texttt{HNF} = .48 \cdot \texttt{BGF} \tag{34}$$

$$\texttt{VF} = d(\texttt{Officetype}) \cdot \texttt{Workplace} \tag{35}$$

$$\texttt{FF} = e(\texttt{Officetype}) \cdot \texttt{Workplace} \tag{36}$$

$$\texttt{KGF} = f(\texttt{Officetype}) \cdot \texttt{Workplace} \tag{37}$$

The values of c, d, e, f are given by Table 1.

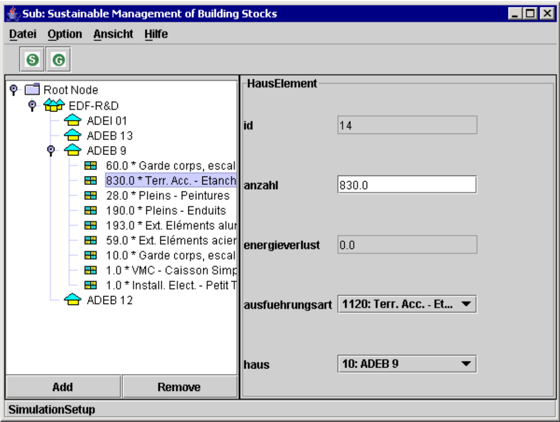
`Officetype`	c [sqm]	d [sqm]	e [sqm]	f [sqm]
`standard`	22.4	3.8	0.9	1.6
`combi`	23.1	3.9*	1.4*	1.7*
`group`	25.9	3.9*	1.4*	1.7*
`openplan`	26.4	2.9	2.3	1.3
`comfortcell`	28.9	4.9	1.1	2.1

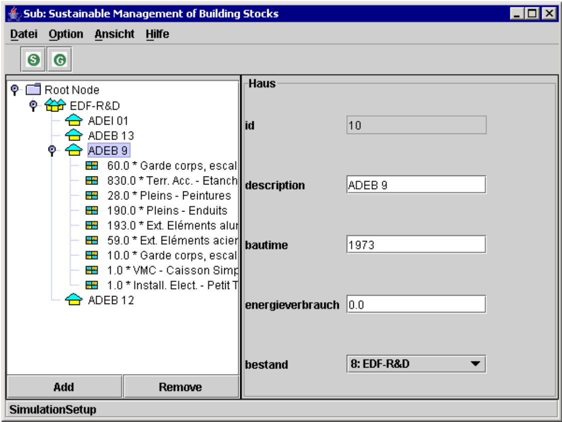
TABLE 1. Values of some constants (* means: estimated by authors).

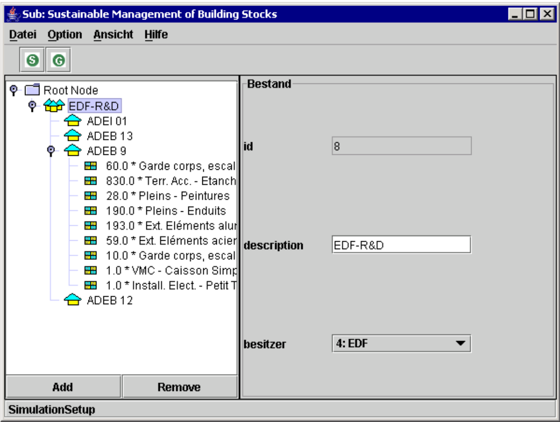
APPENDIX E

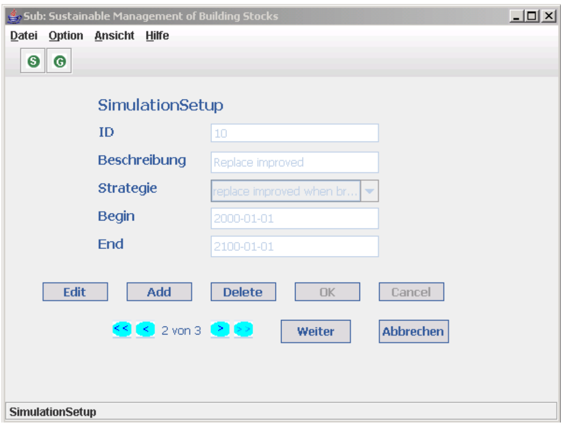
Screenshots

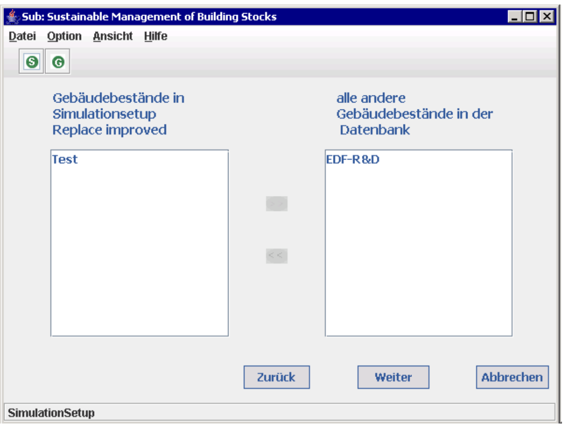
1. The Java frontend



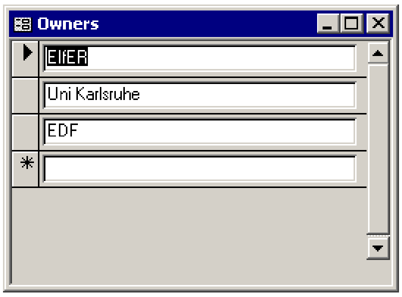






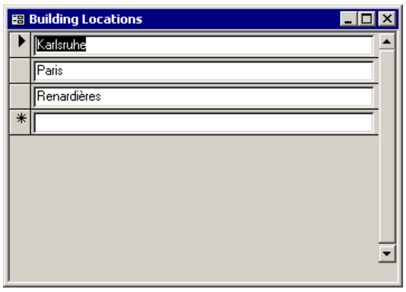


2. The Access frontend



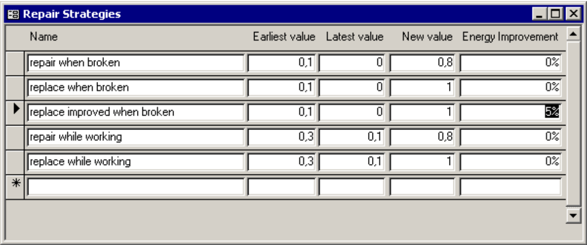
Owners

EIfER
Uni Karlsruhe
EDF



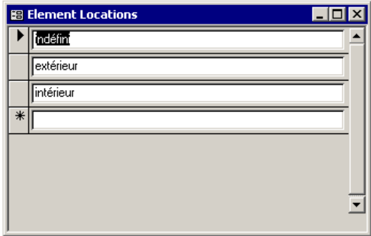
Building Locations

Karlsruhe
Paris
Renardières



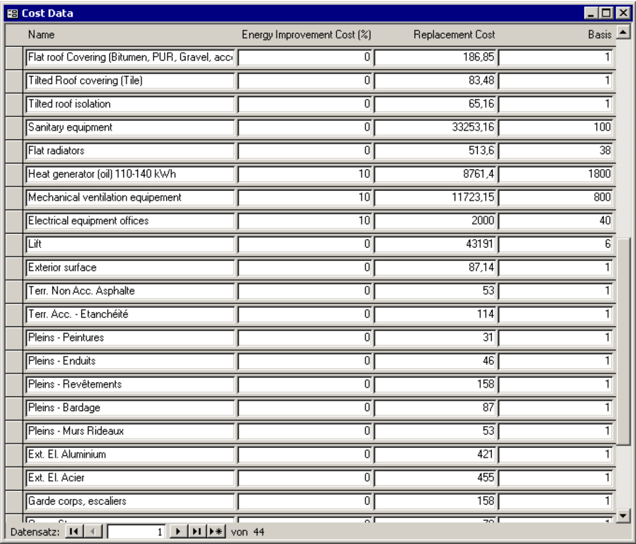
Repair Strategies

Name	Earliest value	Latest value	New value	Energy Improvement
repair when broken	0,1	0	0,8	0%
replace when broken	0,1	0	1	0%
replace improved when broken	0,1	0	1	5%
repair while working	0,3	0,1	0,8	0%
replace while working	0,3	0,1	1	0%



Element Locations

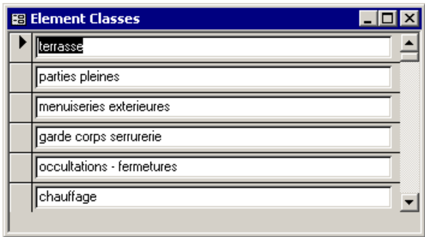
indéfini
extérieur
intérieur



Cost Data

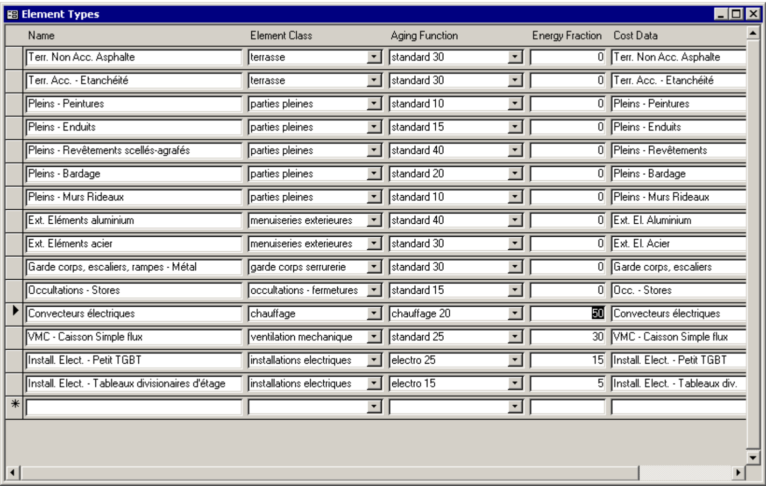
Name	Energy Improvement Cost (%)	Replacement Cost	Basis
Flat roof Covering (Bitumen, PUR, Gravel, acc	0	186,85	1
Tilted Roof covering (Tile)	0	83,48	1
Tilted roof isolation	0	65,16	1
Sanitary equipment	0	33253,16	100
Flat radiators	0	513,6	38
Heat generator (oil) 110-140 kWh	10	8761,4	1800
Mechanical ventilation equipement	10	11723,15	800
Electrical equipment offices	10	2000	40
Lift	0	43191	6
Exterior surface	0	87,14	1
Terr. Non Acc. Asphalte	0	53	1
Terr. Acc. - Etanchéité	0	114	1
Pleins - Peintures	0	31	1
Pleins - Enduits	0	46	1
Pleins - Revêtements	0	158	1
Pleins - Bardage	0	87	1
Pleins - Murs Rideaux	0	53	1
Ext. El. Aluminium	0	421	1
Ext. El. Acier	0	455	1
Garde corps, escaliers	0	158	1

Datensatz: 1 von 44



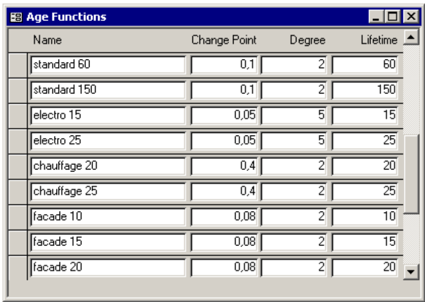
Element Classes

terrasse
parties pleines
menuiseries exterieures
garde corps serrurerie
occultations - fermetures
chauffage



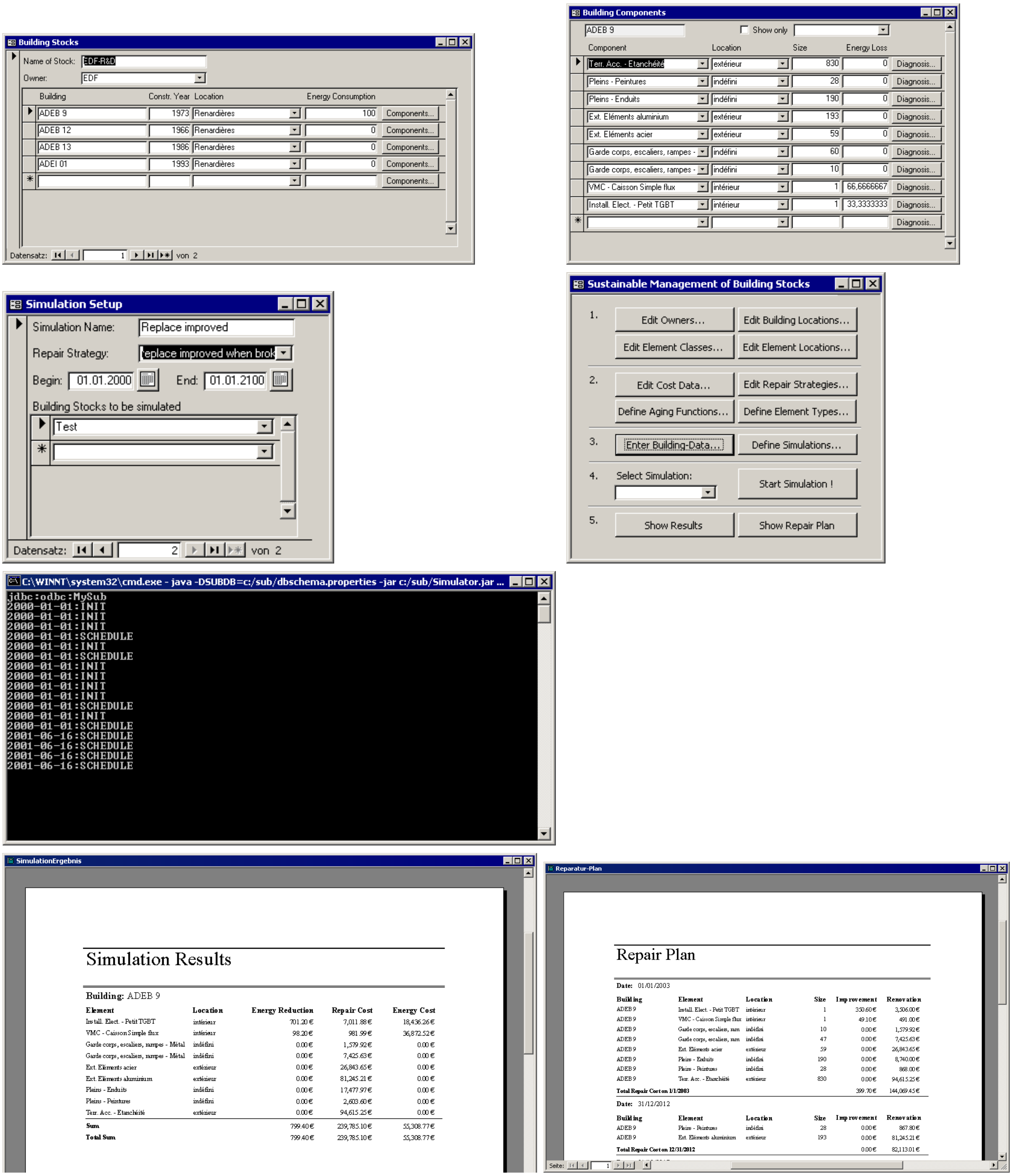
Element Types

Name	Element Class	Aging Function	Energy Fraction	Cost Data
Terr. Non Acc. Asphalte	terrasse	standard 30	0	Terr. Non Acc. Asphalte
Terr. Acc. - Etanchéité	terrasse	standard 30	0	Terr. Acc. - Etanchéité
Pleins - Peintures	parties pleines	standard 10	0	Pleins - Peintures
Pleins - Enduits	parties pleines	standard 15	0	Pleins - Enduits
Pleins - Revêtements scellés-agrafés	parties pleines	standard 40	0	Pleins - Revêtements
Pleins - Bardage	parties pleines	standard 20	0	Pleins - Bardage
Pleins - Murs Rideaux	parties pleines	standard 10	0	Pleins - Murs Rideaux
Ext. Eléments aluminium	menuiseries exterieures	standard 40	0	Ext. El. Aluminium
Ext. Eléments acier	menuiseries exterieures	standard 30	0	Ext. El. Acier
Garde corps, escaliers, rampes - Métal	garde corps serrurerie	standard 30	0	Garde corps, escaliers
Occultations - Stores	occultations - fermetures	standard 15	0	Occ. - Stores
Convecteurs électriques	chauffage	chauffage 20	50	Convecteurs électriques
VMC - Caisson Simple flux	ventilation mechanique	standard 25	30	VMC - Caisson Simple flux
Install. Elect. - Petit TGBT	installations electriques	electro 25	15	Install. Elect. - Petit TGBT
Install. Elect. - Tableaux divisionaires d'étage	installations electriques	electro 15	5	Install. Elect. - Tableaux div.



Age Functions

Name	Change Point	Degree	Lifetime
standard 60	0,1	2	60
standard 150	0,1	2	150
electro 15	0,05	5	15
electro 25	0,05	5	25
chauffage 20	0,4	2	20
chauffage 25	0,4	2	25
facade 10	0,08	2	10
facade 15	0,08	2	15
facade 20	0,08	2	20


Building Stocks
Name of Stock: EDF-R&D
Owner: EDF
Building Constr. Year Location Energy Consumption
ADEB 9 1973 Renardières 100 Components...
ADEB 12 1966 Renardières 0 Components...
ADEB 13 1986 Renardières 0 Components...
ADEI 01 1993 Renardières 0 Components...
Datensatz: 1 von 2
Building Components
ADEB 9 Show only
Component Location Size Energy Loss
Terr. Acc. - Etanchéité extérieur 830 0 Diagnosis...
Pleins - Peintures indéfini 28 0 Diagnosis...
Pleins - Enduits indéfini 190 0 Diagnosis...
Ext. Eléments aluminium extérieur 193 0 Diagnosis...
Ext. Eléments acier extérieur 59 0 Diagnosis...
Garde corps, escaliers, rampes - indéfini 60 0 Diagnosis...
Garde corps, escaliers, rampes - indéfini 10 0 Diagnosis...
VMC - Caisson Simple flux intérieur 1 66,6666667 Diagnosis...
Install. Elect. - Petit TGBT intérieur 1 33,3333333 Diagnosis...
Simulation Setup
Simulation Name: Replace improved
Repair Strategy: replace improved when brok
Begin: 01.01.2000 End: 01.01.2100
Building Stocks to be simulated
Test
Datensatz: 2 von 2
Sustainable Management of Building Stocks
1. Edit Owners... Edit Building Locations...
Edit Element Classes... Edit Element Locations...
2. Edit Cost Data... Edit Repair Strategies...
Define Aging Functions... Define Element Types...
3. Enter Building-Data... Define Simulations...
4. Select Simulation: Start Simulation !
5. Show Results Show Repair Plan
C:\WINNT\system32\cmd.exe - java -DSUBDB=c:/sub/dbschema.properties -jar c:/sub/Simulator.jar ...
jdbc:odbc:MySub
2000-01-01:INIT
2000-01-01:INIT
2000-01-01:INIT
2000-01-01:SCHEDULE
2000-01-01:INIT
2000-01-01:SCHEDULE
2000-01-01:INIT
2000-01-01:INIT
2000-01-01:INIT
2000-01-01:INIT
2000-01-01:SCHEDULE
2000-01-01:INIT
2000-01-01:SCHEDULE
2001-06-16:SCHEDULE
2001-06-16:SCHEDULE
2001-06-16:SCHEDULE
2001-06-16:SCHEDULE
SimulationErgebnis
Simulation Results
Building: ADEB 9
Element Location Energy Reduction Repair Cost Energy Cost
Install. Elect. - Petit TGBT intérieur 701.20 € 7,011.88 € 18,436.26 €
VMC - Caisson Simple flux intérieur 98.20 € 981.99 € 36,872.52 €
Garde corps, escaliers, rampes - Métal indéfini 0.00 € 1,579.92 € 0.00 €
Garde corps, escaliers, rampes - Métal indéfini 0.00 € 7,425.63 € 0.00 €
Ext. Eléments acier extérieur 0.00 € 26,843.65 € 0.00 €
Ext. Eléments aluminium extérieur 0.00 € 81,245.21 € 0.00 €
Pleins - Enduits indéfini 0.00 € 17,477.97 € 0.00 €
Pleins - Peintures indéfini 0.00 € 2,603.60 € 0.00 €
Terr. Acc. - Etanchéité extérieur 0.00 € 94,615.25 € 0.00 €
Sum 799.40 € 239,785.10 € 55,308.77 €
Total Sum 799.40 € 239,785.10 € 55,308.77 €
Reparatur-Plan
Repair Plan
Date: 01/01/2003
Building Element Location Size Improvement Renovation
Total Repair Cost on 1/1/2003 399.70 € 144,069.45 €
Date: 31/12/2012
Total Repair Cost on 12/31/2012 0.00 € 82,113.01 €

Bibliography

[1] BKI Kostenplaner. Baukosteninformationszentrum, CD-Rom, 2001.

[2] P. Baccini and P.H. Brunner. *Metabolism of the Anthroposphere*. Springer, Berlin, 1991.

[3] H.-G. Bächtold. Nachhaltigkeit. *Schweizer Ingenieur und Architekt*, (13/1989):194–197, 1998.

[4] Basler & Hofmann Ingenieuere und Planer AG. STRATUS Gebäude/Bâtiment/Building. http://www.bhz.ch/stratus/methode/html#punkt2.

[5] Wolfgang Bischoff, Patrick Erik Bradley, Claudio Ferrara, and Niklaus Kohler. Überlebensanalyse von Gebäudebeständen. Das Beispiel Ettlingen. *Stadtforschung und Statistik*, (1/05):32–34, 2005.

[6] Hans Hermann Bock. *Automatische Klassifikation*. Studia Mathematica/Mathematische Lehrbücher, Band XXIV. Vandenhoeck & Ruprecht in Göttingen, 1974.

[7] Patrick Erik Bradley. Validierung eines integrierten, dynamischen Modells des deutschen Gebäudebestandes: Statistischer Teil, 2004.

[8] Patrick Erik Bradley, Ebba Buergel-Goodwin, Claudio Ferrara, and Niklaus Kohler. Survival functions of building stocks and components. The 2005 World Sustainable Building Conference in Tokyo, 2005.

[9] Patrick Erik Bradley and Claudio Ferrara. Abschlussbericht des DFG-Projekts: *Validierung eines integrierten, dynamischen Modells des deutschen Gebäudebestandes*. Institut für industrielle Bauproduktion, Universität Karlsruhe, 2004.

[10] Patrick Erik Bradley, Claudio Ferrara, and Niklaus Kohler. Estimating survival fucntions of building stocks. 10DBMC International Conference On Durability of Building Materials and Components, Lyon, 2005.

[11] Brundtland-Committee. World Commission on Environment. Our Common Future, 1987.

[12] Bundesministerium für Verkehr, Bau- und Wohnungswesen. *Leitfaden Nachhaltiges Bauen*. January 2001.

[13] Ebba Bürgel-Goodwin. Vergleichende Studie zu Erneuerung, Unterhalt und Betrieb von Bestandsgebäuden auf Bauteilebene. Institut für Industrielle Bauproduktion, Universität Karlsruhe, 2004. Diploma thesis.
http://www.ifib.uni-karlsruhe.de/de/beval/EbbaBuergelGoodwinDiplomSS2004.pdf.

[14] Kurt Christen and Paul Meyer-Meierling. Optimierung von Instandsetzungszyklen und deren Finanzierung bei Wohnbauten. Forschungsbericht. vdf Hochschulverlag AG, Zürich, 1999.

[15] H. Daly. *Steady State Economics*. Earthscan Publications, London, 1992.

[16] Deutscher Bundestag. *Enquete Kommission zum Schutz von Mensch und Umwelt des deutschen Bundestages. Konzept Nachhaltigkeit. Fundamente für die Gesellschaft von morgen*. Bonn, 1997.

[17] European Commission. Sustainable development of urban historical areas through an active integration within towns. http://www.lema.ulg.ac.be/research/suit/.

[18] European Commission. *European Sustainable Cities. Report of the Expert Group on the Urban Environment*. Eureopean Commission, Directorate General XI, Brussels, 1996.

[19] Uta Hassler and Niklaus Kohler. Cultural and environmental long-term strategies for the built environment. *In:* N.S. Baer, F. Snickars. Rational Decision-making in the Preservation of Cultural Property. 235-248. Berlin, 2001. Dahlem University Press.

[20] INVESTIMMO. Competitive and sustainable growth. Partially financed by European Commission, Directorate General XI. G1RD-CT-2000-00371. Brussels.

[21] IP Bau. Alterungsverhalten von Bauteilen und Unterhaltungskosten. Grundlagendaten für den Unterhalt und die Erneuerung von Wohnbauten. Impulsprogramm IP Bau, Bundesamt für Konjunkturfragen, 1994. ISBN 3-905234-67-X.

[22] ISO/TC207/SC5. Life cycle assesment—principles and guidelines.

[23] LEGEP. Ein Werkzeug für die integrierte Lebenszyklusanalyse. http://www.legep.de.

[24] Ernst Neufert. *Bauentwurfslehre*. 36. ext. and rev. ed. Vieweg, 2000.

[25] Norbert Paul. StratSim. a strategy simulator. Documentation of the ER Diagram of the LCA-Database Scheme. In preparation.

[26] J. Schröder. Zustandsbewertung grosser Gebäudebestände. *Schweizer Architekt und Ingenieur*, (17/1989):449–459, 1989.

[27] Staatliches Baumanagement Niedersachsen. Handbuch facility management, 2002. http://www.ofd.niedersachsen.de/.
[28] SUREURO. Sustainable refurbishment in europe. http://www.sureuro.com.
[29] World Resources Institute. Tackling the problems of poverty, environment and health: Tackling indoor air pollution, 1998. http://www.wri.org/wri/wr9899/indoor.htm.

Universität Karlsruhe, Institut für Industrielle Bauproduktion, Englerstr. 7, D-76128 Karlsruhe, Germany

e-mail: {bradley, ferrara, niklaus.kohler, norbert.paul}@ifib.uni-karlsruhe.de