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Dissertation

THE CONSIDERATION OF ENERGY EFFICIENCY IN THE STRATEGIC PLANNING OF REFURBISHMENT IN BUILDING PORTFOLIOS

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THE CONSIDERATION OF ENERGY EFFICIENCY IN THE STRATEGIC PLANNING OF REFURBISHMENT IN BUILDING PORTFOLIOS

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Foreword

Energy efficiency is at the forefront of the minds of many building managers. Without restrictions, most, if not all, building managers would be happy to convert their existing building stock into one that is more energy efficient. Restrictions, of course, however, exist. Making buildings more energy efficient requires changing them or how they function, which costs the owners money for the work and materials required, and negatively affects the occupants of the buildings, through temporary restrictions in the ability to use the building, or even closure.

In making the decision to embark on energy efficiency improvement campaigns for portfolios of buildings, building managers need to have a good idea that the benefits of their decision outweigh the costs. This is challenging. It is challenging due to the heterogeneity of buildings often found in building portfolios, the myriad of potential energy efficiency improvement interventions that can be executed, and the large uncertainties associated with the estimation of both the benefits and costs of such interventions. The latter is made even more difficult by the fact that most energy efficiency improvement interventions occur at the same time as normal maintenance interventions, meaning that the full cost of the energy efficiency improvement is not incurred, with the extent of the reduction depending on the maintenance intervention executed. Building portfolio managers need a simple useful method to help them in their decision-making.

In his thesis, Marc Christen, tackles this problem. He proposes the cost performance-indicator (CPI) method to be used by building portfolio managers to plan energy efficiency interventions at the strategic level. The CPI method, which is based on an energy performance indicator and the assumption that there are increasing relative costs for improvement in energy efficiency, increases the ability of building mangers to accurately take into consideration the costs and benefits of the interventions when they are executed at the same time as other maintenance interventions. The CPI method is, when compared to existing methods,

- a simpler and less expensive way to represent condition, performance and functionality for the strategic planning for buildings,
- a simpler way to approximate the costs and benefits of energy efficiency interventions in the strategic planning for buildings, and

- consists of improved steps that help ensure that both the costs and benefits of energy efficiency interventions are considered simultaneously to those of normal maintenance interventions.

In addition to the development of the CPI method, Mr. Christen provides evidence that corroborates the assumption that there are increasing relative costs for improvement in energy efficiency. He also demonstrates how the CPI method can be used;

- on a high strategic level for an entire portfolio (where only incomplete data exists) to show the thought processes that a building portfolio manager needs to use his method, and
- on a low strategic level to develop an intervention program for 73 specific buildings (for which data exists).

These examples show that the CPI method leads to fundamentally different and improved intervention campaigns and programs for buildings. In other words, the use of the CPI method will lead to more building portfolio managers embarking on energy efficiency campaigns, which will lead to a more sustainable building stock.

I, personally, would like to thank Marc, for his constant investment in his thesis and for the many interesting discussions over the years. I wish him all the best in his future efforts to improve the management of buildings portfolios.

Zürich, 08.09.2018 Professor Dr. Bryan T. Adey

Executive Summary

The existing building stock accounts for more than 40% of the world's total energy consumption. Since zero emission houses have become an option, refurbishment and energy efficiency improvement of existing buildings offers the single largest potential for energy conservation and CO_2 emission reduction without restricting our way of life. Energy efficiency in existing buildings is therefore of major relevance for the future of all societies concerning all three aspects of sustainability (environmental, economic, and societal). Energy conservation measures on existing buildings, however, are often only economically feasible if executed simultaneously with necessary maintenance and refurbishment measures. In order to achieve the needed reductions, portfolio managers require specific instruments, especially on the strategic level, which are unfortunately unavailable to date. This lack is one of the things that hinders them from tapping into the full potential of available energy efficiency gains.

This research aims to develop an instrument for real estate portfolio managers in order to better plan and budget energy efficiency measures in their stock of existing buildings in combination with due maintenance, refurbishment, and other enhancement measures.

In the course of this work four papers have been written, reviewed and published:

- Paper 1 'Impact of new European Facility Management Standards on Building Cost Structures' focusing on the opportunities of the new cost structure in relation to existing cost structures and specifically for achieving the goals of this research.
- Paper 2 'Application of Industrial Maintenance Methods on Building Maintenance' focusing on the differences between the industrial and the real estate sector in maintenance practice and specifically on synergies between the two in the application of maintenance methods.
- Paper 3 'Strategic building maintenance and refurbishment budgeting method Schroeder – application and evaluation' focusing on describing and evaluating the method Schroeder as a basis for this research - new methods that are fundamentally different to the method Schroeder and used for strategic planning have not been observed.

- Paper 4 ‘On the usefulness of a Cost-Performance-Indicator curve at the strategic level for consideration of energy efficiency measures for building portfolios’ proposing a new method called cost-performance-indicator (CPI) method to plan the additional costs for energy efficiency enhancement measures and their benefits in order to achieve a desired performance.

The four papers are interconnected and support one another in covering a number of topics in the real estate portfolio processes and focus on strategic planning. The papers are joined together by an introductory text that connects them to the title of the thesis, describes the common context, the methodology, and the relevance as well as giving examples and a recommendation for further research.

In order to be able to better plan measures to enhance energy efficiency in conjunction with refurbishment on the strategic level i.e. without costly analysis on the object level, the relation between a measurable indicator and the additional cost to improve it, as well as the respective benefits, have been researched. Although relations between different performance indicators and additional costs to improve them are imaginable, the proposed innovative cost-performance-indicator (CPI) method and the respective CPI curve, based on the well-defined energy performance indicator, seems to be best suited for this task. Ample evidence was found that corroborates the hypothesis that energy conservation measures follow the law of increasing relative costs. However, there is insufficient data available to prove this as a general law. As a result, research concentrated on the usefulness of such a relation in regards to strategic planning. The lack of relevant data from executed energy efficiency projects was found to be a restriction. The also proposed generic cost and benefits structures may lead to more systematic data collections and thus reduce this restriction.

The CPI method combines existing maintenance and refurbishment planning methods with a new planning and budgeting method to take energy efficiency, on a strategic portfolio level, into consideration. Consequently this newer method complements the pre-existing ones. The CPI method has the potential to close the observed gap between the methods that are available and used today. No other method has been found that would be equally suitable for this task and only a few methods in related fields have been accepted by the market until now. The usefulness of the CPI method is demonstrated through two case studies and two examples. The potential is discussed for using this curve for the planning and budgeting of refurbishment and energy conservation measures including the creation of scenarios. It is also applicable as a tool to explain in an understandable way cost and benefits of measures that enhance building energy efficiency, including the production of renewable energy to investors. The CPI method provides portfolio managers with acceptable and inexpensive means to plan and value and thus justify necessary expenses in energy efficiency. Thereby, it may help them to tap into the full potential of available energy efficiency gains

'*There is nothing more practical than a good theory*' Kurt Lewin 1952

Zusammenfassung (in German)

Die bestehenden Gebäude verursachen rund 40% des weltweiten Energieverbrauchs. Seitdem Null-Energie-Häuser möglich geworden sind, bietet die Erneuerung von Bestandsgebäuden das grösste Potential zur Reduktion des Energieverbrauchs und somit zur Reduktion der CO2 Emissionen und zwar ohne Einschränkungen unserer Lebensgewohnheiten. Eine höhere Energieeffizienz in bestehenden Gebäuden ist daher zentral für die Zukunft unserer Gesellschaft, und zwar in allen drei Dimensionen der Nachhaltigkeit (ökologisch, ökonomisch und sozial). Energiesparmassnahmen in bestehenden Gebäuden sind jedoch oft erst wirtschaftlich, wenn sie zusammen mit notwendigen Instandhaltungs- und Instandsetzungsmassnahmen geplant und ausgeführt werden. Um die notwendige Verbrauchsreduktion zu erreichen brauchen Portfolio Manager spezielle Instrumente für die strategische Planung. Diese Instrumente sind heute nicht verfügbar. Dieser Mangel ist einer Gründe, warum das vorhandene Potential von möglichen Energieeinsparungen nicht ausgeschöpft wird.

Die vorliegende Arbeit zielt daraufhin, Portfolio Manager zu unterstützen mit einem Instrument zur besseren strategischen Planung von Energieeffizienzmassnahmen in ihren Bestandsgebäuden im Zusammenhang mit notwendigen Instandhaltungs-, Instandsetzungs- und Erweiterungsmassnahmen.

Im Rahmen dieser Arbeit sind folgende vier Artikel geschrieben, begutachtet und publiziert worden:

- Artikel 1 ‚Impact of new European Facility Management Standards on Building Cost Structures‘ [Einfluss der neuen Europäischen Normen im Facility Management auf Kostenstrukturen in Gebäuden] über die Vorteile der neuen Kostenstruktur im Vergleich zu bestehenden Kostenstrukturen und spezifisch im Hinblick auf die Erreichung der Ziele dieser Arbeit.
- Artikel 2 ‘Application of Industrial Maintenance Methods on Building Maintenance’ [Anwendung industrieller Instandhaltungsmethoden auf Gebäudeinstandhaltung] über die Differenzen in der Instandhaltungspraxis zwischen dem Industriesektor und dem Gebäudesektor und spezifisch über möglichen Synergien zwischen den beiden in der Anwendung der Instandhaltungsmethoden.
- Artikel 3 ‘Strategic building maintenance and refurbishment budgeting method Schroeder – application and evaluation [Die Methode Schroeder zur strategischen Planung und Budgetierung von

Instandhaltungs- und Instandsetzungsmassnahmen in Gebäuden - Anwendung und Evaluation] mit einer Beschreibung und Evaluation der Methode Schroeder im Hinblick ihrer Verwendung als eine Grundlage für diese Arbeit – neue Methoden, welche sich fundamental von der Methode Schroeder unterscheiden und für die strategische Planung verwendet werden können, wurden keine gefunden.

- Artikel 4 'On the usefulness of a Cost-Performance-Indicator curve at the strategic level for consideration of energy efficiency measures for building portfolios' [Über die Nützlichkeit einer Kosten-Leistungs-Indikator-Kurve für die Berücksichtigung von Energieeffizienzmassnahmen in Gebäudeportfolios auf strategischer Ebene] schlägt eine neue Methode vor zur strategischen Planung der zusätzlichen Kosten von Energieeffizienzmassnahmen inklusive deren Nutzen mit dem Ziel eine gewünschte Energieeffizienz zu erreichen. Die Methode heisst Cost-Performance-Indicator Methode (CPI).

Die vier publizierten Artikel sind aufeinander aufgebaut. Sie decken verschiedene Prozesse im Portfolio-management von Gebäuden ab und fokussieren dabei auf die strategische Planung. Die Artikel werden eingerahmt durch einem einführenden Text, welcher die Artikel mit dem Titel der Arbeit verbindet, den Kontext, die angewendete Methodik sowie die Relevanz für die Gesellschaft beschreibt, Beispiele aufführt und eine Empfehlung für weiterführende Forschung enthält.

Ausgangspunkt dieser Thesis war die Frage, wie Massnahmen zur Verbesserung der Energieeffizienz im Zusammenhang mit Erneuerungen auf strategischer Ebene besser geplant werden können, d.h. ohne vorgängige, aufwändige Analysen auf Objektebene. Zu diesem Zweck wurden die Beziehungen zwischen einem messbaren Indikator und den über die notwendige Instandsetzungen hinaus gehenden Kosten für Massnahmen zur Verbesserung dieses Indikators sowie der entstehende Nutzen erforscht. Obwohl verschiedene Beziehungen zwischen einem Indikator und den zusätzlichen Kosten zu dessen Verbesserung denkbar sind, hat es sich gezeigt, dass sich die vorgestellte Cost-Performance-Indicator Methode mit der auf der bekannten Energiekennzahl basierenden CPI Kurve am besten für diese Aufgabe eignet. Es wurden viele Indizien zusammengetragen welche die Hypothese stützen, dass Energiesparmassnahmen dem Gesetz der steigenden Grenzkosten folgen. Aufgrund ungenügender Daten in diesem Bereich ist der Beweis für diese Hypothese und damit für deren Gesetzmässigkeit noch ausstehend. In der Folge hat sich die Arbeit auf die mögliche

Nützlichkeit der Anwendung einer solchen Gesetzmässigkeit für die strategische Planung konzentriert. Das Fehlen von relevanten Daten zu abgeschlossenen Energieeffizienzvorhaben hat sich dabei als Hindernis erwiesen. Die ebenfalls vorgeschlagenen, allgemeingültigen Kosten- und Nutzenstrukturen können dazu führen, dass mehr Daten systematisch gesammelt werden und so dieses Hindernis reduziert wird.

Die CPI Methode kombiniert und ergänzt bestehende Methoden zur Planung von Instandhaltung und Instandsetzung mit einer neuen Methode zum Einbezug von Energieeffizienzmassnahmen auf strategischer Ebene. Die Methode hat das Potential, die beobachtete Lücke zwischen den heute bestehenden Methoden zu füllen. Bisher konnte keine andere Methode gefunden werden, welche gleichermassen geeignet ist für diese Aufgabe, und nur wenige Methoden in angrenzenden Bereichen haben bisher eine Akzeptanz und Verbreitung im Markt gefunden. Der Nutzen der neuen Methode wird anhand von zwei existierenden und zwei konstruierten Beispielen aufgezeigt. Die mögliche Anwendung der Methode in der strategischen Planung und Budgetierung von Instandsetzungs- und Energieeffizienzmassnahmen und zur Bildung von Szenarien wird diskutiert. Sie dient ebenso als Werkzeug, um Investoren die Kosten und Nutzen dieser Massnahmen oder der Produktion von erneuerbarer Energie aufzuzeigen. Die CPI Methode bietet Portfolio Managern ein nützliches und günstiges Instrument um Kosten von Energieeffizienzmassnahmen zu planen und zu begründen. Dadurch kann es ihnen helfen, das vorhandene Potential von möglichen Energieeinsparungen besser zu nutzen.

Thanks

I wish to thank my first supervisor Professor Holger Wallbaum as well as my second supervisor Professor Bryan Adey for guidance, support, corrections and input. I would also like to thank my wife and friends for patience and inspiration and a large number of people for all the interesting discussions.

Great thanks goes to the late Jules Schroeder, the inventor of computer based building refurbishment planning, to all the survey responding portfolio managers, to Basler & Hofmann (Stratus), to the Stiftung Klimarappen (Climate Cent Foundation) and the TNC Consulting AG, to the energy efficiency organisation Energo, to the authorities of the Canton of Zürich, for sharing their data and experience, and Erin Day for British English proof reading.

I would also like to thank my employer, the ETH-Rat (Board of the Swiss Federal Institutes of Technology), to give me the unique opportunity to undertake this research study.

'Imagination is the mother of all theory' after E. Kaeser, NZZ, 2016

Abbreviations

List of abbreviations part 1

BIM	Building information modeling
CAPEX	Capital expenditure (listed as an asset in the balance sheet)
CPI	Cost performance indicator
DCF	Discounted cash flow
DIN	German standardisation institute
EBF	Energiebezugsfläche (energy reference area)
EMs	Enhancement measures (often referred to as retrofit)
EEMs	Energy efficiency measures
ECMs	Energy conservation measures
EPMs	Energy production measures
EPI	Energy performance indicator
EPIQR	Energy performance indoor environmental quality retrofit
EN/CEN	European standard / Comitee European de la normalisation
ETH	Eidgenössische Technische Hochschule (Swiss Federal Institute of Technology)
FM/CAFM	Facility Management / Computer aided FM
GDP	Gross domestic product
GER	German for (translation)
GFA	Gross floor area
HVAC	Heating ventilation air conditioning
I(C)T	Information (and communication) technology
IRR	Internal rate of return
ISO	International standardisation organisation
KTI	(Swiss) Kommission für Technologie und Innovation
LCC	Life cycle costing
LCA	Life cycle analysis (including environmental and societal aspects)
LOS	Level of services
MD-LCB	Multi dynamic life cycle budgeting
MMs	Maintenance measures
MMS	Maintenance management system
NFA	Net floor area
NPV	Net present value
OPEX	Operational expenditure (expense in the income statement)
RE	Real estate

List of abbreviations part 2

RMs	Refurbishment (often referred to as renovation) measures
R&D	Research and Development
SIA	Swiss Society of Engineers and Architects
PDCA	Quality or controlling cycle: Plan-Do-Check-Act
PV	Photovoltaic (electricity production)
WLCC	Whole life cycle costing

Table of Content

1 Introduction

1.1 Background

"The existing building stock accounts for up to 40% of the world's total energy consumption (World Business Council for Sustainable Development WBCSD [1]), and a large share of this energy is being produced from non-renewable fossil fuels. The large share of consumption is combined with low energy efficiency compared to the technical potential of state-of-art in new construction. Example efforts to improve the technical-economic options of building owners are the development of passive (using less than 15 kWh/m².a), zero emission and plus energy buildings. Therefore, the existing building stock offers the single largest potential for energy conservation and, consequently, reduction of the CO_2 emissions.

An example effort to ensure that countries improve the energy efficiency of their buildings is the European Energy Performance of Buildings Directive (EPBD) [2], which requires in its article 9 that from 2020 all new buildings be nearly all zero-energy ones (text borrowed from Paper 4 [P4])".

1.2 Relevance of the thesis to economy, society, environment and science

To illustrate the relevance of the subject of this thesis, the term sustainability is introduced. Sustainability is a frequently used word. Most definitions either refer to the well-known Brundtlandt Report [69] and/or mention its three main aspects, environment (e.g. emissions and measures to mitigate these), economy (e.g. long-term value of sustainability to owners due to reduced risks), and society (e.g. user comfort and/or health, satisfaction and productivity of employees). As such, it covers most aspects of our life. On the one hand, the wide scope of this term is advantageous as it is used to illustrate the research topic's relevancy here. On the other hand, it can lead to misinterpretations and conflicting objectives causing it to be disadvantageous. This statement is echoed in the large number of differing sustainability rating systems (Annex G) or in the almost inflationary use of the term in advertising. Therefore, in this thesis, the term is used only when referring to the three aspects that are described in this section or when relating to a sustainability rating system.

1.2.1 Relevance found when focussing on the environmental aspect of sustainability

There are two reasons to specifically reduce energy consumption and the associated CO_2 emissions beyond the short-term economical energy savings measures. The first is the potential climatic change caused by a rising concentration of CO_2 in the atmosphere. The second is that our society is up to 80% dependent on imported, non-renewable, fossil fuels and thus vulnerable to possible shortages and price spikes. The real estate sector should contribute to the solution of these problems.

1.2.2 Relevance found when focussing on the economic aspect of sustainability

The total reconstruction value (refer to section 2.2 in Paper 4) of the existing built infrastructure in Switzerland is estimated at 2,400 Billion CHF [3]. However, the existing building stock is refurbished or replaced at a very low annual rate (Wallbaum et al [4]). Required building maintenance and refurbishment investment to prevent this building stock from deteriorating is estimated to be in the range from 0.5 to 2% of the value per annum. The resulting large sum (between 10 and 50 Billion CHF per annum) needs to be invested at the right time in order to avoid a maintenance backlog and in consideration of future user requirements or regarding the three aspects of sustainability. Sustainability rating labels and government programs offering subsidies are intended to help building owners to consider all three aspects of sustainability more systematically in their decisions.

1.2.3 Relevance found when focussing on the social aspects of sustainability

In some cases, maintenance and refurbishment of buildings are not only the prevention of a loss of functionality, in a traditional sense, but also the preservation of our built heritage as part of our culture. Benefits of an enhanced consideration of the social aspect of sustainability may also be found for example in higher comfort, less noise, better access for disabled persons, and additional safety and security through better building standards, fewer health risks through better indoor air quality, and enabled social contacts through well planned public spaces. The social aspect is the least researched and defined aspect and, consequently, there are fewer methods and instruments supporting the calculation of costs and benefits than the other two aspects. Newer developments are e.g. the Social Life Cycle Assessment [90] and a shift towards the consideration of well-being. This is reflected for example in the WELL-certificate [91].

1.2.4 Use of term sustainability

The term sustainability is used to illustrate the research topic’s relevancy. In summary, refurbishment and at the same time enhancement of the existing building stock is of major relevance for the society in all three aspects of sustainability.

1.3 Scope

In this thesis, three sectors of built infrastructure are mentioned. Firstly and primarily, the thesis focuses on the real estate (RE) sector, which includes all buildings e.g. residential, commercial, and parcels of land. The second sector is the industrial sector, which encompasses mainly production plants. The third sector is the network infrastructure sector, which includes e.g. roadways or railways. The second and the third sectors are used only for comparison in order not to miss an interesting method. Overlaps such as buildings that house production facilities or network infrastructure on an industrial area are not addressed separately.

The three building related measures that are considered are maintenance measures (MMs), refurbishment measures (RMs; refurbishment is also referred to as renovation) and enhancement measures (EMs; enhancement is also referred to as retrofit or deep retrofit) including energy efficiency measures (EEMs; covering energy conservation measures (ECMs) and energy production measures (EPMs). New construction, daily operation, enhancements other than EEMS, and deconstruction - to complement and close the life cycle of buildings - are not within the scope. Maintenance, refurbishment, and daily operation may have some overlaps with each other. In the industrial sector, the term maintenance usually covers refurbishment measures while in the RE sector legal and economic arguments require a separation of these two (cost) categories, e.g. to calculate rent and additional charges correctly.

This work concentrates not only on the environmental aspect of sustainability. The economic aspect is covered with the consideration of cost benefit ratios of EEMs and the social aspect in form of certain co-benefits of such measures.

This work, and specifically the method presented in Paper 4, primarily targets managers and owners of building portfolios (can be a person or an organisation). For them it is a constant task to plan and budget optimal measures. They are in a good position to gather data systematically and, therefore, acquire more and more experience. Owners of single buildings, which execute measures only sporadically, could eventually benefit from this experience later via published research, improved tools or trained consultants.

1.4 Strategic process matrix

This work is set within the framework of RE processes that require decisions and activities on strategic, tactical and operational level. This section describes the respective process matrix. Special attention is drawn to the strategic level and the steps on tactical and operational level that are needed to consider EEMs on strategic level.

1.4.1 Process matrix

To ensure a common understanding of the role of support processes in an organisation, including the provision of buildings, a process matrix is shown in Figure 1. The process matrix shows how the processes on the strategic level, the tactical level and the operational level interact to ensure that the level of service provided by buildings is aligned with the needs of the portfolio managers. It also shows where the contributions to this process, as explained in each of the four presented papers, are located.

1.4.2 Description

The process matrix (Figure 1) is based on the standard EN 15221-4 Taxonomy, Classification and Structures in Facility Management. The standard defines Facility Management (FM) as the management and coordination of support processes on the strategic level (this term and this standard are central in Paper 1). Support processes are providing services and/or facilities (output) for the primary processes (or core business) of an organisation. The standard defines the provision of RE as a support process. The RE strategy[1], which is developed on the strategic level, needs to be aligned with the prevailing strategy of the organisation. The relationship between the CPI process, (see Annex B) is indicated by the respective process step numbers shown in the matrix.

In this presented matrix special attention is drawn to the strategic level and how EEMs are included on tactical and operational level.

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[1] A RE strategy firstly needs to be aligned with and support the core business strategy of an organisation. It should cover topics such as market position and (future) user requirements, goals and constraints, ownership and sourcing including decision making between refurbishment and new construction and make or buy, desired performance including sustainability and assumed future development. Derived from this, statements about quantity, quality, flexibility, and adaptability of RE and their consequences for future maintenance, refurbishment, and investment budgets should be made and a time frame be given. This could be done in a separate maintenance sub-strategy which also defines maintenance methods and tactics. Within the frame of these strategies and one level further down follow the specific object strategies.

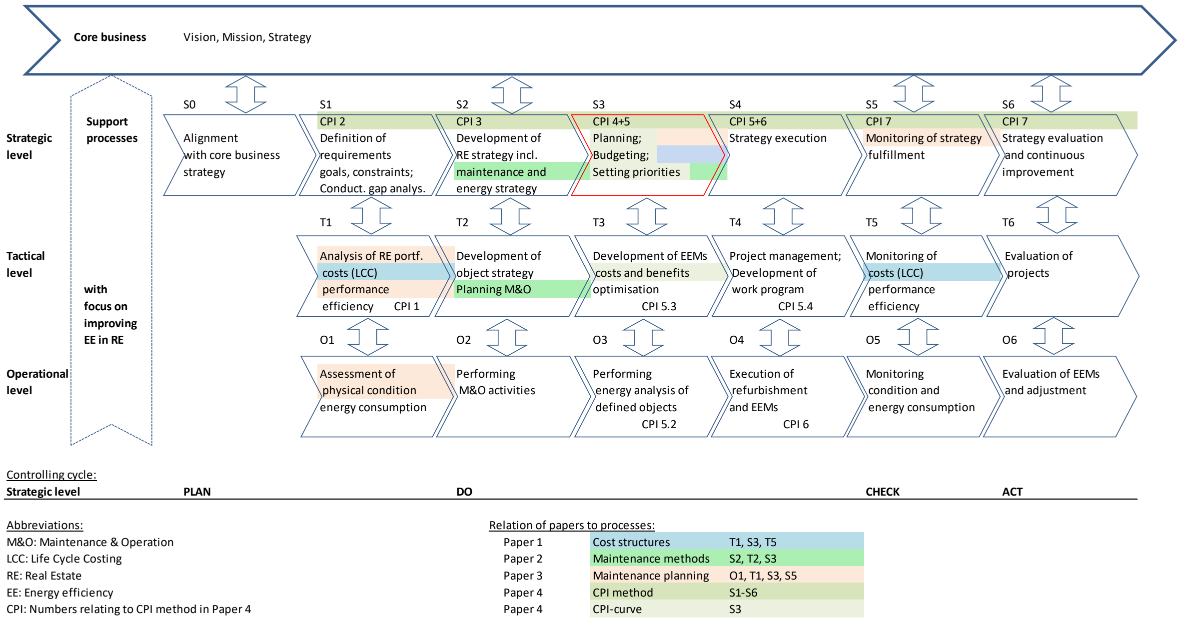


Figure 1 *Process matrix with focus on the strategic level and enhancing energy efficiency in RE (for a larger copy see Appendix A)*

The processes on the strategic level are defined on a rather generic, high level and may include several sub-processes and activities. These can be individual for each organization. Processes on the tactical and operational levels are displayed in the matrix as well due to their interdependencies with the strategic processes and to provide a complete picture. These processes are depicted with a special focus on improving energy efficiency. Of course, such a process matrix and especially the attribution of processes to the different levels are a matter of definition and other definitions are possible. The two-way arrows between processes on different levels symbolise that there is an interaction and information flow in both directions.

1.4.3 Description of the strategic process steps

The process steps on the strategic level can briefly be described as follows:

- S0: Alignment with core business strategy: To get to know the needs and expectations of the client (core business) is the first step in the provision of support services. The result influences all other steps.

- S1: Definition of requirements, goals, constraints and gap analysis: In this step, the requirements, goals and constraints are derived from the needs and expectations. Further, the gap between requirements and goals and the as-is situation is analysed within the constraints. To conduct this gap analysis, results of a portfolio analysis on tactical level based on data collection on operational level in T1 and O1 are needed [2].

- S2: Definition of RE strategy including maintenance and energy strategies: Strategy developing is the central step on the strategic level. The strategy needs to be closely coordinated with the strategy of the core business. Developing of sub-strategies like maintenance or energy strategies could alternatively be a task on tactical level (T2). Based on the strategy, daily maintenance and operation (M&O) activities and services provision are initiated (O2).

- S3: Planning, budgeting[3], and setting priorities: In order to execute the strategy and fulfil the requirements within the restrictions it is necessary to plan a timetable, to budget costs, and to set priorities amongst a portfolio of projects. This step relies on the results of the energy analysis on tactical and on operational levels in T3 and O3.

- S4: Strategy execution: Following the setting of priorities, the projects need to be initiated and steered on the strategic level (e.g. by a steering committee). Project management is placed on tactical level (T4) and execution of measures on operational level (O4).

- S5: Monitoring of strategy fulfilment: In this step, results or the degree of fulfilment of requirements are being reported back to the client.

- S6: Strategy evaluation and continuous improvement: This is the last step in the strategy making controlling cycle (refer to section 9.6) where improvements are initiated and from where the cycle starts again. This step may result in changed priorities or even in a new version of the strategy.

[2] Throughout this thesis the terms condition, performance, and functionality are used in the following way: Condition relates mainly to the physical state of building elements. Performance is used in conjunction with indicators. Functionality also encompasses the usability and other factors that are of value for the owner or tenants.

[3] Planning in this work is used for considerations about the kind of measures and their time of execution. Budgeting is used for financial considerations. Design is used for engineering considerations.

1.4.4 Connections to Papers 1-4

Within the process matrix, the processes which are connected to one or more of the Papers 1-4 have been colour coded. The connections can be described as follows:

Paper 1 'Impact of new European Facility Management Standards on Building Cost Structures' (Section 4) shows that the new cost structure in EN 15221 is useful by making the real costs of ECMs transparent, through the clear separation of maintenance, refurbishment and enhancement costs. This is mainly happening on the tactical level (T1) where costs, which have been collected on operational level, are attributed to elements in cost structures and monitored (T5). The new cost structure also supports planning and budgeting on the strategic level (S3) through its clear hierarchy making costs more transparent and its definitions which can be used for benchmarking.

Paper 2 'Application of Industrial Maintenance Methods on Building Maintenance' (Section 5) looks at the industrial sector for new methods to plan maintenance and refurbishment in the RE sector. However, differences between the requirements in these sectors hinder the direct transfer of typically industry-specific instruments into the RE sector. On the other hand, the paper and its addendum indicate that there are sufficient maintenance planning methods (T2) and maintenance tactics to choose from (S2, S3) available and applied in the RE sector to form a sound basis for this thesis in this field.

Paper 3 'Strategic building maintenance and refurbishment budgeting method Schroeder – application and evaluation' (Section 6) evaluates a practical maintenance and refurbishment planning method (S3, S5) theoretically and with real life data. Such a method is a prerequisite for the use of a method that allows for improved consideration of EEMs due to the close relation between MMs, RMs, and EEMs. Without, it would be necessary to develop a maintenance and refurbishment planning method first. The method Schroeder is not only applicable on the strategic level, but also useful for condition assessment on operational level (O1) and portfolio analysis on tactical level (T1).

Paper 4 'On the usefulness of a Cost-Performance-Indicator curve at the strategic level for consideration of energy efficiency measures for building portfolios' (Section 7) contains a new method for the consideration of EEMs. The use of the CPI method has ramifications on many of the processes shown in Figure 1, including those on the strategic level (S1-S6) where the first and most important decisions are made. It has the most effect on the strategic planning and budgeting process (S3) where there is a lack of useful tools suspected.

1.4.5 Additional consideration of EE

In this section, a short description of the steps on tactical and operational levels, which are necessary for the consideration of EE in the strategic planning, is provided:

- O1 Assessment of physical condition and energy consumption – In this step, data on physical condition is assessed and data on energy consumption and cost is measured or collected. For each assessed building, a value for the condition and the energy performance indication (EPI) are calculated from this data.
- T1 Analysis of portfolio - In this step, data of assessed buildings is aggregated into a portfolio view showing the average condition and the distribution thereof.
- T2 Definition of point in time for measures – In this step, buildings, which need measures according to their condition and/or EPI, are identified and the result is aligned with the RE strategy and user requirements (S2). Costs are estimated and compared to available budgets, buildings are prioritised, and a time plan is drawn in step S3.
- O3 Walk through analysis – In this step, buildings prioritised and earmarked for refurbishment are inspected and analysed on-site to reconfirm assumptions about the physical condition and energy efficiency and to collect data needed for the development of measures.
- T3 Development of measures – In this step, measures and alternatives are developed and optimised and formed into a work program in step T4.
- T5 Monitoring and T6 Evaluation – these two steps are part of continuous improvement.

1.4.6 Conclusions from the process matrix – suspected gap

Processes in RE can be displayed in the form of a (support) process matrix of an organisation. It is assumed that most processes in this matrix, are well researched and understood and that state-of-art and state-of-practice instruments do exist for these processes (refer to Papers 1-3).

The improvement of the energy efficiency of a building portfolio can be depicted within this matrix. However, it is suspected that there is a lack of useful tools for this task on the strategic level. This suspected gap in the process of planning and budgeting enhancements of energy efficiency appears where the strategic decisions are made (red process arrow in Figure 1). The gap can also be seen when conducting a literature review (refer to section 2), i.e. there has been very limited research activity on the planning and budgeting of energy efficiency enhancement, and there is a nearly complete absence of state-of-practice instruments to influence strategic decisions of owners/investors towards more energy efficiency. This gap has significant ramifications on the energy efficiency of buildings, when one takes into consideration the fact that the energy efficiency of a large share of the overall stock of existing buildings could be improved. These ramification are intensified by a reported lack of sufficient maintenance activities.

1.5 Connection between refurbishment and energy efficiency measures

RMs and EEMs are both closely linked and intertwined as can be seen in the process matrix. Despite this, they are often planned and treated as separate items, a situation which leads to a suboptimal outcome. On their own, only a few EMs are economically feasible when it comes to improving aspects of a building's sustainability. Consequently, the number of sustainability rated building refurbishments is still negligible, which is in strong contrast to the number of rating systems on the market. However, if EEMs were planned and implemented in the course of due maintenance and refurbishment they would be more successful. Taking a holistic approach, refurbishment should be part of overall sustainability considerations and vice versa.

Nowadays, building owners or portfolio managers may choose between more than 100 sustainability rating systems and labels (Annex G). However, none of these show them the most cost efficient measures or the overall costs to achieve the desired level of sustainability in their portfolio.

Figure 2 shows a matrix with only four quadrants. Each quadrant refers to either a low to fair or fair to good position in relation to either sustainability rating or general performance as well as displays the direction in which measures in these quadrants should go. For example, if sustainability and performance are both rated low to fair, a combination of RMs and EMs improving aspects of sustainability are recommended as optimal measures.

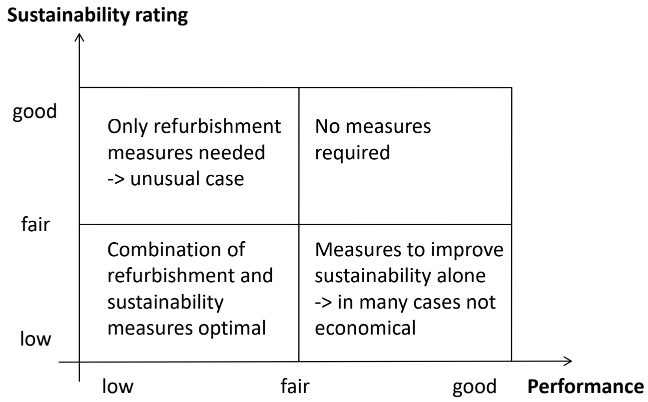


Figure 2 *Quadrants of measures in relation to sustainability rating and performance (adapted from Paper 2)*

“An example to show the link between RMs and EEMs would be the painting of a building’s exterior wall as a RM and adding insulation to said wall as an ECM and both needing scaffolding. If executed simultaneously, synergies can be achieved resulting in lower combined costs. In this case, since the scaffolding would already be available for the refurbishment measure, the additional amount to be spent on the energy efficiency measure would be less than if it were executed alone. Since the benefit of the ECM would remain the same, this reduction in cost would increase its net benefit, which would increase the chances that a building owner would execute it. In order to investigate the viability of executing ECMs at the same time as RMs, it is necessary to understand the potential costs incurred from the RMs, with or without the execution of the ECMs. Production of energy from renewable sources is also a measure (EPM) used to enhance the energy efficiency of a building. Often a comparison with conventional ECMs is needed to evaluate the best available option (text borrowed from Paper 4 [P4])”.

In practice, reported figures indicate that refurbishment activity in RE is neither quantitatively (investments, e.g. measured in % of value per annum) [10] nor qualitatively (depths of measures, e.g. measured by EPI or number of sustainability ratings achieved after execution of measures) [60][4] sufficient to improve the stock of buildings in reasonable time towards more energy efficiency (Figure 3) [62]. It is even questioned if activities are sufficient to maintain the long-term value of the assets [10]. It must be suspected that strategic decisions

[4] The study for the ‘Bundesamt für Wohnungswesen’ found that between 2001 and 2003, around 8-9% of existing residential units were in some form refurbished. However, only 0.8% had insulation applied on the walls. At this rate, it would take 125 years for all units to be improved thermally.

are taken without adequate information due to the lack of suitable methods. It is the aim of Paper 4 and this thesis to provide such a method for the improvement of energy efficiency.

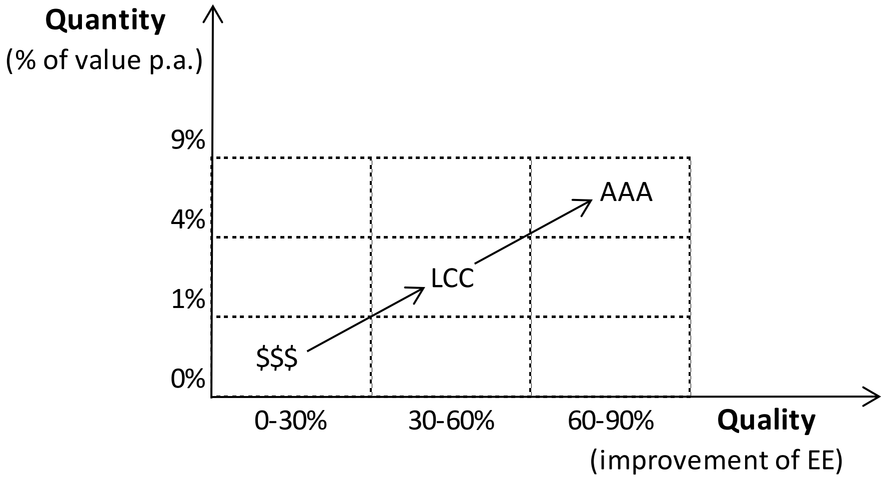


Figure 3 *Conceptual illustration of three types of refurbishment decisions and their consequences on quantitative and qualitative refurbishment levels with indicative numbers*

The conceptual Figure 3 illustrates three different types of refurbishment decisions and their consequences. The numbers in the figure are indicative, but, their magnitude is backed by references [60, 71, 41, Paper 4]. Refurbishment decisions are often made without adequate information and methods [61]. Accordingly, such refurbishment decisions guided by personal preferences or based on mainly short-term cost arguments ($$$) currently lead to insufficient results (only 0,5-1% invested p.a. and reaching savings of 0-30%). In contrast, decisions based on cost benefit considerations for optimisation e.g. using life cycle costing (LCC) are likely to lead to higher benefits and possibly higher investment due to the optimisation (1-4% invested p.a. and reaching savings of 30-60%)[5]. Thirdly, decisions reaching a maximum of savings and eventually a good sustainability rating (AAA) may require an optimised consideration of all three aspects of sustainability and their resulting co-benefits.

[5] Note: 2% p.a. refurbishment investment leads to a complete renewal roughly every 50 years, which is near the estimated average service life of buildings. At 1% p.a. the renewal would take around 100 years. Not accounted for in this calculation are demolition (and new construction) and the longer service life of structural elements, which reduce the need for refurbishment.

The suspected gap in the strategic decision process concerning the consideration of EEMs and the reported, insufficient levels of RMs and EEMs lead to the following three questions.

1.6 Questions from practice

This work addresses three questions portfolio managers and building owners are faced with today:

- Portfolio analysis: How can the condition, performance, and functionality of a RE portfolio be measured in an effective way? Knowing the current state is a precondition for planning and budgeting measures in accordance with the RE strategy. Paper 1 discusses a new cost structure to be used to collect and allocate costs and Paper 3 evaluates an existing method to measure condition with minimal effort and compares it to other such methods. The calculation of energy performance is standardised and expressed as the EPI [44]. In contrast, measuring of functionality of RE is less defined as it includes different qualitative, non-monetary aspects. A measure often used instead is the market value.

- Planning and Budgeting: What are the best methods to plan and budget MMs, RMs, and EEMs on the strategic level? Maintenance and refurbishment planning and budgeting methods are in use and effective. Planning and budgeting of EEMs, however, is not supported by an effective method on the strategic level to date (see section 2). Paper 2 explores if there are advanced maintenance planning methods used in the industrial sector which could also be applied in the RE sector. Paper 3 evaluates a maintenance and refurbishment planning and budgeting method using real life data [10] to investigate the effectiveness of such methods. A new method to budget EEMs in conjunction with planned RMs has been developed and is presented in Paper 4.

- Decision making based on costs and benefits: How can the additional costs of EEMs be justified to investors? Companies with high environmental awareness have started to demand a certain sustainability rating for their buildings. There is neither instrument nor experience-based benchmarking available to calculate the costs of achieving such a rating in all the existing buildings of a portfolio. Little is known about the potential benefits apart from the direct measurable energy savings. The definitions section of Paper 4 contains proposals for a new method on how to budget and new structures on how to present costs and possible benefits of EEMs.

Planning and budgeting of MMs, RMs, and EMs is a regular task for building owners and portfolio managers. As will be shown in section 2, there is no effective method or instrument available to support this task when it comes to planning and budgeting additional investments in EEMs in conjunction with RMs specifically on the strategic level i.e. without prior and costly energy analysis of each object. What is needed is an easy-to-use tool that is based on easily accessible data at this level and which gives an indication (or estimation) of the additional costs required to improve the energy efficiency of a building portfolio up to a certain level. Based on these questions the following objective has been defined.

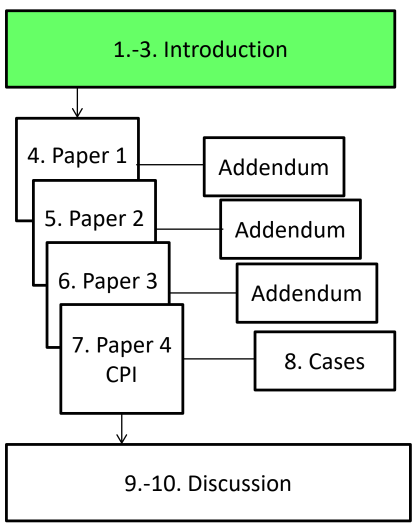
1.7 Objective

The objective of this thesis is to develop a method to improve the consideration of energy efficiency measures during the strategic planning and budgeting of maintenance and refurbishment measures in building portfolios.

1.8 Structure of thesis

The thesis is divided into 10 sections. Section 2 contains a review of the state-of-the-art and, consequently, the need for a new method. In section 3 the method is discussed. In sections 4-7, the four published papers are presented and the first three complemented with an addendum from the new position taken at the end of this work. Section 8 complements Paper 4 with real life examples. Section 9 discusses specific questions relating to this work. The final section 10 contains a summary and conclusion of the thesis.

In order to support orientation within the document, the following coloured graphic summary of the content has been inserted where appropriate.



2 State of the art

„Academic publications present new ideas building on earlier work, which establish trends in a specific field. Analysis of these trends shows patterns of evolution including the sources, output, influence, challenges, collaborations as well as emerging and neglected topics. This exercise contributes to the development of a more cumulative knowledge base by providing a strategic overview of the field, raising new research questions and generating new perspectives and future research agenda.” (Ilter und Ergen [5])

The following section gives a selective overview of the best international work relevant to the intended research with the aim to establish the state-of-the-art of methods and where applicable standards and to give comments on the availability of data in the fields of maintenance, refurbishment and enhancement considering energy efficiency.

2.1 General

As will be seen in this section, compared to the environmental, economic, and social relevance of the existing building stock due to its sheer size, relatively little research activity has been conducted to date in the combined fields of maintenance and refurbishment and enhancement of aspects of sustainability and specifically energy efficiency.

In the first field, maintenance and refurbishment, more research activity can be observed in industrial maintenance than in building maintenance and refurbishment, which is presumably due to the former’s immediate effect on productivity and consequently on income and profitability. Building maintenance is seen by portfolio managers as having less potential impact on building operations whereas industrial maintenance is seen by plant managers as having considerable impact on plant operations. So RE practices are, therefore, usually lagging a few years behind industrial maintenance practices [P2].

The second field, enhancement of aspects of sustainability, is often treated as a separate research item without connection to the first field. Results of such research are e.g. methods for lifecycle cost analysis (LCA) that have been published and are well known, but have not been often applied in RE practice. As well, characterisation factors for the calculation of primary energy, embodied energy, resource consumption or environmental impact such as CO_2 emissions etc. are readily available. These are regularly used for environmental reporting.

Sustainability rating systems (some do consider refurbishments specifically, see Annex G) have become a popular form of presentation, although the large number of rating systems on the market contrasts with the relatively small number of rated buildings, especially, when the number of rated refurbished buildings is considered. Reasons for this may be that new construction offers more flexibility in the design phase and that most rating systems are focused on new construction. Of course, achieving such a rating is - in most cases - a non-mandatory, additional effort and the benefits of it are not always straightforward or well known in the market.

While little research activity was found that combines these two fields, even less seems to be conducted on a strategic portfolio level that considers costs and benefits and supports decision making.

2.2 Maintenance and refurbishment planning

It is a common concept that all (building) elements have a limited, useful service life, which is influenced by different factors [7, 70]. Maintenance generally prolongs the service life while refurbishment aims at renewing an element in such a way that its functionality is partially or fully restored or even enhanced and a corresponding new service life starts. For planning reasons, some knowledge about the service life of elements is indispensable.

In his Dissertation „Lebensdauer von Bauteilen und Bauelementen" [70] Ritter provides „ a systematic study of factors affecting the service life of" elements. He states that the service life of elements is a stochastic process where the influencing factors are principally known, but not in an explicit, quantitative way for any given element. The weather, for example, is influencing an outside façade. The weather itself is usually measured and known. However, the impact of the weather on the façade depends on additional factors like material, colour, quality, weather protection, direction, usage, etc. to name a few. It follows that published values for the service life of elements have considerable variations due to the many unknowns and uncertainties. Ritter adds that a large number of statistical methods (e.g. Markov chain) to model these uncertainties and to better calculate the service life have been described in literature. Most of these are concerned with one factor and its influence on one element (apart from a few multi-variant methods e.g. Flourentzou [59]) and that data is rarely published in a form that allows further research. An additional uncertainty is that user requirements may change suddenly and override the technical service life of building elements.

Ritter also presents and characterizes 19 different sources of recommendations for useful service life times of elements. Most of these have in common that the statistical basis of the listed service life times is not specified and/or that they just reference on another of the 19 sources. Recommendations in these sources for e.g. windows with synthetic frames range from 10 to 60 years, many offering a range spanning over 20 years. A conclusion is that such general recommendations may be helpful at portfolio level, e.g. to determine the depreciation time in the accounting system but, for a specific element, they will be wrong most of the time and therefore need to be used with caution.

The International Standardisation Organisation ISO has developed and defined the ’factor method’ in ISO 15686-1 “Buildings and constructed assets – Service Life Planning” [7] in order to calculate the service life of specific elements in buildings more accurately. It uses seven factors for influences like material quality, climatic conditions, and usage intensity to correct an average reference service life. However, the standardised method focuses on technical factors only and neglects other triggers for measures such as user requirements. The ISO standard itself does not provide any values or factors, which hinders a practical application. Published recommendations for average service life times need to be used with caution as has been shown above and the determination of the correction factors requires a lot of guessing based on practical experience, which is usually not available. Environmental aspects are not covered by this ISO standard either. These may be some of the reasons why this method has not found wider acceptance to date.

Consequently, Ritter [70] has developed an improved version of the factor method. Based on a questionnaire circulated amongst experts, he proposes a total of 33 weighted and qualitative measurable sub-categories of the seven factors. He then provides quantitative values for the factors, which is a considerable improvement over the ISO standard. However, this improved method has also not found a wider application in RE practice to date. The reason could be that these methods require considerable effort for the calculation of single elements but do not consider a building as an interrelated system. It follows that they are not useful for portfolio managers.

In the 1980’s, J. Schroeder needed to describe the condition of buildings in a portfolio with minimal effort and data in order to be able to plan MMs and RMs and estimate their costs. He was the first to develop non-linear, two-phased devaluation curves for building elements and to propose adding a minimal number of such curves together as to form combined curves of whole buildings. These curves were added together again to give a value for the condition of the whole portfolio and thus the method Schroeder to plan and budget MMs and RMs was created. The method takes a lot of its accuracy from the fact, that assumed average service life times (with all their uncertainties as has been shown above) are being corrected and adjusted by an initial, reproducible on-site inspection and continuous up dating using the results of executed measures. The method provides a timetable with potentially due measures as well as an estimation of necessary budgets and supports grouping of measures for execution. For his professional needs, he initiated the development of a software program at that time, which later became a commercially available product. The method, however, does not incorporate EMs or aspects of sustainability [6]. The theory behind the method is still valid and used in adapted form in other methods, e.g. in the also widely-used software tool EPIQR [11]. A detailed evaluation of the fundamentals of the method Schroeder using real life data is presented in section 6.

The Nordic Standard NS 3424 "Condition Survey of Constructions" developed in 1995 describes a similar method as the already mentioned method Schroeder [8]. It is not clear if there is a connection between the two. Based on this standard, a survey covering 10'000 Norwegian public buildings (40% of the portfolio of public buildings in Norway) was conducted making it one of the few large databases in this field [9]. One of the findings was that it was necessary to cluster 40-50 buildings covering at least 55,000 m^2 to be able to conduct a global budgeting process for future maintenance costs. Again, enhancements were not covered in the method or the survey.

The development and validation of new methods usually needs plenty of data. The survey of research projects has shown how narrow the base of scientifically analysed data in the field of building maintenance and refurbishment generally is. As an outstanding exception, Bahr and Lennerts [10] have conducted a detailed examination of the maintenance and refurbishment costs of 17 buildings over several decades resulting in a unique set of data regarding the distribution of such costs in function of variables such as the age of a building. The analysis of the data showed, for example, that maintenance costs in all these buildings were not linear but had a similarly rising curve over the first 30 years before additional refurbishments were started with costs that depended on variables such as the complexity of the building's exterior shape. One conclusion was that global budgeting methods for maintenance are imprecise and, consequently, that maintenance budgets are generally too low[6]. The findings were then used to develop the budgeting method “praxisorientierte, adaptive Budgetierung von Instandhaltungsmaßnahmen” (PABI), which provides an indication for annual budgets based on a small number of factors.

In their recent literature review about building information modelling (BIM)[7] and maintenance and refurbishment, Ilter und Ergen [5] summarise the latest developments. However, no new maintenance and refurbishment planning method for RE yet has to be observed in the review. New are some advanced operational techniques to assess energy performance such as digital and thermal imagery, as-built models with 3-D (laser) scanning and simulation, and (mobile) augmented reality.

In summary, there is research activity reported in the field of better predicting the service life times of mainly single elements. In the RE practice, however, where a large number of materially different and partly interrelated elements exists, published recommendations for service life times are not reliable due to the large number of uncertainties and influencing factors, which need to be quantified with considerable effort. In this situation, methods that look at a limited number of representative elements and combine average service life times with on-site inspections resulting in approximated, sufficiently accurate predictions for strategic purposes with minimal effort have been developed and found wide acceptance. Fundamentally new methods challenging such existing ones have not been observed.

For more details on maintenance and refurbishment planning methods refer to Paper 3 in section 6. Common maintenance management systems and their application are also discussed in section 6.

2.3 Combination of RMs and EEMs

Research on maintenance and refurbishment of buildings in combination with enhancement considering aspects of sustainability only started 20-30 years ago and is far from terminated. This is demonstrated by the

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[6] Note of the author: This finding about generally insufficient maintenance budgets should be taken into account when drafting public private partnership (PPP) contracts running over a 30-year period or even longer.

[7] “Building information modelling (BIM) allows for multi-disciplinary information to be superimposed within one model. It creates an opportunity to conduct analyses more accurately and efficiently as compared to the traditional methods” Azhar et.al. [52]

partial lack of definitions and standards, which are an essential requirement for common databases and derived performance indicators or benchmarking figures.

Around the turn of the millennium, some research on developing combined planning methods, based mainly on the EPIQR (energy performance indoor environmental quality retrofit) method, was undertaken. The method, developed in a EU project, uses detailed information of about 50 building elements (with up to 6 types of each element and 4 codes specifying the condition = up to 1200 choices)[8] to assess physical condition and to model aspects of sustainability such as those mentioned in its full name. MMs, RMs, and EEMs are then planned using this information. The supporting software of the method is commercially available and used mainly in Germany [11] and as such is the only one found that is specifically built for this combination. However, the assessment of 50 building elements plus complementary information per building seems to be a fairly large effort for strategic planning.

A near-standard is the EUREKA project SINUS "Instandhaltungsmanagement und Ökologie" whose aim is to integrate environmental aspects into building maintenance practice [12]. It describes a quality management system with checklists for the fields of maintenance and consideration of aspects of sustainability in buildings where processes on mainly the operational level of these two fields are merged. However, there is no reported commercial application to date.

Where data is concerned, probably the best example of a public database to be found in the context of refurbishment and energy efficiency is provided by the Deutsche Energieagentur DENA [13]. Although it has only a few hundred entries to date and is restricted to residential buildings, the structure in which it is set up looks very promising and could act as role model for other such databases.

Considering the obvious interrelation between RMs and EEMs, there is very little research activity in these combined fields. There is a clear gap in the current knowledge.

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[8] Types of a roof may be tiled, bitumen, glass, metal or green; Codes specifying the condition may be a=very good, b=good, c= fair; d=needs measures

2.4 Combination of economic, environmental, and social aspects

This section presents two approaches to combine the quantification of economic, environmental and social aspects and discusses their application in RE.

An interesting and comprehensive approach is whole life-cycle costing (WLCC). It incorporates external environmental or social impacts and risk considerations in all phases (e.g. design, construction, operation) of a building into costs in the LCC model in order to provide "a far more accurate assessment of the long-term cost effectiveness of a project rather than standard economic methods that focus solely on first costs or on operation related costs in the very short term" [14]. Boussabaine and Kirkham define it as "… a dynamic and on-going process which enables the stochastic assessment of the performance of constructed facilities from feasibility to disposal. The WLCC assessment process takes into account the characteristics of the constructed facility, reusability, sustainability, maintainability and obsolescence as well as the capital, maintenance, operational, finance, residual and disposal costs. The result of this stochastic assessment forms the basis of a series of economic and noneconomic performance indicators relating to the various stakeholders' interests and objectives throughout the life-cycle of a project" [14]. This lengthy definition is remarkable as it signifies the complexity of the task and the difficulty in explaining it to the general public and potential users. They openly discuss problems as to why the method has not found wider acceptance in the RE sector, including missing definitions, insufficient data and experience, uncertainties in risk prognostication, and financial burden of application. However, there are also good reasons for an application, such as more transparent decisions, increased interest of investors in the subject, information to the public or good governance and reputation.

Another approach was taken by the Center for Waste Reduction Technologies of the American Institute of Chemical Engineers CWRT in 1999 in their report 'Total Cost Assessment Methodology' [15]. In the report, they aim to link together life cycle analysis (LCA, focused on environmental impacts) und LCC (focused on costs) in order to reach "decisions that are environmentally sound and reduce long-term liabilities".

Both these approaches show that intelligent solutions have already been developed to combine environmental, economic, and even social aspects of sustainability. However, neither seems to have been adopted by the RE sector. It follows that these methods are either too complex for the target audience or that costs of application are not counterbalanced by the expected benefits.

2.5 Energy efficiency measures

One of the first activities done when enhancing energy efficiency is usually an assessment of energy performance. In his recent paper, Wang [16] gives a very comprehensive overview of "quantitative energy performance assessment methods for existing buildings". He concludes that the "lack of generic, effective and user-friendly tools for practical energy performance assessment and diagnosis is a serious limitation for implementing energy enhancement measures in existing buildings." Considering on the one hand the abundance of such tools [53], combined with the large amount of experience using them, and on the other hand the lack of methods for strategic planning and calculation of (e.g. social) benefits, this statement needs to be relativized.

The second activity done could be to implement a rating system in order to compare the performance beyond the often calculated EPI. The large number of different building sustainability ratings systems (Annex G) indicates that sustainability rating is still in its infancy and a shake-up of this market is to be expected. The reported number of rated buildings, on the other hand, is still very low and the ones that have been rated have been rated using a large number of rating systems. Thus the experience base of most rating systems, i.e. the number of rated buildings and specifically rated refurbished buildings, is very small. It seems that the incentive for interested organisations to create their own rating system is far greater than the incentive of building owners to invest in a rating for a building. It is imaginable that many organisations over-estimated the size of this market or the share they can earn in this competitive situation, or they decided such a rating system is a service they need only offer their members or the general public.

Further activities before execution of measures would then be to identify potential for improvement, to budget costs and benefits, and to design and optimise measures.

A large number of methods covering one or more of these activities leading to energy efficiency improvement is described in the literature. A classification of these methods into 16 classes is proposed and references of examples for each class of methods, where applicable, are provided in Table 1. The table also lists requirements for application of the methods and some advantages and disadvantages, specifically in relation to strategic planning for portfolios. In addition, table 2 clusters the 16 classes into 6 clusters and gives an indication of which of the process steps on the strategic level are supported by each class of methods and table 3 provides a rating of the methods towards their suitability for use in the combined strategic planning of RMs and EEMs on the strategic level.

Table 1 *Classification of methods to analyse and improve energy efficiency found in literature with advantages and disadvantages concerning use on the strategic level – part 1*

Notes to Table 1: Some methods may be used complementarily or parallel to one another. Both advantages and disadvantages may be applicable to other classes of methods as well but they are not repeated each time due to lesser importance in their cases.

Class of methods	Description / Requirements	Advantages	Disadvantages
1) Energy analysis / energy audit; e.g. EN 16427 [17]	Methods for assessment of EE and development of EEMs which involve on-site inspections	Reports with detailed lists of EEM's incl. costs and benefits for each object based on on-site-inspections	Not suitable on strategic level because costly analysis of all objects would be required
2) Virtual energy analysis (no-touch audits or rapid energy modelling); e.g. Gaasch [18]	Remote-office analysis methods which require a building management system with a large number of data points and know-how in data mining	Makes use of available data with advanced analysing techniques; Low cost and fast; Points to specific problems	Results are limited by the availability and quality of data, which would be unevenly spread in a portfolio
3) Simulation of thermal building loads using heat balance techniques: e.g. ISO 13790 [19]	Methods to model a building and ECMs – they need detailed construction data and surface areas of the effective buildings	Proven design method suitable for simulation of thermal condition and influences of different construction related measures	Not practical for strategic decisions in large portfolios due to the need for detailed data of each building which is often not available
4) Assessment of EEMs; e.g. INSPIRE in Eracobuild [20], IEA Annexe 56 [21], EN 15459 [44]	Methods for quantification and comparison of EEMs using generic methods like LCC and incremental cost benefit analysis; They need detailed data on each EEM including a split of cost of RMs and additional cost for ECMs based on refurbishment planning and service life considerations	Costs are attributed to the envisaged benefits for calculation of benefit/cost ratios in described ways for comparison; INSPIRE: Taking into consideration missions or goals	Not suitable on strategic level because costly analysis of specific objects is required; INSPIRE: Limited number of only 7 EEMs and their combinations considered
5) Top-Down building stock modelling; e.g. Kavgic [22]	Building stock modelling methods which use past data e.g. energy use in an economy and related variables such as gross domestic product GDP	Suitable for modelling of impact of policies and regulations on an economy scale	Not suitable to model costs and benefits of EEMs in portfolios because of focus on an entire economy

Table 1 *Classification of methods to analyse and improve energy efficiency found in literature with advantages and disadvantages concerning use on the strategic level – part 2*

Class of methods	Description / Requirements	Advantages	Disadvantages
6) Bottom-up building stock modelling (see also simulation of thermal loads or archetype modelling); e.g. Kavgic [22], Kesicki [23], Heeren et al. [24], Kost [51]	Building stock modelling methods which use data of archetypes, their distribution, and the impact of changes in variables such as different energy technologies and policies	Suitable for modelling of energy consumption of the whole building stock and impact of different energy technologies and policies	Limited empirical data available, therefore application on portfolio level questionable
7) Assignment of buildings to archetypes and modelling of savings using a list of EEMs; e.g. Chidiac [25], IEA [26] (see also EPBD [2])	Methods to model EEMs based on a number of archetype buildings with a list of applicable EEMs per archetype and their cost and benefits (e.g. from list of 500 EEMs in [26])	Can include any type of building; Produces an estimation of current energy consumption and potential benefits	Restricted to researched archetypes; Subgroups due to differences in building design necessary; Large uncertainties; No practical application reported
8) Definition of reference buildings with fitting EEMs: e.g. EPBD [2], SLABE [27]	Methods to model EEMs using representative (for type, functionality, climate, etc.) reference buildings and fitting EEMs with costs and benefits	One such method is defined in an EU directive (definition of cost effective minimal energy performance standards as a side-effect)	Extensive research required to determine sufficient references and ever changing measures, costs and benefits; No results available to date
9) Calculation of a reference project and marginal costs of element specific EEMs: e.g. Jakob et.al [28]	Methods to plan EEMs using estimation of marginal costs for improvement of common building elements including associated benefits	Effective figures for residential buildings in the Swiss market are provided by the authors (in CHF/m^2 (element) per 2002)	Large effort required to determine costs and benefits and to keep up-to-date due to technical development; Only a limited number of elements is covered
10) Methods to find optimal solutions (multi-objective optimisation between alternative EEMs); e.g. Menassa [29], Juan [30], Kaklauskas [31], Diakaki [32], Fawcett [33], Wu [34], Adey [35], Esders [36], Martinaitis [55]	Applications of methods for (multi-objective) optimisation of EEMs; A list of measures with calculated costs and benefits as well as relations between alternatives are required	Support of the design phase in determining priorities and choosing the best alternatives	Large effort and experience base required to optimise a list of predefined measures with costs and benefits to choose from
11) Process based refurbishment strategy and measures optimisation; e.g. 4-step model and tool IMMOWIN in Pichler [37]	Methods which take a process approach and model a small number of empirical variables; Costs, benefits, and inter-dependencies of EEMs in relation to alternative strategies are required	Integrated approach covering several steps in the decision making process; Includes strategic options such as up-grades for better functionality	Example IMMOWIN: Designed for single residential apartment buildings (min. 8 flats) only; A detailed list of EEMs is required for strategic decision making; Tool not publicly available

Table 1 *Classification of methods to analyse and improve energy efficiency found in literature with advantages and disadvantages concerning use on strategic level – part 3*

Class of methods	Description / Requirements	Advantages	Disadvantages
12) Specific decision making methods e.g. retrofit advisor [38] or tools to choose the best heating system	Decision making methods to e.g. decide between refurbishment and new construction; Example retrofit advisor: Condition of 5 elements required	Example retrofit advisor: Fast and easy-to-use, Answers one of the first questions in strategic refurbishment planning	Example retrofit advisor: Assumptions are neither transparent nor variable; Only three basic alternatives calculated; Not scalable up to portfolio level
13) Element based addition to such methods for refurbishment planning, e.g. Method Schroeder [6], EPIQR [11]	Methods which use indicators for additional costs and benefits of potential EEMs per building element in addition to refurbishment planning (see section 9.2)	Indicators, based on practice in energy conservation, can be expressed in % of value of building elements and summarised for the whole building	EPIQR: Assessment of 50 building elements plus complementary information is a too large effort for strategic planning; Limited empirical data available
14) Energy performance based addition to element based methods for refurbishment planning, such as the proposed CPI curve	Method which use a (dynamic) indicator to model additional costs and benefits of EEMs in addition to refurbishment planning (see Paper 4)	Costs and benefits can be expressed in % of building value or per m^2 and summarised for portfolios; Designed for use on strategic level with little effort for data collection	Limited empirical data available; Usefulness is not proven because development of such a method is in the research phase only
15) Risk quantification, e.g. Economic Sustainability Indicator ESI [39]	Methods to place a value on risks as part of the building valuation resulting in an incentive to reduce the risks; Prerequisites are the will and the effort of investors to make risks transparent on the balance sheet	New approach that is adapted to an investors language; Low EE seen as a risk	Only few figures or references available; The market's acceptance of this new method yet needs to be proven
16) Use of indicators or benchmarking figures such as the energy performance indicator EPI ($kWh/m^2.a$)	Methods to describe an aspect with one static figure; Common structures and definitions and a large number of similar cases are needed	Fast and easy-to-use – "one figure tells it all"; Enables comparison between similar objects and ratings systems	Limited accuracy; Not practicable concerning costs of refurbishment and EEMs due to their complexity

These 16 classes of methods in Table 1 cover a wide range of activities and do not all support the same steps in the process matrix. The following Table 2 provides a grouping of the classes into 6 clusters and gives an indication of the steps which are supported by each.

Table 2 *Clusters of classes and supported strategic process steps by each*

Classes of methods no.	Name of cluster	Strategic process step no. addressed
1-3	Analysis of EE and development of EEMs	O1: Assessment of consumption O3: Energy analysis of defined objects T3: Development of EEMs
5-6	Building stock modelling of EE	Economy scale (outside of scope)
7-9	Archetype modelling of EEMs	T3: Development of EEMs
4, 10-12	Calculation of costs and benefits of EEMs and optimisation of execution of EEMs	T3: Costs and benefits, optimisation T4: Work program
13-14	Addition to refurbishment planning to consider EEMs	T3: Development of EEMs **S3: Planning and budgeting**
15-16	Benchmarking, risk consideration including EE	T1: Analysis of performance T5: Monitoring of performance S1: Definition of goals S5: Monitoring of strategy fulfilment

This Table 2 shows that the listed classes of methods largely support all energy efficiency related activities in the process matrix. Most classes are located on an operational or tactical level. Only the classes 13-16 may have a direct effect on the strategic level.

It is notable that class 1, energy analysis, is the only class of methods, which actually generates lists of measures based on on-site inspections. A number of other classes may indicate where ECMs could be found (e.g. by looking at insufficient insulation or the age of the heating system) theoretically or may rely on an energy analysis for further decision making. All classes do, in one form or another, support decision making, but not all on the strategic level.

A qualitative rating of the wide range of classes of methods listed in Table 1 was performed using six criteria to compare the suitability of these 16 methods for the task of strategic planning of RMs and EEMs combined on a portfolio level. The results are given in Table 3 (for details of the quantitative rating see Annex D). The criteria were derived from the experience gained in setting up the list of classes of methods in Table 1 (type of building), from the scope of this work (number of objects and level in the organisation), from general requirements for such methods (availability and usability), and from a major hurdle, which hinders development and application (data required). It is believed that these six criteria cover the relevant aspects without going into too much detail. The suitability for the task of strategic planning is seen to be covered in the sum of these criteria.

Table 3 *Evaluation of methods for use in the combined strategic planning of RMs and EEMs*

Criteria **No., Class of Method s**	**Type of Buildings**	**Number of Objects**	**Level in Organisation**	**Availability, Status of Development**	**Usability**	**Data required**	**Total rating**
	A= All R= Residential C= Commerc. I= Industrial G= Governmental	O= single Object G= Group of Objects **P= Portfolio** E=Economy	O= Operational T= Tactical **S= Strategic**	I= Theor. idea R= Research S= Some Appl. **W=Well known** **U= Universal**	**E= Easy** F= Fairly Easy C= Complicate K= Expert knowledge needed	**A= Usually available** S= Some effort needed L= Large effort needed	**Bold =** larger than 5
1) Energy analysis / energy audit	**A**	O	O	**U**	K	L	4
2) Virtual energy audit	C, I, G	G	O, T	S, **W**	K	**A**	**7**
3) Simulation of thermal building loads	**A**	O	O	**U**	K	L	4
4) Assessment of EEMs	R, A?	G	T	R, S	F	L	4
5) Top-Down building stock modelling;	A	E	**S**	S	K	S	**7**
6) Bottom-up building stock modelling	R, A?	E, G?	**S**	S	K	L	5
7) Archetypes modelling	R, A?	O, P?	O, T	R, S?	F	S	**6**
8) Definition of reference buildings/EEMs	R, A?	G	O, T	R, S?	F	L	5
9) Reference project and marginal costs	R, A?	G	T, S?	R, S?	F	A	**7**
10) Multi-objective optimisation	**A**	O	O	R, S?	K	L	3
11) Process based optimisation	R	O	**S**	R, S?	F	S	5
12) Specific decision making tools	(A?)	(O)	(T)	(R, S?)	(F)	(S)	5
13) Element based planning	**A**	O, **P**	O, T, **S**	**W**	F	L	**9**
14) Energy performance based	**A**	O, G, **P**	**S**	R	**E**	**A**	**10**
15) Risk quantification	C, I	O, G, **P**	**S**	R, S	F	L	**7**
16) Indicators, benchmarking	**A**	**all**	**S**	R, S	**E**	L	**9**

Bold = Desired rating for the purpose of strategic refurbishment planning
(Brackets) = Applicable for a specific tool or instrument representing the method
? = Method may have the potential for this rating, but has not been described this way

The results of this evaluation can be summarized as follows: No class of methods was found to meet all the criteria by gaining the maximum rating of 12 points (for attribution of points see Annex D). The energy performance based addition to element based methods (number 14) achieved 10 points (refer to last column of Table 3) followed closely by number 13 element based planning and number 16 indicators and benchmarks with 9 points each. All other classes have at most 7 points. Some of the reasons that led to this result are described as follows: Only two operational and single-object oriented classes of methods (numbers 1+3) are being used universally on a large scale. The more the methods are on the strategic level, the smaller the base is of reported applications. Most of the methods are still in the research phase with the associated limited number of cases. A huge effort is needed to collect data either in the preparation, e.g. to develop sufficient data to produce reliable characterisation factors or indicators, or in the application of the methods. This could be seen as the main reason why they have not found their way into practice so far. Furthermore, many of the methods have been developed to deal with the residential sector although the methods themselves could have the potential for a broader application (numbers 4, 6-9, 11). Presumably, this is because availability of data is higher and measures on buildings are relatively easy to standardise in the residential sector. Several of the classes of methods (numbers 4+10, the latter encompassing 6 methods) require a list of measures with known costs and benefits to choose from and then go on to describe ways to optimise between alternative measures. Such an effort is not often undertaken in a building prior to refurbishment and rarely in all major buildings in a portfolio purely for planning reasons. The archetype modelling (number 7) and the reference buildings (number 8) are suitable for application on a strategic portfolio level while (static) benchmarks are possibly too simplified for the given task. Again, the disadvantage of these classes of methods is the huge amount of effort that would be needed to develop sufficient data in order to develop and verify characterisation factors or indicators. Unlike the network infrastructure sector where data is centrally collected and available which enables the optimisation of interventions [77, 79, 81, 82, 83, 84], the RE sector lacks this kind of data and this seems to be the main reason why most of these methods have not been further developed and put into practice.

If taking away class number 14, which includes the method proposed in this work, then there is no method in sight that covers actually or potentially the set criteria sufficiently. The gap in the strategic process step S3 Planning and Budgeting of EEMs remains.

2.6 Costs and benefits

Behind the stated lack of data lies the problem that common structures are missing for the collection of costs and benefits. While there are numerous published cost structures – a situation similar to the one found with sustainability rating systems – a common structure that the majority of portfolio managers uses or refers to is missing. Specifically, the split between anyway costs and additional costs is rarely addressed. This omission is unfortunate because it presents EEMs as more expensive than they really are [55]. On the benefits side, the development of structures has just begun. In his more recent publication 'How to calculate and present deep retrofit value' Lovins [40] proposes a benefits structure aiming to raise awareness amongst RE investors for benefits other than just energy cost savings (refer to Table 22). This proposal marks a new approach in presenting benefits and could be used in most of the listed classes of methods (see also section 9.11.4).

Where the development of costs is concerned, Jakob and Madlener CEPE [41] have studied the learning curve for ECMs such as insulation and better windows, as well as the impact on energy policy. They have developed patterns according to which measures and materials used are getting better and cheaper over time thanks to technological and productivity advances. The existence of learning curves for ECMs is an important factor that needs to be taken into account when prognosticating future costs of ECMs. Learning curves can also be observed for the costs of producing renewable energy. These curves are well documented.

On the benefits side, Feige [42] has worked on the added value and benefits generated for the different stakeholders by incorporating aspects of sustainability in their decisions about RE investments with the aim of finding additional economic arguments for such investments. Specifically, the study investigates the relations between certain building features and social aspects of sustainability such as comfort levels, work engagement, and consequently, productivity. Because the costs of the workforce during one lifecycle are much larger than the initial construction costs of a building, additional features influencing productivity may be well worth it. The study provides an interesting new input when discussing about social aspects of sustainability where proven facts are hard to find. However, energy efficiency seems to have an indirect influence on productivity only. Where data is concerned, there is only a minimal amount that has been systematically collected and available about costs and benefits of EEMs. The study was part of a larger KTI project (CH: Kommission für Technologie und Innovation) that resulted in the 'handbook for sustainable office buildings' (original in German: Handbuch für nachhaltige Bürogebäude) published in 2015 [43]. It contains the latest research and as such is the state-of-the-art in achieving office buildings that consider specifically social aspects of sustainability.

2.7 Optimisation of measures to be executed

A large amount of research work is dedicated to multi-objective optimisation of EEMs before execution (methods class 10). As a basis, EEMs are often developed on-site (methods class 1), off-site (methods class 2), or modelled using a simulation tool (methods class 3). Alternatively, a list of common or reference EEMs can be used as the basis (methods class 7-9). Then, according to Ma, "for the multi-objective optimisation problem, global optimisation techniques, such as genetic algorithm (GA) [85], branch and bound (B&B) [86], simulated annealing (SA) [87], etc., can be used to search for globally optimal retrofit solutions" [54].

This optimisation step is certainly important in order to achieve the best results from a refurbishment project. However, in practice, none of the many proposed methods is in use in the RE sector. Some of the reasons for this contradiction are:

- Application of techniques is too complicated for the target audience
- Restrictions of methods are too tight for the amount of uncertainties
- Expected benefits do not justify the considerable effort

Or, as Diakaki [32] formulates it: "…when the energy efficiency improvement problem is faced in its real-world dimensions, it possesses inherent difficulties that complicate both the modelling and the solution approach."

All these methods have been developed for the tactical (object) level. They do not bridge the stated gap.

2.8 Conclusion

Although there has been a substantial amount of work in the development of methods covering various aspects of sustainable (mainly residential) building refurbishment and enhancement, no one has focused on a method to allow appropriate consideration of EEMs in the stock of existing buildings at the strategic level where the first and often most determinant decisions are made. Consequently, a practical method integrating planning and budgeting of MMs, RMs, and EMs that consider energy efficiency and can be used for the prognostication and optimization of costs and of benefits of RMs and EEMs on a strategic portfolio level has not been developed until now.

The reasons can only be guessed. Energy conservation in buildings is a relatively new task. It became a focus in the eighties after the oil crisis and has been on the agenda since, mainly on an operational level, due to its potential for cost savings or due to mandatory requirements. In the last ten years, a much greater interest has arisen due to its potential to reduce emissions of greenhouse gases and the effects of climate change. Consequently, the topic has only recently landed on the strategic agenda of organisations and has the need for such a method arisen. Additionally, much comes down to the fact that only little data is collected and available which, for example, would be necessary to develop and verify probabilistic models. The random nature of many of the variables used to determine the condition and performance of buildings adds to the complexity of such models and their application. Reasons for the lack of data may be the fragmentation of the ownership in RE, missing common structures, and the monetary effort needed compared to the immediately visible benefits (i.e. low hanging economic fruit are underestimated and side benefits of energy efficiency are not properly considered).

The work in this thesis was conducted in order to contribute to filling the identified gap in the existing methods.

3 Methodology

In the writing of the four papers, methodologies such as literature research, deductive method development, survey conducting, and presentation of case studies or examples have been used. Some of these will be described in more detail in the following sections. Furthermore, the development from Paper 1 up to Paper 4 is explained.

3.1 Methodologies used

The work in this thesis applies an integrative approach to two closely related fields: a) maintenance and refurbishment of existing building portfolios and b) enhancement of existing building portfolios taking into consideration aspects of sustainability in general, and energy efficiency, specifically. It integrates theoretical and empirical fundamentals such as experience from industrial maintenance, sustainability rating - mainly of newly constructed buildings - recently developed standards and existing quality management systems as well as the latest research findings in these fields and a validation using existing databases and an example based on real data.

The work is based on the assumption that in an existing building portfolio synergies between maintenance and refurbishment and enhancement of aspects of sustainability are possible. A new method for integrated strategic planning and budgeting in these two related fields has been developed. The method complements established maintenance and refurbishment planning methods and is part of a controlling cycle (e.g. Plan – Do – Check – Act or PDCA) approach. How the new method is to be used is shown using empirical data, an exemplary building within a portfolio, and an example on portfolio level. The advantages and disadvantages are discussed.

3.1.1 Literature review

A literature review starts with a description of what is to be achieved, which normally is to give an overview of the best work that people have been doing internationally and that is relevant to the planned research. It ends by showing that there is a gap in the current research. The work done fulfils these points. However, there is no complete list or evaluation provided. The literature review followed several paths. One path was to search the internet for combinations of pre-defined terms. Another path was to browse through several years of relevant journal issues. The third path followed was to go through the list of references in relevant papers. After having conducted this literature review the initially suspected gap in the existing methods for strategic planning remained.

3.1.2 Survey

A survey was conducted in the course of writing Paper 3. The questionnaire was added to a letter asking portfolio managers for permission to use the data that they have stored in the software application STRATUS [58, Paper 3] for scientific research. The questionnaire addressed questions related to the application of the software, which were relevant for this work, as well as questions related to the general maintenance practice. As the survey was conducted amongst a closed group of users, no questions to check the consistency of the answers was added.

3.2 Development from Paper 1 to Paper 4

To illustrate the path that was followed in researching and writing the four papers, a glance at the process matrix in Figure 1 is helpful. The following relations apply (Table 4):

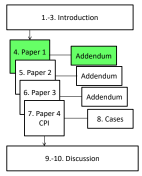
Table 4 *Relation of papers to process steps*

Paper no. (section)	**Topic**	**Relation to process steps**
Paper 1 (4)	Cost structures	T1, S3, T5
Paper 2 (5)	Maintenance methods	S2, T2, S3
Paper 3 (6)	Maintenance planning	O1, T1, S3, S5
Paper 4 (7)	CPI method and CPI-curve	S1-S6 S3

Before the identified research gap of a strategic planning method for enhancing energy efficiency could be tackled, basic terms and definitions needed to be clarified and existing methods for maintenance and refurbishment planning and budgeting needed to be evaluated to lay the foundation for the new method. During this preparatory work, the needs for new or adapted definitions and structures were identified. These were later developed and proposed.

The path starts in Paper 1 with costs structures - based on standards - which are needed to collect and allocate costs. Industrial maintenance methods are presented and their application on building maintenance discussed in Paper 2. Planning and budgeting methods for maintenance and refurbishment measures are compared and one method evaluated in detail in Paper 3. The evaluated method fulfils certain criteria making it suitable for strategic planning. Building on such a method and new definitions, namely new cost and benefits structures, a complementary method was developed for strategic planning of enhancement measures specifically designed to consider the energy efficiency of buildings in Paper 4.

In the following four sections the four published papers are presented.



4 Paper 1 [P1]: Impact of new European Facility Management Standards on Building Cost Structures

Published in the conference proceedings of the sixth International Structural engineering Conference ISEC, held in Zurich in June 2011 (ISBN-13: 978-981-08-7920-4)

Authors: M. Christen and H. Wallbaum

Connection to the title of the thesis

Following the definition of the RE strategy, including the maintenance strategy, planning methods are needed to determine the right time to execute measures based on the results of a portfolio analysis. Maintenance, refurbishment, and enhancement of EE are often combined when executed on existing buildings. Rarely, are buildings refurbished due to low energy efficiency only. Usually, EEMs are executed at the same time as RMs, which are initiated for technical reasons and/or changing user requirements, depending on the RE strategy.

This thesis proposes a method for the consideration of energy efficiency measures within the refurbishment planning in building portfolios. To this end, the costs and time plans of maintenance and refurbishment measures, as well as measures to improve energy efficiency need to be known.

Paper 1 looks at a new cost structure in FM from different perspectives. Some of these, like the split between initial investment, refurbishment and enhancement costs, are relevant for the goals of this thesis.

The paper is followed by an addendum (section 4.1) that provides more details and a classification of the methods which were referred to in the paper. The addendum has been written from the new position taken near the end of this work. The paper is presented in its original, published form (including numbering of sections, tables, figures, and references).

The results of this paper and the addendum are that the new structure solves a number of problems with the existing structures and supports the division between maintenance, refurbishment and enhancement costs, which is requested in this work. It also indicates that there is a suitable cost structure on the market and applied in RE to support parts of the process steps S3, T1, and T5 in the process matrix in Figure 1.

SUMMARY

There are many different cost structures for building construction and building operation, both in standards and in guidelines. Changes in these structures have far reaching consequences as they are often used for a whole series of activities, ranging from cost calculation and tendering to benchmarking in the country of origin. The European Committee for Standardization (CEN) is currently developing standards in the field of Facility management (FM). It is now working on the topics processes, quality, taxonomy (classification, products and structures), space measurement and benchmarking in FM. To overcome the problem of disparity in national cost structures, it has defined requirements for a harmonized support cost structure. No single structure was found to meet these requirements. What is needed is a system of interlocked structures e.g. for costs codes, facilities, activities/processes, etc. Central in this system is the new facility product structure. The new European standards in FM mark a shift from a building perspective to an organization perspective and from construction phase thinking to life cycle costing (LCC). The consequences are new requirements for the building construction industry and new opportunities towards the sustainability of buildings. This paper reviews existing cost structures and examines closely the question of whether the facility product structure is compatible with the different existing construction cost structures.

Keywords: facility management, European standards, building cost structures.

1. Introduction

How can an internationally operating company compare or benchmark its support costs? There are numerous different cost structures for building construction and building operation, both in standards and in guidelines. Some known examples are Building Cost Information System BCIS (Royal Institute of Chartered Surveyors RICS), Code of Measurement for Cost Planning CEEC (European Council of Construction Economists (2008)), Elementkostengliederung EKG and Baukostenplan BKP (Swiss Building Cost Codes, Schweizerische Zentralstelle für Baurationalisierung CRB (2009)), International Total Occupancy Cost Code ITOCC (Investment Property Databank IPD (2006)), DIN 276 and DIN 18960 (Cost code standards of the German Institute for Standardization DIN (2008)). Changes in these structures have sometimes far reaching consequences as they are often used for a wide range of activities from cost calculation and tendering to benchmarking and legal compliance matters in the country of origin. Based on this it is assumed that an international harmonization of construction cost structures further than attempted e.g. by CEEC will not be reached in the foreseeable future.

2. Review of Existing Cost Structures

What are the reasons for this large number of differing cost structures and what are some of the characteristics of these structures preventing them from gaining a wider acceptance?

2.1 Mixture of cost types

The first point of critique is that many of these existing building cost structures are trying to integrate different cost types in one structure. This results in a comparison of apples and pears. Most prominent is the integration of initial building construction costs (activated investment) and annual operating costs (expenses). Comparing or adding up these figures makes no sense, see Eq. (1):

$$\begin{array}{l}\quad \text{Initial construction costs} \\ \underline{+ \text{ Annual operating costs}} \\ = ???\end{array} \qquad (1)$$

This could be done in a life cycle analysis based e.g. on a discounted cash flow method (DCF). There, initial construction costs are being activated and thus converted into annual capital costs and can then be added to the annual operating costs resulting in the annual total costs.

However, in most organizations, the building value is not based on activated building construction costs but on a rated (or estimated) value like capitalized earning power (GER: Ertragswert). This results in calculated annual capital costs, which may be different from the effective construction costs.

2.2 Dimensions

Cost codes (used in financial or operational accounting systems), facilities (to be found in the asset database) and activities performed on these facilities each are a separate, independent dimension. Some structures attempt to represent these independent dimensions in a one dimensional list. The result is either a repetition of elements, lost data or confusion by overlapping elements.

2.3 Non-building related support costs

Looking at a single building is just one perspective possible. Professionals from the construction and real estate side tend to attribute many costs to the building which effectively are tied to the specific organization using the building. The same building may need extensive security if the occupier is a bank and it may need much less security if the occupier is a public administration. The inclusion of non-building related costs in building cost structures complicates benchmarking and does not add value to the organization.

2.4 Operation and maintenance costs

The separation of operation and maintenance costs is a difficult subject. Related terms are repairs, refurbishment, restoration, inspection and servicing. It may be done by a division between Investment (activated, restoring the original value) and annual expenses (income statement). In some countries, this division decides if a bill is included in the rent or if it may be charged separately to the tenants (e.g. as service charge). In practice, the split is often decided by the accountancy department based on the amount of the bill (e.g. everything above 2000€ is being activated and attributed to maintenance). In most existing cost structures, these differences are not reflected properly.

2.5 Else

Further problems with existing building cost structures are:

- An international agreement or common standard is not in sight or even planned.

- There are different roles of stakeholders in buildings like owner, user, landlord, tenant, financial investor, architect, builder or service provider. Each role looks from another angle onto the building and requires different information.

- Some structures mix costs (operational accounting) with expenses (income statement, financial accounting), annual costs with activated costs (balance sheet, added value), dept capital (e.g. mortgage or bank loans) with equity capital and depreciation for tax reasons with amortization.

- Cost of the land is often found as a separate item, but the construction of outdoor infrastructure is often not attributed to the land but included in building construction costs.

3. Examples of Structures

There are thousands of ways to create a support services structure. Real estate usually is the major support service in an organization. Some examples of building cost structures are presented below:

The CEEC structure (2008) is divided into:

- Construction costs
- Design and incidental costs
- Costs in use (maintenance, operation, disposal, de-commissioning, taxes)
- Land and finance

The CEEC structure is an interesting attempt to harmonize construction cost structures in Europe. Its international adoption and recognition is uncertain. It includes annual operating costs within a structure of initial construction costs. The division between maintenance and operating costs is not clearly defined.

The DIN 18960 cost structure (2008) is divided into:

- Capital costs (dept/equity capital, depreciation)
- Management (personnel costs, material costs)
- Operating costs (utilities, cleaning indoor/outdoor, safety and security, operation, inspection and servicing)
- Maintenance costs (structure, building technique)

The DIN 18360 structure (2008) is short and simple. However, the subdivision of capital costs is questionable. Safety and security are more organization than building related. The difference between maintenance and operation is not clearly defined. The substructures are a mix of cost, facilities and activities structures.

The ITOCC-IPD (2006) total occupancy costs are:

- A Property occupation costs
- B Adaptation and equipment costs
- C Building operation costs
- D Business support costs
- E Management costs

The ITOCC-IPD is probably the most comprehensive of all existing building cost structures. Activated costs are converted to annual capital costs. Maintenance and operation is summarized within C, the difficulties with their separation are admitted and a common sense approach recommended. The separation of building and organization related cost is an issue, but not implemented properly and the list of support services remains incomplete.

4. New European Standards in Facility Management

A Technical Committee of the European Committee for Standardization (www.cen.eu), the CEN TC348, is developing standards in the field of Facility management (FM). In a first phase it has defined the basic terms and definitions (what is FM?) and developed guidance for FM contracts. FM has often been confused with operational building management. Nowadays it is more broadly defined as the integration of the support processes/services in an organization which is a high level management task (2007). In a second phase CEN TC348 is now working on the topics processes, quality, taxonomy (classification, products and structures), space measurement and benchmarking in FM.

5. Solution to different national cost structures

To overcome the problem with differing national cost structures defined in national standards and guidelines, the CEN TC348 has defined requirements for a harmonized cost structure. What are the requirements of such a structure? Some of the characteristics which need to be fulfilled are: comprehensible, hierarchical, scalable, compatible with existing structures and accounting systems and being developed from a client (organization) perspective. After the evaluation of existing structures, it was found that no existing and no single one dimensional structure can meet these requirements. What is needed is a system of interlocked structures for e.g. costs codes, facilities, activities/ processes, etc. The proposed system is called FM relationship model. Central in this system is the new facility product structure.

6. Integration of Structures

The proposed standard 'taxonomy of FM' defines a high level product and cost structure. The products can be used e.g. for tendering, service level definition, cost allocation and benchmarking. The product structure does not replace existing construction cost structures, but relies on them. Construction cost structures define the facilities used in the product space and partly in other products like outdoors, cleaning or workplace. Take the example of a window as a common element in a construction cost structure (part of building fabric in Figure 1). This element needs to be planned and installed during the construction phase. The same window needs to be cleaned, inspected, maintained, painted, upgraded, replaced etc. during the operation phase. These are different activities performed with the same element window (tangible facility hence facility management). The new standard on FM proposes to use existing national construction cost codes on the level of construction elements throughout the whole life cycle of a building which is not common practice today. International benchmarking is then enabled on the level of facility products effectively leveling out national differences on construction element level. International companies have no special interest in the construction costs of windows unless it is their primary activity as a manufacturer of windows. But they want to know what the total cost of their occupied space is and compare it to costs of other organizations.

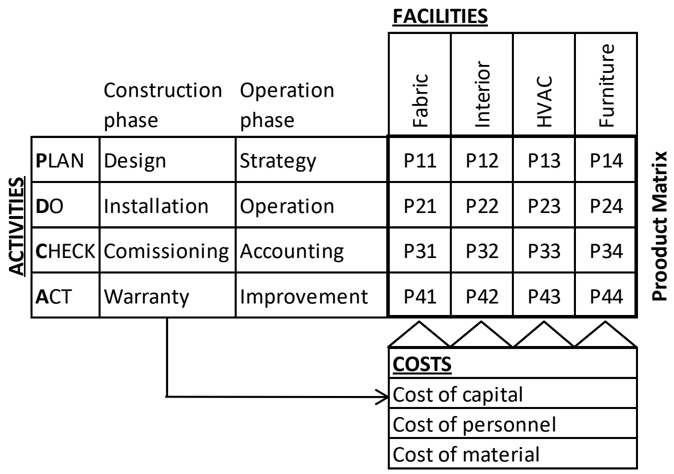


Figure 1. Exemplary facility product matrix with separate facilities, activities and cost structures.

(Figure based on prEN15221-4 (2010))

While the exemplary products from P11 (development of maintenance strategy for the building fabric) down to P44 (continuous improvement of furniture) in Figure 1 may be of interest for the service provider to control his own costs, from a client perspective they may be summarized under one product ‘Accommodation’. Such a high level product is defined wide enough to be comparable to other organizations. On the other hand, the matrix can be scaled down to a single piece of equipment (e.g. heating pump). The arrow points to the fact that construction phase costs are activated and transformed into capital or rental costs and as a consequence become part of the operation costs.

7. Main Facility Product Structure

The new structure defined in EN 15221-4 is integrating all costs and services on strategic level. On tactical level, there is an important division into the two main groups “Space & Infrastructure” and “People & Organisation”. On operational level, there are close to 100 products defined on three more levels (a total of five levels have been defined, three of which are shown below):

FM Stategic Integration

- Space & Infrastructure (includes: Space, Outdoors, Cleaning, Workplace, Industry Branch Specific)
- People & Organization (includes: Health, Safety, Security, Environment HSSE, Hospitality, ICT, Logistics, Business Support, Primary Activity Specific)

8. Discussion/Benefits

What are the advantages and benefits of the facility product structure that justify the creation of another cost structure?

- It is European wide harmonized (EN standard) and as such overrules national standards.
- It has been built from a client (organization) perspective.
- It is the first system that recognizes the different nature of the independent dimensions and structures needed to describe building costs and that separates them consequently.
- It integrates existing nationally different standards for building elements (construction cost structures).
- The structure makes use of the possibilities a standard database (e.g. CAFM software) is offering in linking different structures.
- Building related costs are per definition separated from organization related costs (e.g. steam boiler for production processes).
- The same structures and data can be used throughout the whole life cycle of the facility.
- It can be integrated in a standard accounting system, there is no separate building accounting system needed.
- A new product level has been created as cost collector in the operational accounting of the support cost center (FM). On the product level, different national structures are being equalized and can thus be compared.
- Provision has been made for the charging of utilities and services bills (GER: Nebenkostenabrechnung) under different national legislation.
- Land and building costs are counted separately.
- It is a strictly hierarchical structure with well-defined cost allocation for effective benchmarking.
- It forms an integral part of quality management systems using PDCA cycle (based on ISO standards).

9. Consequences

What are the consequences for the building industry and their processes resulting from the adoption of this new standard? The new facility product structure and the associated FM relationship model are a step towards the goal that the same data can be used throughout the whole life cycle of a building. To reach this goal, there is more coordination needed between construction phase and operation phase professionals in order to speak the same language and use the same layers in their drawings and the same fields in their databases. If the new EN standards find the intended acceptance amongst real estate professionals, there will be new requirements coming from the investor/occupancy side to construction professionals to adapt to them.

What is the impact on sustainability? Sustainability is addressed in the facility product map as a product of its own on strategic level (as a central/horizontal function) and on operational level e.g. concerning legal compliance. Furthermore, life cycle considerations are built into the product 'Space' as initial construction costs are separated from annual running costs and as construction and material information can more easily be archived for later usage.

Where are further studies necessary? The activities during construction phase are well standardized and used for tendering. For the operation phase every call for tender looks different. Activities and service quality (e.g. how can cleanliness be measured?) in the operation phase need to be become more standardized.

10. Conclusion

It is remarkable to note the differences in the various building cost structures. There is no right or wrong. What is needed is a common definition which finds wide acceptance. The new European standards in FM mark a shift from the traditional building perspective to an organization perspective and from construction phase thinking to life cycle costing. The consequences are new requirements for the building construction industry and new opportunities towards the sustainability of buildings. The new facility product structure in EN 15221-4 has the potential to unify high level cost allocation in real estate while integrating different national construction cost structures.

Acknowledgments

The author as convener of the workgroup taxonomy wishes to thank the members of all workgroups within CEN TC 348 and of the Swiss mirror committee who have contributed to the new standards in FM.

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4.1 Addendum Paper 1

The Paper 1 on cost allocation methods in FM has been written early in the process of writing this thesis. In this section, some complementary information and classification of the methods is provided as well answers to some questions, which arose from the new position taken at the end of this work.

4.1.1 Characterisation of existing cost structures

In order to provide more details on the existing cost structures in comparison with the new one, a list has been generated with a characterisation of these structures (Table 5).

The characterisation is based on the following accounting types:

Financial accounting: This is the main accounting in an organisation. It consists of an income statement (OPEX) and a balance sheet (CAPEX, listed as an asset). The aim is to calculate the profit or loss of the financial year. It is based on a detailed table of accounts that often refers to a standard, e.g. international accounting standards IAS. Listed are effective costs.

Operational accounting: This one is used to allocate costs and income to cost centers and their products. It usually consists of a number of cost centers and their cost units, which represent products and sub-products of the organisation. The aim is to allocate costs to products and so to calculate the profit or loss of a product. Listed are effective costs and calculated costs using cost unit rates (e.g. for cost of capital or staff).

Asset accounting: Detailed list or inventory of assets in the balance sheet. The aim is to calculate the book value from the initial CAPEX by deducting annual depreciation. This information can be linked to the products and the associated assets in the operational accounting.

Object accounting: This is the main instrument of an object manager. It lists all costs related to an object in a structure that enables to charge rent (usually for CAPEX) and additional services (usually OPEX) to one or more tenants. In doing this, different legislation exists in different countries. In order to calculate the rent, the CAPEX (investment or, alternatively, an estimated market value may be used) are transformed into annual OPEX of capital (imputed capital expenses) consisting of interest (usually calculated and not effective), depreciation, and an added margin.

For a definition of CAPEX, OPEX refer to Paper 4 in section 7.

Behind each of these accounting types stands a cost structure. Structures, which include interest, depreciation, insurance or taxes etc., are more useful for object accounting. Those listing rent or occupancy cost (e.g. based on a cost unit rate per m^2) are more applicable for operational accounting (rentable space seen as a product or service).

Most structures display a mix of purposes between object and operational accounting and even between CAPEX and OPEX. A classification (1-4) has been made according to the purpose that takes account of this mix.

1) Structures concentrating on product cost units – the two structures listed in this class are closest to the purpose of the new structure but show other disadvantages
2) Structures mixing object and operational accounting – the mix limits the applicability of these structures for any purpose
3) Structures concentrating on object accounting – these structures have a clear purpose, but are not directly suitable for portfolios
4) Structures concentrating on processes/activities - these structures have a clear purpose that is beyond the scope of a cost structure

Table 5 *Classified and commented list of cost structures*

Name of cost structure	Headers	Elements	Accounting focus	Characterisation	Advantages	Disadvantages
New European FM cost structure:						
EN 15221-4	18	150	Product cost units (support services); Operational accounting	Hierarchical on 5 levels; OPEX including for capital; separated from and preferably linked to financial and asset accounting	Broad and comprehensive; Flexible	For single objects, an extension is required
Existing (national) building cost structures:						
1) Structures concentrating on product cost units						
OPIK - FM Products in hospitals	0	25	Product cost units for hospitals; Operational accounting	Building as product (rent) plus services; Mix of RE and hospital specific products; Based on a detailed table of accounts	Linked to table of accounts (financial accounting)	Low level of detail; Hospital specific; No hierarchy
ITOCC - IPD	5	33	Product cost units (support services); Operational accounting	Hierarchical on 2 levels; Mixing financial (property tax) and operational (transportation services) accounting	Clear, minimal top level structure	Low level of detail; Mix of CAPEX and OPEX?
2) Structures mixing object and operational accounting						
Danish FM cost structure	2	24	Object accounting and cost units for facility services	Hierarchical on 2 levels		Low level of detail; Accommodation cost missing
France - Apogee	3	24	Object accounting and cost units for facility services	Hierarchical on 2 levels; Mixing financial (property tax) and operational (internal cleaning) accounting		Low level of detail; Purpose unclear; Accommodat. missing
UK Buillding Cost Information Service	8	29	Object accounting and cost units for facility services	Hierarchical on 2 levels; Mix of financial (property insurance) and operational (porterage) accounting		Low level of detail; Purpose unclear; Accommodation missing
JELLEMA	6	35	Object accounting and cost units for facility services	Hierarchical on 2 levels; OPEX; Mix of financial (interest) and operational (reception) accounting		Low level of detail; Purpose unclear
NEN	5	38	Object accounting and cost units for facility services	Hierarchical on 2 levels; OPEX	Detailed accounts for IT services	Low level of detail; Purpose unclear (interest, but not depreciation)
IFMA WORKPOINT ACCOUNTING	5	23	Object accounting and cost units for facility services	Hierarchical on 2 levels; OPEX; Mix between financial/object (insurance) and operational (food services) accounting	Specific for a rented object (rentee perspective)	Low level of detail
IFMA/GLOBAL FM BENCHMARKS	0	24	Object accounting and cost units for facility services	No hierarchy given; OPEX; Mix between financial/object (leasehold improvement amortisation) and operational (internal planting) accounting		Low level of detail; Purpose unclear
GEFMA/IFMA SUBMISSION CODES	0	22	Object accounting and cost units for facility services	No hierarchy given; OPEX and CAPEX (Instandsetzung)?; Mix between financial/object (Mängelansprüche) and operational (Fahrdienste) accounting		Low level of detail; Purpose unclear
GEFMA 200	10	46	Object accounting and cost units for facility services	Hierarchical on 2 levels; OPEX and CAPEX (Instandsetzung&Erneuerung)?; Mix between financial/object (Mängelansprüche) and operational (Administrative support) accounting	Covers all life cycle phases of an object	Low level of detail; Mix of CAPEX (construction phase) and OPEX unclear
Nordic Life Cylce Cost Structure LCC	8	50	Object accounting and cost units for facility services	Hierarchical on 2 levels; OPEX including for capital; Mix between financial/object (Taxes and Fees) and operational (Administrative Support) accounting	Specific for life cycle costing of an object	Low level of detail;
CRB Nutzungskosten (CH)	10	33	Object accounting and cost units for facility services	Hierarchical on 2 levels; OPEX; Mix between financial/object (interest) and operational (internal mail) accounting		Low level of detail; Purpose unclear
3) Structures concentrating on object accounting						
BOMA CHART OF ACCOUNTS	4	31	Commercial object accounting	Table of accounts on several levels; Covering income and expenses; Some facility services (copiers); OPEX and CAPEX (improvement)?	Specific for commercial objects	Low level of detail
QUICKSCAN (related to JELLEMA)	6	28	Object accounting	Hierarchical on 2 levels; OPEX	Specific for object accounting	Low level of detail
CEEC Cost groups	10	0	Object accounting	Headers only; OPEX and CAPEX (Construction costs)? Mix between project mangement and operational accounting	Specific for life cycle costing of an object	Very low level of detail; Mix of CAPEX and OPEX unclear
DIN 18960	4	17	Object accounting	Hierarchical on 2 levels; Mixing OPEX for capital including owners equity and CAPEX for refurbishment	Well known and used in Germany; Linked to construct.	Low level of detail; Mix of CAPEX and OPEX
4) Structures concentrating on processes/activities						
ProLeMo IFMA (CH)	7	40	Process definition in building administration	Hierarchical on 2 levels; Mix between building administration (activities) and facility services (products)	Detailed activities of building administration	Different level of detail; No cost structure

Some of the observed problems with the existing structures are:

- Based on national customs and legislation, preventing international benchmarking,
- Purpose unclear due to mix of different cost types (e.g. CAPEX and OPEX) and mix of accounting principles (financial, operational, asset or object accounting),
- Unclear link to the organisations financial and asset accounting,
- Generally low level of detail, specifically incomplete list of facility services,
- Different level of detail within the structure depending on authors point of view or targeted type of objects or services,
- No inherent flexibility to adapt to different requirements or industry branches,
- Vague description of costs (e.g. 'Non-specific repairs and maintenance'), no explanation given.

Features which justify the development of an all new structure and that have solved some of the problems with existing structures are (advantages):

- Benchmarking between companies on a national and international level,
- Translation of most elements of other structures into an element in the new structure (translation of elements means that the new structure can be run in parallel in an IT system in order to be able to benchmark without changing the existing structure) due to its broad and comprehensive nature,
- Focus on operational accounting of all support services – every product cost unit includes capital cost, labour costs, material costs and taxes or fees etc. (link to separate financial and asset accounting),
- Clear (cost) hierarchy over several levels with flexibility to add additional levels or to add sums between levels (number of levels used can be decided organisation specific),
- Standardised definitions of the products/cost units (facility services), reducing the uncertainty about what is included and what is not and thus supporting tendering and comparison,
- Scalable towards more detailed cost types, asset structures, and processes/activities,
- Separate categories for initial investment, refurbishment, enhancement, and maintenance and operation supporting the calculation of rent and additional charges,
- LCC is supported by treating CAPEX and OPEX differently and being able to convert both in annual costs (CAPEX are transferred into annual costs for interest and depreciation which then can be summed up with OPEX for total annual costs),
- Built in interfaces (reserved blocks of numbers at specific places in the hierarchy) making branch specific (e.g. hospitals, refer to example in section 4.1.3 below) adaptations easier.

Problems with the new structure are (disadvantages):

- There is currently little support on national level and RE associations because stakeholders are used to their old, local structures and associations rather promote their own structures,

- It is currently designed for use on the strategic level. Therefore, it is most useful when managing a wide scope of support services/facility products. An individual addition of details on lower level could be required for the administration of single objects,
- Up to now it is only standardized on European level (CEN) and not on a world-wide scale (ISO) which limits the implementation.

The new structure is designed for operational accounting in organisations owning a portfolio of buildings. It can serve as a framework for object accounting of single buildings as it is, but would need a restriction of the number of elements used and some additional details in administration for direct application for this purpose.

4.1.2 Application

As mentioned under disadvantages, there are barriers to the widespread application of the new structure. On the other side, using a conventional computer aided FM system (CAFM), the new structure can be implemented in parallel to the existing one (e.g. for international benchmarking reasons) without the need to switch immediately as most elements of any existing structures can be directly related to an element in the new structure.

4.1.3 Example of a practical application of the presented new cost structure

The new cost structure presented in Paper 1 has not remained theoretical. After the introduction of the new tariff system called SwissDRG[9] (diagnosis related groups), Swiss hospitals had the need to better analyse and control their support costs. To this end, the new cost structure has been taken and expanded with hospital specific elements, a procedure that is intended in the standard. This example of a practical, branch specific application is called ‘Leistungskatalog für nicht-medizinische Supportleistungen in Spitälern‘ LekaS (publicly available under: www.ifm.zhaw.ch/fm-healthcare).

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[9] Note: Another result of the introduction of DRG was, that many services which previously belonged to the core business of a hospital like maintenance of medicinal equipment now was shifted to the support or FM department in an attempt to separate and disclose costs and reduce them.

4.1.4 Achievement of goals

The title of the paper may have been chosen to be more accurate, as the paper does mainly refer to building cost structures needed during the operating phase and only partly to building construction cost structures.

The paper has the following goal containing two parts:

The paper reviews existing cost structures (part 1) and examines the question of whether the facility product structure provided in the new European facility management standards [57] is compatible with the different existing construction cost structures (part 2).

In section 2 of Paper 1, problems with existing cost structures are discussed. The first part of the goal has been achieved. An up-dated list of problems from the position taken at the end of this thesis is given in the section above about characterisation. Additionally, a wide selection of such structures are listed in Annex C of this work in a way that allows a direct comparison of them. To this end, each element in the structures in the Annex has been classified, ordered and marked with either:

- A -> Capital costs and/or rental costs,
- B -> Administrative costs,
- C -> Maintenance and operation costs,
- D -> Services costs, or
- E -> other costs.

The comparison of elements in each class in each structure clearly illustrates some of the mentioned differences and problems in these structures. Especially in class A, the elements show a confusing variety and often no clear logic.

For the achievement of the second part of the goal, it has to be admitted that the compatibility with construction cost structures is mentioned and shortly explained but not as closely examined as stated.

The compatibility of the new FM cost structure and existing building construction cost structures can be explained with the help of the following example. A window needs to be planned, designed, constructed, installed and accepted during the construction phase and cleaned, operated, maintained, refurbished and eventually deconstructed in the operating phase. These activities listed here are more or less generic and applicable to all construction elements. The new FM cost structure effectively provides a list of such generic activities but does not contain specific construction elements itself. If combined with any given structure of construction elements it can be scaled down to e.g. window cleaning if required. The new FM cost structure is called compatible because it can be combined with any existing structure of construction elements and even relies on them for certain purposes. This has not been explained clearly in the paper. With BIM, however, such compatibilities will become increasingly important when it is the aim to use the same data in all phases of a building.

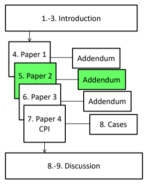
4.1.5 Additional requirements

The paper lists a number of requirements such a cost structure has to fulfil. For the additional consideration of energy efficiency as mentioned in the title of this thesis, the following ones need to be added:

- It supports a division between maintenance, refurbishment and enhancement cost
- It can be used for single objects and whole portfolios
- It lists detailed operating costs where energy is concerned

The new FM cost structure fulfills these three additional requirements. Most existing other cost structures fulfill the third point, but almost no other structure fulfills the first requirement and only a few ones the second requirement.

In summary, the Paper 1 indicates that a cost structure that supports the idea of this thesis does exist and is even standardized in European standards. It also, however, indicates that most existing cost structures have shortcomings, which may hinder the implementation of the idea.



5 Paper 2 [P2]: Application of Industrial Maintenance Methods on Building Maintenance

Published in the conference proceedings of the sixth International Structural engineering Conference ISEC, held in Zurich in June 2011 (ISBN-13: 978-981-08-7920-4)

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Connection to the title of the thesis

Following the definition of the RE strategy, including the maintenance strategy, planning methods are needed to determine the right time to execute measures based on the results of a portfolio analysis. Maintenance, refurbishment, and enhancement of EE are often combined when executed on existing buildings. Rarely, are buildings refurbished due to low energy efficiency only. Usually, EEMs are executed at the same time as RMs, which are initiated for technical reasons and/or changing user requirements, depending on the RE strategy.

This thesis proposes a method for the consideration of energy efficiency measures within the refurbishment planning in building portfolios. To this end, the costs and time plans of maintenance and refurbishment measures, as well as measures to improve energy efficiency need to be known.

This Paper 2 investigates the possibility of using the maintenance planning methods used in the industrial sector in the RE sector.

The paper is followed by an addendum (section 5.1) that provides more details and a classification of the methods, which were referred to in the paper. The addendum has been written from the new position taken near the end of this work. The paper is presented in its original, published form (including numbering of sections, tables, figures, and references).

The results of the paper and the addendum are that most methods are too production specific for e.g. a standard office building. Two methods are discussed that were found to have some limited potential to improve processes if applied in the RE sector. Consequences regarding aspects of sustainability are also briefly discussed. The paper and the addendum indicate that there are adequate methods available to support the process steps S2, T2 and S3 in the process matrix in Figure 1.

Summary

Currently, the existing building stock is refurbished or replaced at a very low annual rate. Nevertheless due to its immense total value this slow replacement requires a considerable part of the GDP. It is important to ensure that this capital is invested in the best way with most profit for the society and future generations as well as for the investors.

This presentation explores differences between maintenance of industrial facilities and maintenance of real estate. Industrial maintenance has developed different instruments to optimize the costs of maintenance while ensuring the required productivity or reliability. Building maintenance historically was more driven by external factors like profitability or the urban development in the surrounding area. Based on the assumption that maintenance of industrial facilities is more advanced, industrial maintenance methods have been classified and their application in real estate maintenance explored. The paper gives examples of these methods and explores if it is possible to adapt proven methods from industrial maintenance for building maintenance and looks at the potential to improve the sustainability of buildings by using industrial maintenance methods on buildings.

Keywords: industrial maintenance methods, building maintenance, sustainability, quality cycle, facility management, keywords

1 Introduction

According to the Oxford Dictionary, maintenance is defined as cause to continue (maintain) a state of affairs and/or the provision to preserve equipment in good repair. Many other definitions do exist, for example in EN 13306 Maintenance (2008).

In practice, maintenance is considered by most as an undesired necessity. Who wants to be reminded that everything is withering and altering and constantly loosing value and to spend money just to slow or counteract these processes? As a consequence, maintenance is an optimization problem between the direct cost of maintenance activities and the indirect (avoided) costs resulting from insufficient maintenance (e.g. loss of productivity, usability or value).

The optimization problem encompasses items like cost of maintenance (labour, materials, etc.), strategic goals (e.g. reliability, leasing capacity, cost effectiveness, etc.), expected lifetime of assets, scenarios of different maintenance measures and evaluation (e.g. risk based) of consequences (costs or benefits from avoided costs).

An analysis was undertaken to evaluate the potential for better optimization of building maintenance by applying industrial maintenance methods and taking into account their impact on sustainability.

2 Differences between Industrial and Real Estate Maintenance

Industrial maintenance has developed a large array of instruments to optimize the costs of maintenance while ensuring the required productivity or reliability of production equipment. Building maintenance historically was more driven by factors like profitability, leasing capacity or the urban development in the surrounding area. What are the major differences between those two?

2.1 Motivation

In different sectors there is a different motivation to spend money on maintenance activities. For example in the transport sector, the foremost motivation is the safety of passengers and personnel followed by the reliability of the services (timetable). In the industry sector, the biggest motivator is the reliability of the production facilities (productivity) which of course includes the safety of the production and maintenance staff. In the real estate (RE) sector, motivation is more focused on profitability (leasability or leasing capacity), the value of buildings and low operating costs.

2.2 Organisation

In the industry sector, maintenance is often a part of the primary activity of the organization. Reasons for this are that the production facilities are often unique and in some cases even secret and that specific knowledge and very short reaction times are necessary. In the RE sector, building structure and HVAC equipment is no secret and can be maintained by any trained person. There is a large and competitive market for HVAC maintenance services. Maintenance therefore is often being undertaken by external providers (outsourced), ordered by a central administration. In the building itself, there may be a caretaker or janitor for inspections and first level interventions only. The janitor often acts as the direct contact to the users of a building, as a kind of personal help desk, and decides on the urgency of repairs.

Maintenance staff in the industry, being part of the production, has a close, sometimes personal relationship to the assets to be maintained. The staff members of external HVAC and building maintenance providers on the other hand have more a professional service oriented motivation.

2.3 Further differences

In this section, further examples of differences between industry and real estate are given:

Table 1. Difference between industrial and real estate maintenance.

Difference	**Industry** (e.g. production facility)	**Real estate** (e.g. commercial building)
Type of assets to be maintained:	Industry specific or one off	Standard (off the shelf).
Life cycles:	Short life time (e.g. 5-10 years)	Long life times (e.g. 40-60 years)
Ownership of assets:	Owner/user	Investor (landlord)/tenant
Relevance for primary activity:	Direct impact on productivity and earnings	Support services
Cost of failure due to:	Loss of production/ endangering people	Reduced comfort
Required reaction time:	Very short, action must be preplanned (eg. chemical production process)	Time to plan before action is taken (a bucket under the leaking roof might do

All these differences have an influence on the maintenance methods to be applied and used. Of course, these differences may not be generalized. The tallest building in the world, the Burj Khalifa in Dhubai with estimated 120 maintenance employees and 50 escalators, is probably as complex as a production facility.

3 Maintenance Methods

Before the application of industrial maintenance methods in RE could be explored, a structuring and classification of existing methods was necessary. At the start, a list with more than 100 entries on maintenance methods has been generated.

Dankl and Stuber (2010) have chosen to classify the methods in historical order. Figure 1 is showing the qualitative development of industrial maintenance since 1940. According to the authors, preventive maintenance started around this time with new methods for planning and analysis.

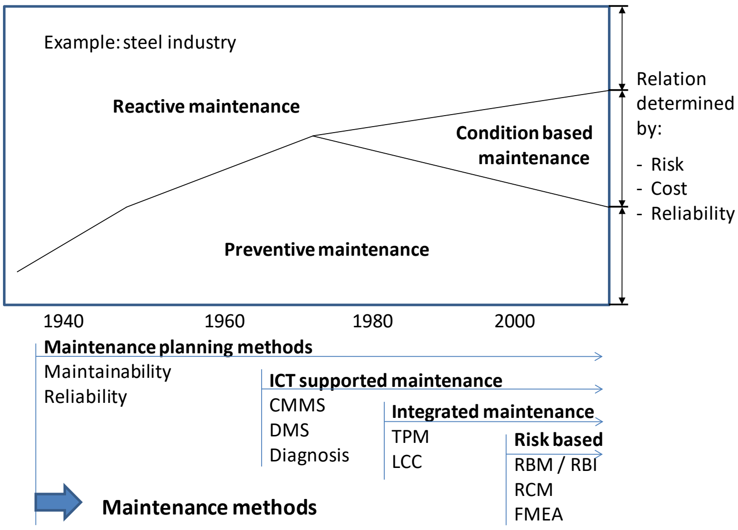

Figure 1. Development of maintenance methods.

Abbreviations are explained in the text. (Translation from Dankl und Stuber (2010))

In the absence of a useful classification system, the quality cycle of Plan, Do, Check and Act (PDCA or Deming cycle) was chosen for the structuring. PDCA is a common method used in ISO and EN standards. The outcome of the classification was an almost even distribution of the methods with a slight predominance of planning methods. Interestingly, only few methods cover all four phases of the quality cycle and most methods cover just one or two of its phases. If a full quality cycle is to be achieved, the combination of methods is necessary.

The methods were then rated into three categories with some examples listed below:

Methods found to be too specific for industrial production to be used in RE:

- FTA, Fault Tree Analysis
- FMEA, Failure Mode and Effects Analysis
- LCIA, Low Cost Intelligent Automation
- QRQC, Quick response Quality control
- SMED, Single Minute Exchange of Die
- Production restart monitoring

Methods which may be adapted to RE:

- Poka Yoke, avoidance of unintended mistakes
- RCM, Reliability Centered Maintenance
- RBM/RBI, Risk Based Maintenance/ Inspection
- TPM, Total Productive Maintenance
- SPC, Statistical Process Controlling
- 5S, quality achieved through cleanliness

Methods which are commonly used in RE:

- CM Condition Monitoring
- Preventive and Condition based Maintenance
- CMMS Computerized Maintenance Management System (ICT = Information and Communication Technologies)
- DMS, Document Management System
- LCC Life Cycle Costing

4 Known Application in Real Estate

The central questions to be answered in building maintenance are:

- What is the condition of elements and infrastructure of the building and what is the remaining life time of them?
- What is the best maintenance strategy in accordance with the overall portfolio strategy?
- What are the costs and benefits of intended maintenance measures?

The performed analysis of methods has shown that maintenance of industrial facilities and maintenance of real estate has basic differences. But, some methods are already now used for both tasks.

Examples for the application of the same methods, even if sometimes used in different ways, are given below:

- Condition based maintenance (measuring of equipment variables / visual inspection of building structure)
- Infrared cameras (connectivity of electrical distribution / heat losses of buildings)
- Benchmarking (productivity / energy consumption per m^2)

Two methods which are used in industrial maintenance and which are not commonly used in real estate but might offer a potential to improve the latter have been chosen and are described in the following sections:

In Total Productive Maintenance (TPM) according to Edward and Hartmann (2007) standards are defined based on strategy. TPM is introduced in a step by step process by integrating different existing methods and incorporating all persons involved. In industry, this is foremost the production and the maintenance staff. To this end, TPM is promoting workshops in groups to discuss improvements. Facility Management (FM) is defined in European Standards EN 15221-1 (2007) as the integration of processes to support the primary activities of an organization. An application of TPM in building maintenance is therefore self-evident. Examples would be the systematic incorporation of cleaning or reception desk staff in maintenance duties like inspection and first level intervention. This requires a new definition of duties, responsibilities, competencies and service level agreements (SLA). Instead of TPM, a new name like Life Cycle Maintenance (LCM) would be appropriate in RE.

Reliability Centered Maintenance (RCM) has been developed by Nowlan & Heap (1978) to respond to accidents with planes. Important elements are analysis, decision algorithms and condition monitoring. RCM is using statistical methods to analyze failure data. It is not yet state of the art in industry. RCM should be used in important buildings, but even in hospitals, this has not become a standard yet. For RE purposes, reliability could be translated into importance for the organization (primary activity). Risks could be translated into consequences of neglecting regulations (legal compliance), health risks for employees or future loss of value.

It is interesting to be noted that there is also a flow of innovation in maintenance coming from the side of built infrastructure. The Institute of Construction and Infrastructure Management (IBI) of the ETH Zurich developed a risk based, probabilistic life cycle (LC) – net present value (NPV) model for main roads surface maintenance in Girmscheid (2007). It is using the Monte Carlo method to optimize measures. The model is based on a highly standardized method to describe the condition of the roads to be maintained and a defined set of measures. This is an ideal situation for a maintenance manager. In RE, describing the condition of a building and the necessary measurements to improve it are still in the stage of research and development. The LC-NPV model has a potential to be applied in real estate and industrial maintenance as well. Other examples are methods for energy auditing and new tools for portfolio maintenance planning using standardized life cycle curves. However, these examples seem to be the exceptions to the rule and the assumption that industrial maintenance is more advanced and sophisticated than RE maintenance remains uncontested.

5 Maintenance and Sustainability

In central Europe energy consumption of buildings including water heating accounts for about 40% of the total energy consumption. It is essential to reduce this large share if problems like future resource limitations and climate change are to be solved. Currently, the existing building stock is refurbished or replaced at a very low annual rate (Wallbaum et al 2009, Wallbaum et al 2010). Nevertheless due to its immense total value this requires a considerable part of the GDP. It is important to ensure that this capital is invested in the best way with most profit for the society and future generations as well as for the investors. To measure sustainability there is a countless number of rating systems available worldwide. Well known examples are LEED, BREAM, DGNB etc. Of these, DGNB covers the widest array of aspects including social and cultural aspects and process quality.

One exemplary question of maintenance optimization related to sustainability is if it is better to replace inefficient appliances in terms of energy consumption now or to better keep them operating due to the embodied energy (“grey energy” in Switzerland) which was used to produce them. There is usually not a simple answer to this question.

The Figure 2 shows the interdependence of maintenance and sustainability measures. Few measures to improve sustainability are economical of their own. However, additional measures to improve sustainability implemented during normal maintenance activities can be financially very interesting. For example to add another layer of insulation before newly painting the building exterior by having the scaffolding already in place, adds very little cost compared to the benefits of lower energy consumption and raised building value. The reason is that a large share of the cost can be attributed to inevitable maintenance.

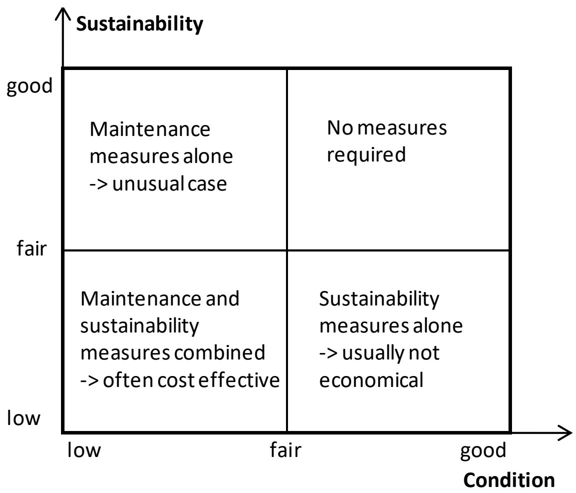

Figure 2. Interdependence of maintenance and sustainability measures in buildings.

For building owners who have included sustainability in their corporate responsibility strategy, it is not only the age and condition of a building element which they need to consider during maintenance planning, but also the additional potential to improve the sustainability rating of the whole building at the same time. This is pointing to the necessity to develop a combined and holistic maintenance and sustainability planning system for RE.

To improve sustainability, adapted industrial maintenance methods could be helpful. Sustainability is normally divided into the following three categories (triple bottom line) showing examples of industrial maintenance methods and their benefits:

- Environment (ecology): CM (detecting heat losses, exhaust analysis), efficiency improvement (replacement of inefficient appliances)
- Economy: TPM (integration of users for keeping windows closed, turning lights off), RCM (reliable cooling of computer centers)
- Benefits for society: help desk (fast reaction on complaints), CM (healthier working environment due to less pollutants)

This short overview summarizes the result that no industrial method was found to specifically improve sustainability significantly more than the methods already known and utilized today.

6 Conclusion

There are significant differences in the application of maintenance methods in industry and real estate. Out of a large number of industrial maintenance methods, two methods where tested on their adaptability for real estate. It is estimated, that there is a potential to improve the cost effectiveness of building maintenance by using these methods. In complex industrial production, every application of a method is a new project of its own. Due to the more standardized nature of elements and of infrastructures in buildings, these methods could be adapted once in an exemplary way and used for a large variety of real estate portfolios. The next step would be to develop a TPM and/or RCM adaptation or tool box based on the specific requirements of real estate and to initiate practical tests.

The impact of applying industrial maintenance methods in RE to improve the sustainability of buildings was found to be less significant than estimated at the start of the analysis.

Acknowledgments

The author wishes to thank A. Stuber for the intense discussions about this subject.

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Acts, Statutes and Standards

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EN 15221-1 2007: Facility Management – Terms and definitions.

prEN 15221-4 2010 (Draft): Facility Management – Taxonomy, classification and structures.

EN 13306 2008: Maintenance – Maintenance terminology.

5.1 *Addendum Paper 2*

The Paper 2 on industrial maintenance methods was written early in the process of writing this thesis. In this section, some complementary information and classification of the methods and tactics is provided as well answers to some questions, which arose from the new position taken at the end of this work.

In general, it is assumed that the industrial sector is ahead of the RE sector what the sophistication of maintenance planning methods concerns. Some of the reasons for this are:

- Often one off industrial production plants are much more complex to maintain than the mostly off the shelf building elements and technique
- Monetary consequences of failures in industry are potentially more severe than the consequences of temporary reduced comfort in buildings
- Industrial performance requirements are very strict compared to the generally large failure tolerance of tenants/users
- Industry employs maintenance specialists trained in the application of different methods while housekeepers and craftspeople often lack this training

In the industrial context of Paper 2, the term maintenance has been used as an umbrella term and includes MMs and RMs. In the RE context of the remaining thesis, the term measures includes MMs, RMS, and EMs.

5.1.1 *Classification of maintenance methods and tactics*

In literature about maintenance, different classifications and terminology can be observed [67, 68]. Here, the following two classes are used:

- 1 Class of maintenance methods found in literature [67, 68] and mentioned in Paper 2 classified by focus of these methods (Table 6)
- 2 Class of maintenance tactics classified in preventive and reactive (Table 8)

The two classes form a matrix. The methods (marked with * in Table 6) in the first class are used to determine the optimal tactic for each asset resulting in a goal oriented (e.g. cost-effective) mix of tactics in a portfolio of assets. The tactics to choose from are listed in the second class. Depending on the chosen method and the goals, the mix of tactics will be different. For example using the method RCM, seven standardised questions are worked through to prioritise all assets. For assets given a low priority a reactive, failure based tactic will be applied while assets given a high priority a preventive, periodic tactic will be applied (Figure 4).

Operational condition monitoring methods like infrared photography e.g. to detect hot electrical connections or vibration analysis to detect worn bearings have not been listed although there is a considerable development of operational methods and a wider application of these in RE to be observed due to reduced cost of equipment. IT-systems (IT = information technology) are generally applicable together with most methods and tactics and, therefore, are listed separately.

The over-arching maintenance strategy determines which method is to be used to decide on the right tactic for each asset and how the performance is measured and evaluated.

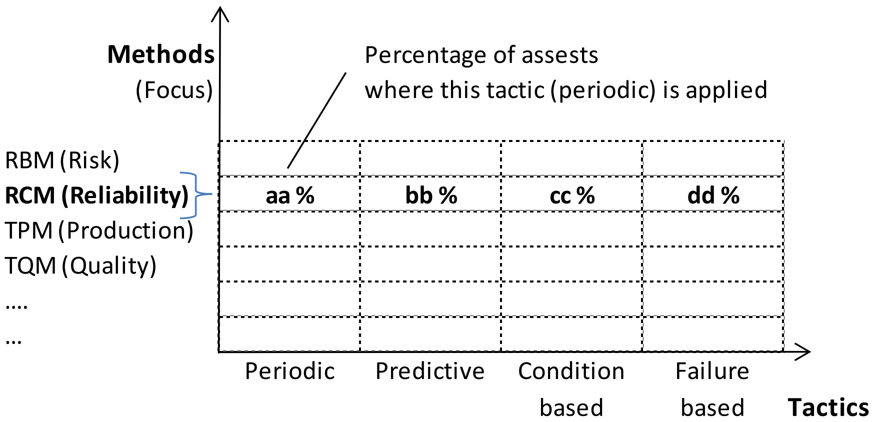


Figure 4 *Maintenance methods are used to determine the right tactic for each asset resulting in a mix of tactics in a portfolio (RCM used as an example; Total = 100%)*

In RE, the mix of maintenance tactics is decided more often on the experience of the portfolio manager and partly by legal obligations than based on a method with a specific focus as it is often practice in the industrial sector. Legal obligations cover, for example, safety relevant elements like elevators. In these cases, certain maintenance tactics are mandated and cannot be chosen. Some organisations use a maintenance management system to plan periodic measures for elements of the building technique (e.g. regular changing of the filters in a ventilation system) based on fixed intervals. For building construction elements, such systems are rarely used due to their much longer and less projectable intervals between measures (see also section 6).

The different effects of the listed maintenance tactics, irrespective of the focus used, on the point of time when measures are executed and thus influencing costs are drawn in Figure 5.

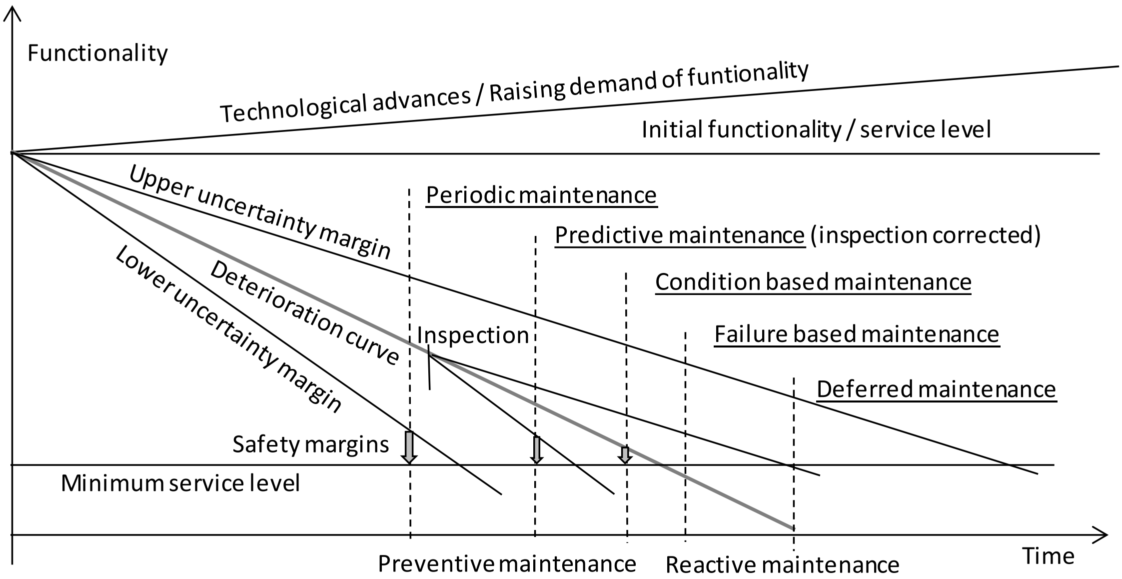


Figure 5 *Conceptual illustration of the effect of different types of maintenance tactics (underlined) on the time of execution of measures*

There is uncertainty in the estimation of the end of service life. The reduction of this uncertainty leads to reduced maintenance costs as preventive measures can be executed later in time or in longer intervals with lesser safety margins. The following reduction in the number of measures is reducing direct costs of measures including use of spare parts and indirect costs like downtime of assets. Predictive and conditions based strategies aim at reducing the wide uncertainty inherent in the basic periodic tactic. Of course, these tactics come with an effort and an optimisation between tactics is required. This is where the methods listed in Table 6 with a different focus each come into play.

Table 6 *Classification of maintenance focuses with examples of methods (in italic) part 1*

Focuses and examples of methods (in italic)	**Description (only keywords)**	**Usability in RE**	**Example of use**
A) Risk focused (risk management) methods	Concentrating on reducing the probability times (negative) consequences (=risk) from undesired states		
*Risk based maintenance (RBM) **	Measures are planed based on risk analysis	Safety relevant issues in RE are covered by standards and regulations or best practice	Functioning of exit signs
Risk based inspection (RBI)	Inspection intervals are planed based on risk analysis and measures derived from results	Applied intuitively or based on experience in RE where no standards or regulations exist	Condition of sewage piping
B) Reliability focused methods	Concentrating on the probability of providing the required functionality (performance or level of service) according to requirements		
*Reliability centered maintenance (RCM) **	Optimisation between maximum of reliability and minimum of maintenance cost	Production specific - not generally applicable in RE due to high effort	Climatisation of a data center or an operating theater
Fault tree analysis (FTA)	Analysis of risks of undesired conditions as a combination of lower level events	Uncommon in RE due to high effort and basically known risks	n/a
Failure mode and effects analysis (FMEA)/and criticality (FMECA)	Similar to FTA	Uncommon in RE due to high effort and basically known risks	n/a
C) Production focused methods	Concentrating on availability of production equipment (productivity)		
*Total productive maintenance (TPM) **	Integrating equipment, process, organization and specifically operational staff	Potential for adaption and wider application in RE	Coordination of maintenance and cleaning staff and eventually users
Production restart monitoring (PRM)	Paying special attention to the specific phase of production restart	Production specific - not generally applicable in RE	Control of restart of a large central wood boiler
Low cost intelligent automation (LCIA)	Avoiding complicated automation and supporting human intelligence (Focus may have changed through new technologies)	Production specific - not generally applicable in RE	Trained house-keepers instead of remote controls

Table 7 *Classification of maintenance focuses with examples of methods (in italic) part 2*

<u>Focuses</u> and examples of methods (in italic)	Description (only keywords)	Usability in RE	Example of use
Single-minute exchange of die (SMED)	Fast change of production from one product to another (only in parts related to maintenance)	Production specific - not applicable in RE	n/a
D) Quality focused methods	Concentrating on quality of output/production according to specifications		
*Total quality management (TQM) **	Similar to TPM but more focused on quality of production	Production specific - not generally applicable in RE	n/a
Statistical process controlling (SPC)	Control of production processes using statistical methods for early detection of failures	Production specific - not applicable in RE	n/a
Quick response quality control (QRQC)	Production problem solving through a fast controlling cycle (PDCA)	Production specific - not generally applicable in RE	Improving of service of a help desk
Quality achieved through cleanliness (5S)	Good housekeeping for better production quality	Common in RE	Keeping the boiler room clean and tidy
E) Safety focused methods	Concentrating on preventing health hazards or injuries		
Contingency planning (CPl)	Planning to prepare for an emergency	Common in RE	Fire escape plans
Poka-Yoke (PY) (Engl: mistake-proofing)	Avoidance of mistakes through fault-proof design	Safety relevant issues in RE are covered by standards and regulations or best practice	Different plugs for different voltages which cannot be mixed
F) Cost of assets focused methods	Concentrating on minimal life cycle costs of assets		
Life cycle costing (LCC)	Calculation of the cost of an asset over its entire lifetime in order to minimize them	Common in RE	Comparing heating alternatives

Note: RE covers a wide range of applications. An operating theater in a large hospital is not much different from an industrial facility what safety and reliability issues are concerned while a residential building has completely different requirements. In this table, the requirements of a standard medium sized office building were used to assess the usability of these industrial methods in RE

Methods marked with * are used to determine the optimal maintenance tactic for each asset

The methods in *italic* are listed by way of example to illustrate how this proposed classification could be used. However, some of these methods could also be applied in one or more other focuses. They are all mentioned in Paper 2.

Table 8 *Classification of maintenance tactics with examples of operational methods (in italic)*

Tactics and examples of methods (in italic)	**Description (only keywords)**	**Usability RE**	**Example of use**
Classes of tactics			
1) Preventive	Measures start before failure (minimum service level)	Common in RE i.e. where safety is concerned	Fire protection equipment
1.1) Periodic (TbM)	Measures start at regular, fixed time intervals	Common in RE	Lift maintenance, used in MMS
1.2) Predictive (PbM)	Start of measures depends on predicted condition based on (one or more) inspections and mathematical algorithms	Common in RE	Method Schroeder in Paper 3
1.3) Condition based (CbM)	Start of measures depends on (constantly monitored) effective condition	Rarely applied in RE due to high effort (cost) for monitoring	Air filter replacement
Condition monitoring (CMon)	Constant (real time) or periodic reporting of system condition	See 1.3)	
2) Reactive	Measures start after failure/ below minimum service level	Common in RE due to low cost of consequences of failure	Pump replacement in heating system
2.1) Failure based (FbM)	See 2)	See 2)	See 2)
Run to failure (RtF)	See 2)	See 2)	Light bulbs
2.2) Deferred maintenance (DfM)	Starting from another tactic, measures are deferred until e.g. related measures are executed (change of tactic)	Often applied in RE	Imminent refurbishment or new construction

Note: The methods listed in *italic* are operational methods mentioned in Paper 2 which are specifically applicable for a maintenance tactic and not attributable to a focus. Paper 2 does not contain operational methods for each tactic.

Table 9 *Maintenance IT-systems*

IT-Systems	**Description (only keywords)**	**Usability in real estate RE**	**Example of use**
Maintenance management system MMS	Computer aided maintenance planning	Common in management of large building complexes or portfolios	Maintenance of technical equipment
Document management system DMS	Digital management of contracts, inspection reports, etc.	Common in portfolio management	Rental contracts

5.1.2 Motivation behind maintenance efforts

Maintenance always requires an effort, which needs a justification. In section 2.1 the prime motivation for the execution of such measures is discussed. For the industry sector, there are two prime motivations mentioned in literature: achieving the required availability of production equipment (share of time the equipment is ready to produce) or directly productivity (products produced over a certain period) and achieving the required reliability (performing a function according to expectations and requirements). The Paper 2 takes the position, that reliability encompasses availability including quality of output, safety of operation, and service life of assets with priorities set in the strategy. Therefore, reliability is considered as being superior to availability. Both motivations may be complemented by risk considerations [88, 89]. In infrastructure management, these requirements in accordance with the strategy are called level of service (LOS) [76, 80].

For a public transport company, the worst case with the most severe consequences is an accident with injuries or deaths (passengers or employees), especially when due to lack of adequate maintenance. Primary motivation for maintenance or required LOS is therefore an accident free operation. Secondary motivations for maintenance are requirements regarding the timetable, the comfort of passengers or the life cycle costs of assets, also depending on priorities set in the respective strategy.

5.1.3 Achievement of goals

The Paper 2 has two goals.

Goal A) The paper gives examples of industrial maintenance methods and explores if it is possible to adapt proven methods for building maintenance

The results are presented in the form of a classification divided into three categories. Items in the first category were considered to be specific for industrial production either due to a considerable computational effort or an extensive know-how for the application needed or due to a direct link to production. The second category covers items, which may be adapted to RE. This includes those methods, which are used to define the optimal maintenance tactic for each asset. Two of these are discussed in more detail (TPM and RCM) because they were found to have the most potential for application in RE. Items in the third category are commonly used in RE.

However, as can be seen in Table 6 and Table 8, this categorisation is not as strict as it may seem in the Paper 2. For many methods there can be an example of application in RE found as a complex function in a building is not far from an industrial facility in maintenance terms. Therefore, the requirements of a standard medium sized office building were used to assess the usability of these industrial methods for RE in a comparable way in the two tables.

The result of this goal was less spectacular than initially thought. The know-how transfer between these two sectors has either largely already happened or is not feasible due to the different requirements in each.

Goal B) The paper looks at the potential to improve the sustainability of buildings by using industrial maintenance methods in RE

Maintenance undeniably has an effect on all three aspects of sustainability. These effects may include:

- Environmental aspect: Reduced energy consumption, emissions, and embodied energy
- Economic aspect: Optimised operation and functionality, service life, and use of spare parts
- Social aspect: Reduced risk, adhered legal requirements and improved safety

While the majority of these examples have an effect on two or all three aspects, the paper gives specific examples for each aspect in RE. These are shortly repeated in more detail:

- Detecting heat losses with infrared cameras may lead to better insulation and less wasted heat (reduced energy consumption = environmental and economic aspect, higher comfort = social aspect)
- Exhaust analysis with e.g. CO_2-sensors may help to detect inefficient burning of fuel oil or gas (reduced energy consumption = environmental and economic aspect, less pollution = social and environmental aspect)
- Replacement of inefficient appliances, e.g. LED bulbs substituting conventional ones as part of the maintenance activities (reduced energy consumption = environmental and economic aspect, better illumination = social aspect)
- Integration of users (tenants, employees) has come into the focus of research lately as their behaviour can influence a considerable share of overall energy consumption in certain buildings and be changed

with relatively little effort and cost (reduced energy consumption = environmental and economic aspect, higher user satisfaction through participation = social aspect)

- Reliable cooling is a prerequisite for a data centre to be functional and as such relevant for productivity and income (higher productivity of assets = reduced embodied energy = environmental and economic aspect, higher comfort = social aspect)
- A fast reaction on complaints leads to more user/tenant satisfaction e.g. by faster removal of health hazards like ice on the pavement or energy wasting like lights burning all nights (reduced energy consumption = environmental and economic aspect, higher safety/user satisfaction = social aspect)
- A healthier working environment can be achieved by measuring CO_2 levels in the air and adapting fresh air rates or by monitoring the condition of dust filters in the air conditioning and replacing them when the need arises (reduced energy consumption = environmental and economic aspect, better air quality and reduced draft = social aspect)

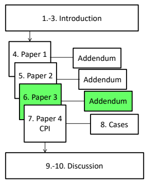
The result of considerations regarding this goal were also less spectacular than initially thought. Regular inspections of e.g. heating systems are normally covered by regulations and mandatory. On the other side, more inspections and cleaning of ventilation ducting, which is not mandatory, could be beneficial in many cases for the health of the employees. An ongoing know-how transfer between these two sectors can be observed in operational condition monitoring techniques, which may have a positive influence on sustainability. These have not been considered specifically.

Nevertheless, the Paper 2 clearly indicates that there are sufficient maintenance planning methods on the market and applied in RE to support the process steps S2, T2 and S3 in the process matrix in Figure 1 as a basis for this thesis.

5.1.4 References

Although the referenced publication of S. Knowlan and H. Heap about RCM dates back to 1978, today, it is seen as classic and as revolutionary at its time and it has influenced research and application of industrial maintenance methods and tactics up to now.

The paper of G. Girmscheid is referenced to as an example of research in the network infrastructure sector because then it was the latest publication in Switzerland in this field. The paper was also used to point to some similarities and differences between the different sectors. It is known and acknowledged that for example authors like D. Frangopol [63], S. Madanat [64]t or P. Thompson [65] have made important contributions to maintenance planning in this sector in their earlier works.



6 Paper 3 [P3]: Strategic building maintenance and refurbishment budgeting method Schroeder – application and evaluation

The paper was accepted by the International Journal of Strategic Property Management (JSPM) in September 2013 and published online in December 2014 (Impact Factor (2014): 1.192),

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Connection to the title of the thesis

Following the definition of the RE strategy, including the maintenance strategy, planning methods are needed to determine the right time to execute measures based on the results of a portfolio analysis. Maintenance, refurbishment, and enhancement of EE are often combined when executed on existing buildings. Rarely, are buildings refurbished due to low energy efficiency only. Usually, EEMs are executed at the same time as RMs, which are initiated for technical reasons and/or changing user requirements, depending on the RE strategy.

This thesis proposes a method for the consideration of energy efficiency measures within the refurbishment planning in building portfolios. To this end, the costs and time plans of maintenance and refurbishment measures, as well as measures to improve energy efficiency need to be known.

Paper 3 evaluates a state-of-practice method for maintenance and refurbishment planning and budgeting. It is the first and only such detailed evaluation known. When first published, this method was state-of-the-art and has become state-of-practice since.

The paper is followed by an addendum (section 6.1) that provides more details and a classification of the methods which were referred to in the paper. The addendum has been written from the new position taken near the end of this work. The paper is presented in its original, published form (including numbering of sections, tables, figures, and references).

The result of this paper, and of the following addendum, is that there is a sufficiently accurate method available to plan time and budget costs of MMs and RMs on the strategic level that has found acceptance in the RE market and that can be used as a basis and referenced to in this work. Additionally, in this and the following

Paper 4, no method was found to plan and budget enhancements of EE on the strategic level, i.e. without costly analysis on object level, which reconfirms the stated gap. There are other methods which require either more detailed data collection for more operational decisions or less data resulting in lower accuracy of results. But, for the given application and the needs of this thesis, there is no alternative method in sight. Through the results of the evaluation, reviews, and publishing of this paper, the method has become state-of-the-art again and so could be referenced to in Paper 4.

The method described in the Paper 3 covers parts of the process steps O1, T1, S3, and S5 in the process matrix in Figure 1.

Abstract:

The method Schroeder is accepted amongst real estate professionals in Switzerland as a near standard for condition monitoring, budgeting of maintenance and refurbishment, and strategic decision support in point of building portfolios. It is based on the devaluation curves of 12 or more building elements. Main results are the actual and the prognosticated future building condition in percentage of its reinstatement value, the residual useful service life of building elements, and the calculation of future maintenance and refurbishment costs. 25 years after its first publication, this paper analyses the assumptions made, compares the method to other methods in this field, and validates the method in several steps, based on scientific or empirical evidence. Furthermore, a desktop simulation of a well-documented portfolio was performed and compared, the answers from a questionnaire amongst users are provided, and the partially controversial conclusions discussed.

Keywords:

Strategic property management, Building portfolio, Maintenance and refurbishment budgeting, Method Schroeder, Devaluation curve

1 Introduction

In every economy and organisation, the existing building stock forms an indispensable and major asset which needs to be maintained, improved, and eventually replaced. This requires a measurable part of the gross domestic product (GDP) and therefore has to be performed in an economical manner by optimising between minimal costs and avoiding a maintenance backlog while considering aspects of sustainability. Kohler and Yang (2007) have investigated the long-term behavior of this enormous asset stock in a combination of flow- and capital-based approaches and have discussed strategies to influence it.

As a consequence of the importance of the existing building stock, budgeting of maintenance and refurbishment is a commonplace as well as challenging task for property owners and managers. In an industrial facility, the potential loss of production and the following loss of profitability justify adequate maintenance budgets based on technical considerations, even in tight economic situations. An extensive range of methods and instruments has been developed to support maintenance in industry. In real estate, it is common practice to postpone maintenance for several years to reduce costs in private organisations or to reduce public spending. Today, maintenance and refurbishment decisions for building portfolios are more based on user requirements and market considerations than on predicted durability of building elements. Consequently, portfolio managers need a strategic instrument which shows the consequences of postponed investments in a portfolio in order to justify the budgets they are demanding. Any method to forecast maintenance and refurbishment costs basically relies on the prediction of durability of single building elements. The British Standard BS 7543 (1992) made a noteworthy statement about this: “Prediction of durability is subject to many variables and cannot be an exact science”. This, combined with individual strategic decisions and other context, adds to the complexity of the task. In recent decades, several methods to overcome this complexity were proposed (see Table 3). However, there are only a limited number of scientists conducting research in this field, consequently publications and data sets are sparse (see section 4). The existing research gap is considerable in light of the size and age of the building stock.

One method which has proven successful in the property market is the method Schroeder, in form of the respective software application called Stratus (in Switzerland) or Spectus (international).Today, the method is used in 100 portfolios encompassing more than 20’000 buildings. 25 years after its publication, this paper analyses the assumptions, compares the method to other methods in this field, and validates the method in several steps based on scientific or empirical evidence.

This paper looks at the terminology in maintenance and the basic formulas in chapter 2, describes the Method Schroeder in chapter 3, and in chapter 4 validates and compares the method to other methods in this field in chapter 4.

2 Fundamentals in building maintenance

2.1 Maintenance terminology

The term maintenance has several definitions. The definition in this paper follows the new European Standard in Facility Management EN 15221-4: Taxonomy, Classification and Structures in Facility Management (2012). The standard defines a hierarchically structured set of more than 100 facility products. These products have been designed to allocate costs, to define, compare and improve quality and to enable benchmarking in the support services market. To distinguish between annual costs (expenses in the income statement) and investments (listed as an asset in the balance sheet), the standard allocates the first ones to the product 'maintenance' and the second ones to the product 'asset replacement and refurbishment'. Fig. 1 shows the relation between the devaluation curve of an asset and the relevant facility products to describe the curve and its values and costs.

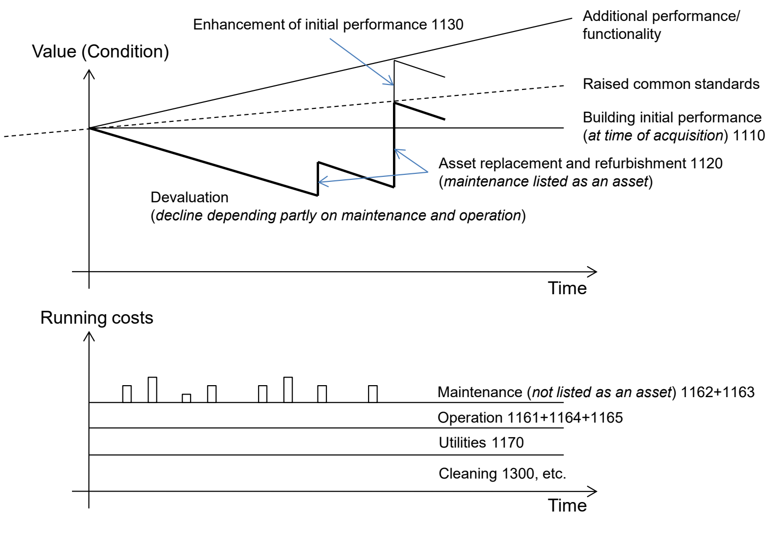


Figure 1. Relation between maintenance and refurbishment and facility products defined in EN 15221-4 (numbers in the figure 1 refer to facility products defined in the standard)

It is important to note that this standard acknowledges the fact that refurbishment not only restores the initial value of an asset but, due to better technology available, very often results in a higher standard. A good example of this regards the replacement of windows. New windows are most certainly better than old ones and at approximately the same, or even lower, costs. It should also be noted that in many organisations the line between maintenance and refurbishment is often drawn based on financial considerations and not on technical definitions, e.g. every measure above a fixed amount/threshold counts as refurbishment and is set up as an asset in the balance sheet. Unfortunately, this threshold is determined at individual levels and within a wide range. This fact adds to the complexity of comparing or benchmarking maintenance costs. Another method to distinguish between maintenance and refurbishment is the maintenance signature presented in section 4.

2.2 Basic formulas to calculate maintenance and refurbishment

Based on the devaluation model of a building and common knowledge about maintenance and property management, the following formulas are proposed (refer also to Bahr and Lennerts 2010).

Annual maintenance expenses for a building: $$Em = Et * Fs \quad (1)$$

E_m: Annual maintenance expenses for a building [% of V_a]

E_t: Expenses required from a technical point of view (e.g. 1.0% of V_a per annum) [% of V_a]

F_s: Factor for strategic decisions influencing maintenance budgets [-]

Methods to estimate annual maintenance expenses usually concentrate on the technical side because of the individual nature of strategic decisions of organisations.

Refurbishment investment for a building at time t: $$Irb = Va * (1 - Ct) * Fr * Fa \quad (2)$$

I_{rb}: Investment needed to bring a building back to its initial condition [currency]

V_a: Reinstatement value of the asset or building (also: replacement or insurance value) [currency]

C_t: Condition of building in % of V_a at time t [%]

F_r: Factor to calculate the required investment based on the total devaluation (1-C_t) to bring the building back to its initial value [-]

F_a: Factor for additional investment required to achieve added value if required [-]

3 Description of method Schroeder

In the mid-1980s Jules Schroeder, a property manager for the canton of Zurich in Switzerland, developed a simple to use method for effective and comprehensible budgeting of maintenance and refurbishment in building portfolios. The initial in-house application was later commercialised and is continuously being improved upon. However, the method itself has not changed since its first publication.

The method was based on the practical experience gained from more than 2'000 buildings, in combination with scientific research at the Swiss Federal Institute of Technology in Zurich (ETH Zurich) in Meyer-Meierling (2011, first published 1994). At the centre are the devaluation curves of building elements like structure, roof, façade, windows, building technique etc. The choice of elements has been an optimization process between minimization of the effort to collect and maintain data and the need for sufficiently detailed data to provide relevant information. Usually refurbished as a package, 12 to 20 elements were found to be optimal (see Annexe 1). The method itself would permit a higher number of elements to be used resulting in higher costs for assessment and data management. The condition of these elements is usually assessed by experts or by trained in-house staff to assure a comparable outcome.

The devaluation curves determine the value or condition of the elements in function of the time. An assessed value from the condition survey, therefore, determines a theoretical age (e.g. independent of effective age or other factors) of the element and, following the devaluation curve, the remaining service life before refurbishment is due. The curve has been given an exponential function ($C_t = 1 - t^a$) and split into two phases in order to better reflect the empirical data (formulas 3+4). The empirical functions for different elements have been validated within IP Bau (1991), a government research program, based on a detailed examination of a portfolio containing 120 buildings. The formulas for the two phases of the devaluation curves (Fig. 2) in the method Schroeder are as follows:

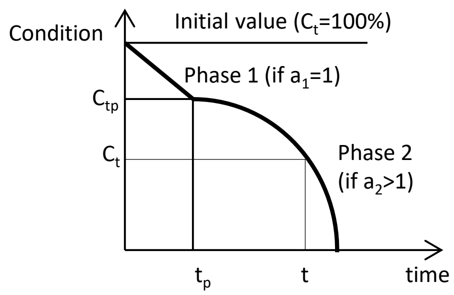


Figure 2. Exemplary model of devaluation curve of a building element with two phases as a condition-time diagram

Condition Phase 1: $Ct = 1 - tp(\frac{1}{tp})^{a1}$ (3) in Schroeder (1989)

Condition Phase 2: $Ct = Ctp - (\frac{Ctp(t-tp)}{Ctp})^{a2}$ (4) in Schroeder (1989)

t_p: Time where phase 1 ends and phase 2 begins [years]

C_{tp}: Condition C_t at time t_p where phase 1 ends and phase 2 begins [%]

a_1, a_2: Exponents determining the form of the devaluation curves in phases 1 and 2 [-]

After the condition has been surveyed on site, the remaining service life of an element or building is determined with the help of the devaluation curves. The next question is: how much does it cost to refurbish an element, or building at a given point in time, and when is it best to perform this task? Of course it would be great if it were possible to only measure the difference between the actual value C_t*V_a and the initial reinstatement value V_a to determine the investment needed for refurbishment I_r. Based on experience, the method Schroeder suggests that this is not so easy. Elements must often be replaced as a whole, not in parts, which means that premature replacement costs more than the calculated devaluation. To replace an element often costs more than its initial construction due to additional costs for e.g. scaffolding, adjustments to adjacent elements or accommodation of users during construction work. So, even at maturity, the costs may be a factor higher than the simple difference mentioned above. In order to solve the problem the method Schroeder uses a refurbishment factor F_r (5) which depends on the condition C_t of the building element for the calculation of the required investments.

Refurbishment factor: $Fr = 1 + \frac{Ct}{(1-Ctp)}$ (5) in Schroeder (1989)

F_r: Condition dependent factor to calculate the investment needed to bring a building element back to its initial value [-]

The factor F_r may depend on additional factors like type of building, ambient conditions or occupation as shown by Lavy and Shohet (2007). The software application offers possibilities for individual adjustments for each building and element. These possibilities were not part of the original method Schroeder.

Annual maintenance on the other hand is modelled as an exponential function of C_t between around 0.5% (at C_t = 100% new condition) and 2% (at C_t = 70%). At lower conditions, it is assumed that only minimal maintenance is being performed because the object is potentially due to be refurbished or demolished and replaced by a new construction.

The following Table 1 lists the required as well as optional input data that the software application Stratus / Spectus (2012) needs to calculate the listed output data. To support the assessment, external assessment services or training of in-house staff is offered by the provider.

Input Data	**Remarks / Description**
Building reinstatement value V_a	Estimated replacement, reinstatement or insurance value, the value may be corrected manually by the property manager if needed
Condition survey of 12- max. 20 elements	Standardised and self-explanatory input sheet available, requires approx. 1 hour per building
Volume (m^3) or area (m^2)	Whatever is available
Construction cost index	Taking the development of past and future construction costs into consideration
Optional: effective portion of total building costs of the elements surveyed	Manual correction of standard values for specific buildings possible if required
Optional: Type of building and level of installed building technique	Influences the choice of building elements especially in regards to building technique
Optional: effective maintenance and refurbishment works performed	Supports documentation of history of buildings and validation of factors based on experience
Optional: Data about energy consumption, earth quake safety, security, etc.	Depending on questions arising from strategic property management

Table 1. Required Input and calculated output from the instrument Stratus / Spectus based on the method Schroeder (part I)

Output data	**Remarks / Description**
For the entire portfolio	
Average condition of portfolio	The condition of the portfolio can be presented in form of a summation curve (Fig. 3) for all objects
Change of condition in function of time and performed maintenance and refurbishment	Annual devaluation (automatically calculated based on the devaluation curves) and maintenance and refurbishment need to be in a balance if the condition is to be kept at the desired level
Annual costs for maintenance and investments for refurbishment over a selectable period	Main figures to support budgeting
Buildings which need refurbishment	Depending on strategic choices, buildings below 70%, 60% or even 50% are visible at a glance in the sum curve and can be selected for detailed planning
Simulation of effects of different maintenance strategies and shifting time of refurbishment works	Simulation typically covers a period of 25 years, shorter or longer periods are possible
For a single building	
Condition of building in % of initial value at a given point in time	Strategic figure to evaluate the need for more detailed planning and to control the actual value in the accounting system at a selected point in time (e.g. in five or ten years)
Annual costs for maintenance over a selectable period/number of years	Depending on condition C_t
Investment for refurbishment in a selected year	Depending on condition C_t
Refurbishment backlog	Due costs of elements which are rated to be mature for refurbishment
Optional: Building energy certificate, assessment of earth quake safety, risk analysis, etc.	Required by law in some countries
For each separately assessed building element	
Condition of element	Based on condition survey and calculated devaluation based on individual curves for each element
Estimated due time for refurbishment of element	based on individual devaluation curves for each element
Estimated cost of refurbishment of element in due time	Based on condition of the element and its average portion of total building new value

Table 1. Required Input and calculated output from the instrument Stratus / Spectus based on the method Schroeder (part II)

Table 1 shows that only minimal input data is needed to calculate the output required for different strategic decisions. In particular, no historical data, which is often unavailable or hidden deeply in some archives, is required. As an option correction factors can be used to incorporate specific knowledge or experience. The condition of each building and therefore the whole portfolio is automatically recalculated each year based on the devaluation curves of the elements. This simulates the effective annual degradation and indicates the dynamic behaviour of the portfolio. Other functions include comparable benchmarking of the overall condition of the portfolio and the bundling of refurbishment works for different buildings in the years to come.

In Figure 3 an example of the representation of an entire portfolio in a sum curve covering all buildings is given.

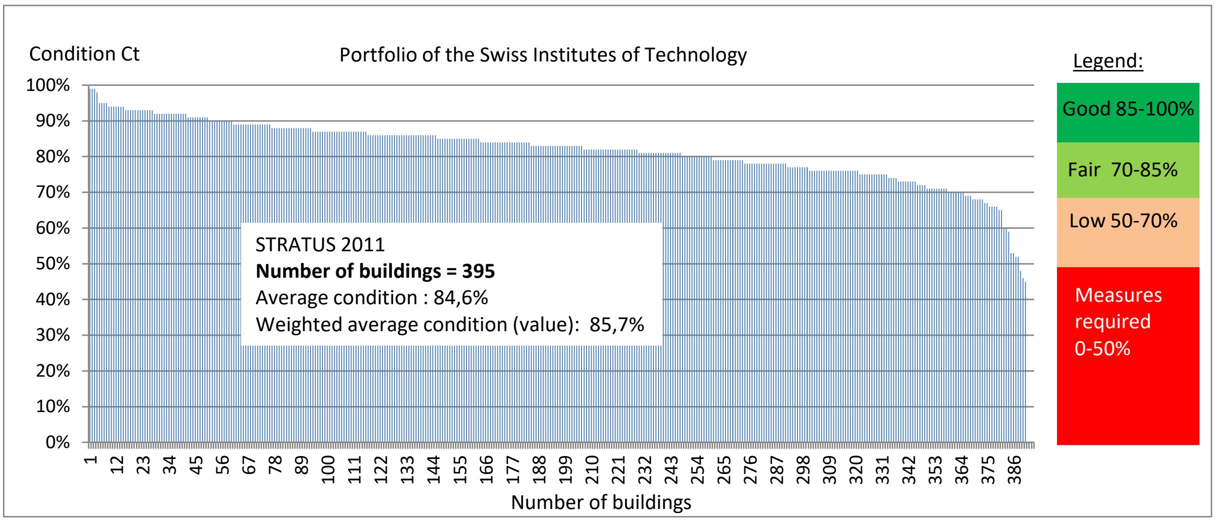


Figure 3. Typical summation curve of the condition of a portfolio – for those objects below 70% an object strategy is needed (Range of descriptions of condition is based on practical experience)

4 Validation of the method Schroeder

The validation process employed in this paper encompasses several steps, a different approach used in each. It includes state-of-the-art research, questioning the assumptions, comparison with other products, answers of users to a questionnaire to get a feedback from the market, and comparison to data from two real portfolios where effective data is available.

4.1 State of the art research

In general, more research is conducted in the field of industrial maintenance than that of building maintenance, because of the former’s immediate effect on productivity and profitability. Building maintenance is seen as less critical and maintenance practices are usually lagging behind industry (Christen et al. 2011). The method Schroeder is specifically adapted to the longevity of building elements and therefore less suitable to the short life cycles of production machinery.

Zavadskas et al. (2004) compared the average market price of refurbished dwellings and the cost of newly-built dwellings in Vilnius (Lithuania). They found that the market price and, consequently the refurbishment strategy, depend on the area where an object is located in order not to exceed the potential market value.

Bjørberg (2008) conducted an assessment of 10'000, or 40% of all public buildings in Norway, in order to identify maintenance strategies and recommend a budget cost level for long term planned maintenance. In each building, 16 elements were graded into four levels to assess the condition. The grading is quite similar to that used in the method Schroeder. He estimates that a portfolio needs to encompass 40-50 different buildings with around 50'000 m^2 to enable a representative estimate of the annual budget for maintenance and refurbishment. This would have to be debated in the light of the findings presented in this paper.

Kumar et al. (2010) identified three principal methods, the probabilistic methods, the engineering methods, and the deterministic methods in order to predict the service life of a building system and their components. Due to the complexity of the other methods, they proposed a deterministic method called capital refurbishment model, which has similarities to the method Schroeder. It uses only six building elements with fixed service life expectancy but spreads the refurbishment costs over a period of 5 years to accommodate variations.

Bahr and Lennerts (2010) compared different maintenance and refurbishment budgeting methods with their findings from a detailed analysis of the costs in 17 buildings over several decades. As part of their findings, they recommend the division between maintenance and refurbishment as found in the method Schroeder and as defined in EN 15221-4. The method Schroeder is represented as propagating a fixed total budget of 1.1% of the building value and this figure is then compared to the combined, fluctuating costs for maintenance and refurbishment from the detailed analysis. As shown in this paper, the method Schroeder is much more differentiated and accurate.

Based on the results of the analysis of the 17 buildings, Bahr and Lennerts developed a new method called PABI (practical adaptive budgeting of maintenance measures) with a similar formula as to the one stated above (1). The method combines fixed percentages for maintenance (1.2%, regular measures) and refurbishment (4.4%, one-off measures) with correction factors relating to age, wear and tear, materials, etc. The result is a fast estimate of average total annual budgets, but only vague information about the future distribution of the costs in time - each differentiated period covers one decade - or the condition and the need for refurbishment of building elements is provided.

4.2 Analysis and Validation of Assumptions in the method Schroeder

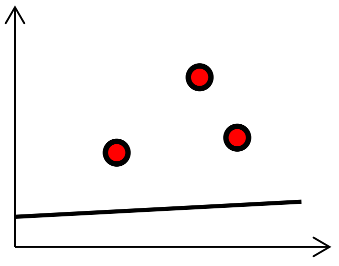
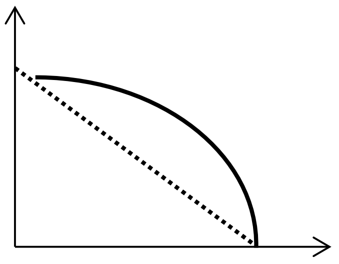
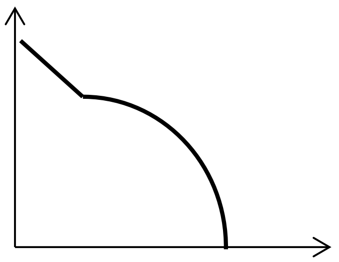
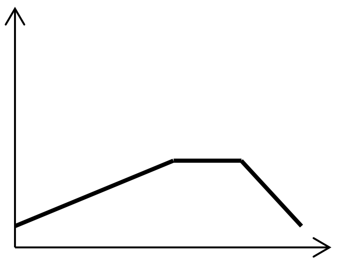
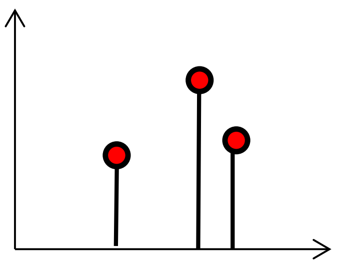
Assumption	Graphic	Empirical evidence	Scientific evidence
1: Division into maintenance (line) and refurbishment (dots) [costs/time]		The difference between annual expenses and investments with project character are also visible in the representation in the accounting system of many organisations	Bahr and Lennerts (2010) stated in their work that this difference must be obeyed and created the method PABI which factors this differentiation in
2: Non-linear devaluation of building elements [condition/time]		The first model using linear curves did not fit the effective expenses in the portfolio the method was originally designed for.	IP Bau (1991) validated the shape of the curves for the different elements based on a detailed survey of 120 buildings.
3: Devaluation divided into two steps [condition/time]		Machines often need some time before they reach stable running conditions. Cracks in buildings usually develop shortly after construction.	IP Bau (1991) validated the shape of the curves. Newer evidence found in Caccavelli (2003) and Meyer-Meierling (2011)
4: Variable condition based annual maintenance expenses [costs/time]		New buildings need less caretaking than used ones – in older buildings, often less money is spent for economic reasons.	Two exemplary portfolios show different results. Further research is needed to verify the assumed function.
5: Condition / service-life based time for replacement and refurbishment investments [costs/time]		The condition determines the time for replacement and refurbishment of building elements based on their predicted durability or service-life.	The concept of statistical service-life of elements is widely accepted, e.g. in ISO 15686 (2008).

Table 2. Validation of assumptions the method Schroeder is based upon [units of diagrams] (part I)

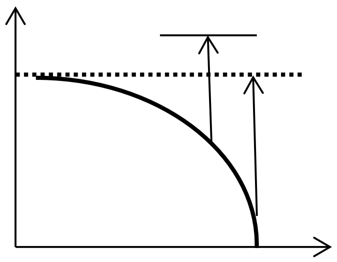
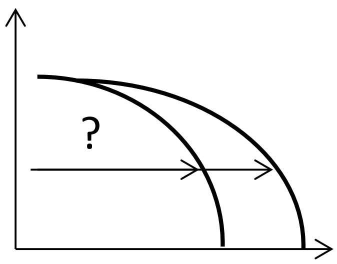
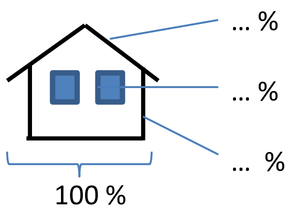
Assumption	Graphic	Empirical evidence	Scientific evidence
6: The condition of an element is an indicator of the costs for refurbishment or replacement (investment to restore the initial 100% condition) [condition/time]		An empirical factor (F_r) as a function of the condition is applied to calculate effects such as whole elements being replaced and additional costs such as scaffolding. F_r can be adjusted manually depending on occupancy etc. if required.	Lavy and Shohet (2007) found dependencies up to 20% on type of configuration and hence introduced the facility coefficient. Bahr and Lennerts (2010) also found building related factors (e.g. complexity of façade).
7: Analysis of actual condition of an element is sufficient, the effective age of an element does not matter (condition/time)		To know age and condition could improve the forecast in the long run. However, the effective age is often not available.	A budgeting period usually covers less than 5 years. The additional effort to analyse the age is therefore not required.
8: Average portion of elements in percentage of total costs is a function of building type [% of costs]		An individual assessment of construction costs for each building requires a large effort.	Graf (2008) has analysed costs of 228 buildings to verify the standard values for different building types.
9: Maintenance strategy influences maintenance intervals	n/a	Empirical factor to take individual strategic decisions into account	No scientific evidence to verify this factor was found.

Table 2. Validation of assumptions the method Schroeder is based upon [units of diagrams] (part II)

Of the nine assumptions in Table 2, the five assumptions including numbers 1 to 3, 5 and 8, have been validated whereas the other four assumptions are based on empirical evidence. These are likely sufficient for strategic budgeting but more research would be needed for validation. Additional investments to achieve added value (factor F_a) are not considered in this method.

4.3 Comparison with other methods for maintenance budgeting

Mickaityte et al. (2008) describe in the context of refurbishment and sustainability different methods for maintenance planning. However, many of these are not broadly applied nor used in the market today. Table 3 provides and comments an incomprehensive selection of instruments covering an array of different such methods.

Method/Instrument	**Focus**	**Limitations**	**Application**
PABI (Bahr and Lennerts (2010))	Portfolio level	Empirical evidence of correction factors	Budgeting without on-site assessment
Factor method ISO 15686-2000 (2008)	Building components of a single building or building type	Factors yet to be defined (based on experience)	Budgeting without on-site assessment
Stratus / Spectus (2012) (based on method Schroeder)	Portfolio management, maintenance and refurbishment, energy and others	Not detailed enough for refurbishment design	Strategic portfolio management incl. adjacent functions like energy certificate
EPIQR (based on EU research project and IP Bau) (2012) www.epiqr.de	Single building, includes portfolio functions and energy flow chart	Requires measuring of area and age of about 50 elements	Analytical calculation of maintenance budgets, includes sustainability criteria
TOBUS (based on EPIQR) Caccavelli (2002)	Single building, includes energy flow chart	Commercial buildings, requires measuring of area and quality of elements	Analytical calculation of maintenance budgets
INVESTIMMO (based on EPIQR) Caccavelli (2004)	Portfolio management, investment decision support	Planning 12 years ahead	Portfolio analysis using different criteria
DUEGA (based on IP Bau (1991+1995)) Gredig (1997)		not supported anymore	n/a
SUREURO (2005) www.sureuro.com (website not updated since 2005)	Includes aspects of sustainability and user participation	Residential buildings	n/a
Building diagnosis idi-al (2012) www.bakaberlin.de	Single building of any type	Certified assessors necessary	Detailed analysis resulting in a refurbishment design proposal with alternatives
Maintenance management systems MMS (different products available on the market, e.g. Maximo, visualFM, etc.)	Systems and elements with fixed periodical maintenance intervals based on maintenance specifications or technical life time of elements	Requires extensive data management; not suitable for building elements due to the large amount of equal elements (e.g. doors, walls) and little periodical maintenance activity performed on them.	Mainly used for important or costly technical equipment requiring regular maintenance intervals

Table 3. Commented list of examples of maintenance budgeting and/or planning methods and instruments (part I)

Method/Instrument	Focus	Limitations	Application
Mathematical methods for industrial maintenance e.g. in Percy and Kobbacy (2000)	Preventive maintenance in industrial production facilities	Less suitable for longer maintenance intervals in buildings, complexity of models	Mainly used for technical equipment requiring regular maintenance intervals

Table 3. Commented list of examples of maintenance budgeting and/or planning methods and instruments (part II)

The list of instruments in Table 3 highlights the differences in their focus and application. To put it into perspective, by looking at the focus of specific instruments and their costs per object, a qualitative rating was performed (Figure 4).

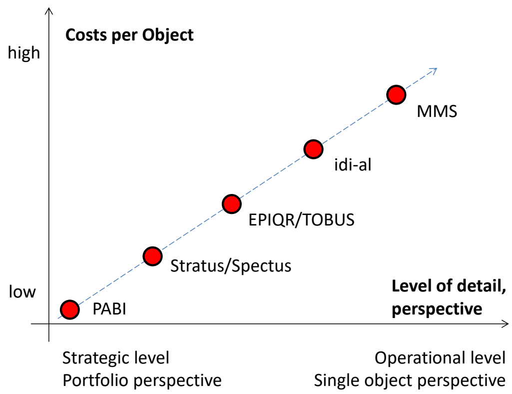


Figure 4. Qualitative rating of maintenance and refurbishment planning and budgeting instruments

The rating gives an indication of the application and the required effort of the instruments. It highlights a possible problem in some of them. The deeper they go into detail (e.g. number of elements) the higher the costs per object are. The relation was assumed to be linear. Eventually, the instruments reach the point where they become too expensive for strategic portfolio considerations. For the design of a refurbishment project, organisations prefer to use standard construction and project management tools.

4.4 Questionnaire

65 portfolio managers who all use Stratus/Spectus were asked for permission to use their data for scientific research. A total of 24 gave a positive response and 18 (28%) additionally answered a questionnaire (Annexe 3) on their usage and opinion of the software Stratus / Spectus. 94 % of the 18 respondents manage all, or the

large majority, of their buildings with the system (question 1). 78% regularly update the building condition data following construction or refurbishment projects (question 2). 39% differentiate between regular maintenance expenses and investments in refurbishment by applying a fixed threshold value. This value varies considerably between 5’000 and 300’000 CHF. For almost 50% this differentiation does not seem required (question 3). 50% have checked the fit of the real expenses with the prognosis and agree partly or fully with the results of the software. As a part of this group, 17% have developed a factor of their own to correct the prognosis for their budgeting purposes. There is no clear tendency towards an overly high or an overly low prognosis visible (question 4). 34% have set themselves a goal for the overall condition of their portfolio. These goals are all between 75% and 85% for C_t (question 5). 44% revalidate their portfolio about every five years (question 6). In short summary, the system is neither used in a uniform way nor in the same depths by the respondents. The answers to questions 3 and 4 especially raise some questions and highlight the need for further research (see chapter 5).

4.5 Comparison with effective data of 60 buildings – maintenance signature

The Swiss Federal Institute of Technology in Lausanne (école polytechnique fédéral de Lausanne EPFL) has introduced a comprehensive scheme of building cost monitoring and controlling called INDIANA (INDIcateurs ANAlytiques) wherein figures for maintenance and refurbishment are collected and presented separately. The figures are published annually, the latest in Chatton et al. (2011).

The level of detail enables the drawing of the maintenance and refurbishment signatures of the 60 buildings of the EPFL. The concept of the signatures is derived from the known energy signatures e.g. used to calculate energy savings in Zmeureanu (1990). The maintenance and refurbishment signature offers possibly a new way to analyse maintenance costs. The aim is to extract certain patterns from measured data like the dependency of maintenance expenses on condition C_t, and to distinguish between maintenance and refurbishment costs independently from individual accounting practices.

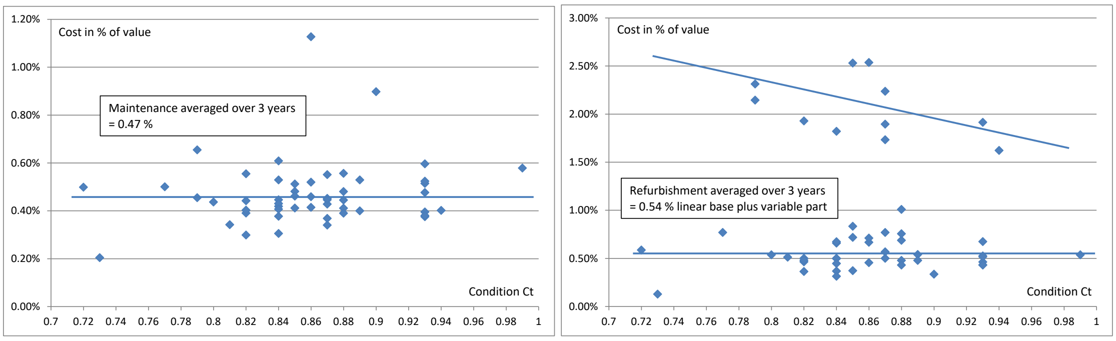


Figure 5. The maintenance and the refurbishment signatures of the 60 buildings of the EPFL showing average annual costs in percentage of the building reinstatement values V_a over the 3 years period from 2008 to 2010 in function of the building condition C_t according to Stratus (Note: the buildings form part of the portfolio shown in figure 3)

The effective expenses in the EPFL portfolio as shown in Figure 5 have been compared with the results from Stratus / Spectus. Adding maintenance and the constant base of refurbishment (averaged over 3 years) together, a figure of around 1.0% of the reinstatement value for regular maintenance is achieved. This is very close to the recommendation of Stratus for this portfolio. Against the assumptions in the instrument, the effective figures for these 60 buildings show a constant level of maintenance, irrespective of the condition C_t. A possible explanation for this could be the high level of installed building technique that requires a constant level of maintenance activities and the planned maintenance schemes (the level of installed building technique is already a criteria in Stratus to characterize a given building influencing the cost split of building elements). The investments in refurbishment during this three year period were found not to be representative in the long-term due to a prevailing program for new construction.

4.6 Comparison with effective data of 17 buildings

The study of Bahr and Lennerts (2010) is the only one known that provides effective and comparable cost data in this field over several decades. Therefore, a desktop simulation of these 17 buildings (see Annexe 2) has been performed on Stratus / Spectus.

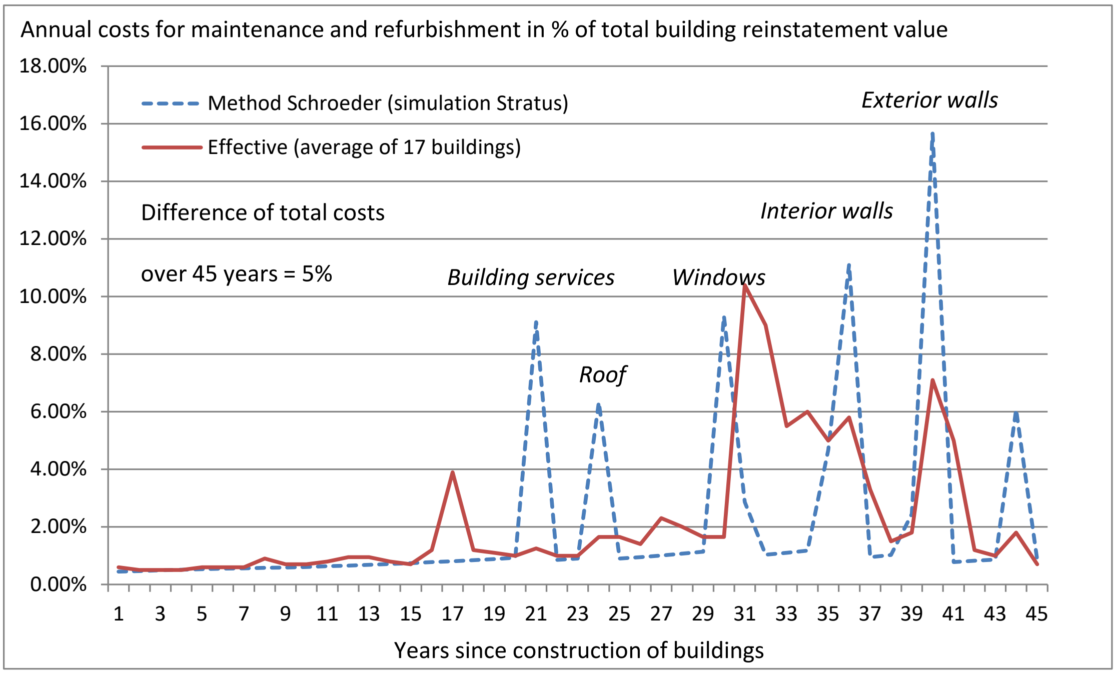


Figure 6. Comparison of the maintenance and refurbishment costs of 17 buildings analysed in detail by Bahr and Lennerts with a desktop simulation using Stratus / Spectus over a period of 45 years (in italic: indication of elements causing the distinct peaks in the theoretical simulation)

The comparison of the results from the detailed analysis of the maintenance and refurbishment costs of the 17 buildings analysed by Bahr and Lennerts with the results from the desktop simulation of this portfolio is shown in Figure 6. The simulation was performed by using the default values in the software tool for 17 virtual buildings of the same type, size and age (all construction dates set at t=0 as in Bahr und Lennerts). It shows a nearly identical sum of total costs over 45 years. The total average costs are around 2.2% per annum with a total difference of only 5% over this lengthy period. Additionally, both curves show some equal trends in the distribution of the costs over this long-term period. Maintenance rises slowly during the first 30 years in both curves. The first replacement of technical building installations (e.g. heating system, sanitary equipment) happened earlier in the effective portfolio than estimated in Stratus / Spectus. This could be due to the construction dates between 1950 and 1980 and the following rapid changes in standards, technology and requirements. Refurbishment works in the effective portfolio are mainly spread over the period of about 30-35 years while the desktop simulation shows distinct peaks for the different building elements according to their assumed durability. The data of the 17 buildings in detail shows more dispersed and partly even larger peaks. The peaks in the calculation of real buildings may differ from the desktop simulation due to the corrections resulting from the on-site assessment of the actual conditions of elements.

In summary, it has been possible to simulate the total maintenance and refurbishment costs of a real portfolio of 17 well researched buildings with astonishingly high accuracy in regards to the total amount of investments while the distribution of major refurbishments works over 45 years shows some differences. In practice, these may be influenced by strategic decisions and amended through periodic on-site assessments. The differences are also put into perspective by the fact that maintenance is not usually planned more than 5 years ahead of time.

5 Conclusions

Maintenance and refurbishment budgeting is not only a technical question but also contains strategic aspects like financial considerations and the need to consider changes in user requirements, market condition and the legal framework. As such, any method to calculate and justify these budgets must be transparent and credible as well as open for strategic considerations.

The method Schroeder implemented in the software Stratus / Spectus has proven itself as a cost efficient, easy-to-use and credible method to support strategic maintenance and refurbishment decisions in property management and to justify the necessary budgets. One limitation is that it is not intended to calculate detailed construction costs of a refurbishment project.

Some of its advantages over most other methods in this field are:

- It is applicable for all types of buildings and can therefore be used for heterogenous/mixed portfolios.
- It is cost efficient to operate as it requires very little input data that is easy to maintain because annual deterioration is calculated automatically.
- It enables a dynamic simulation of the effects of maintenance expenses and refurbishment investments on the condition of a single building or a whole portfolio in the long-term.

Nine assumptions behind the method Schroeder have been evaluated. Five assumptions have been verified. The remaining four are based on empirical evidence and likely sufficient for strategic budgeting, but more research would be needed for validation. The method has also been rated against other methods in this field and out of this rating a possible explanation for its success was extracted. A direct comparison of these methods would require more criteria and is only partially possible because many of those methods have a different focus. The method was originally designed to accurately simulate a given large portfolio. The comparison of simulated budgets with effective cost data of two different portfolios where data was available has found a close match too. This finding is valid for these two portfolios only. The questionnaire amongst users has shown that the standard values used in the application are not equally valid for all portfolios. Different cost calculations (e.g. threshold for maintenance) and characteristics of buildings and portfolios may be the reasons for this. Some of the factors influencing the costs are described in Bahr and Lennerts (2010) or Lavy and Shohet (2007). Caccavelli (2004) mentions 34 cost influencing factors of which the method Schroeder considers only a few. This does not seem to keep portfolio managers from using the method possibly due to other benefits like condition monitoring.

5.1 Further research

In the field of building maintenance and refurbishment there is only little reliable and comparable long-term data available to confirm any such budgeting method so more research is still needed. There is no general agreement in literature about the proper level of maintenance expenses and refurbishment investments, e.g. expressed as a percentage of the reinstatement value. The new definitions in the EN 15221-4 or the proposed maintenance and refurbishment signatures may help to standardise cost data collection in order to get a better understanding of the long-term behaviour of the system 'building portfolio'. For example, the assumption of condition dependent maintenance expenses could have only been verified in one of the two real portfolios where effective data was available. The other one shows a linear distribution. These behaviours are yet to be explained. Another question is if all major cost influencing factors have been considered in the method or if more variables are needed to cover portfolios with specific characteristics.

How the method and its assumptions and parameters can be adapted to different property markets other than those in central Europe also requires further research. The focus of such research should be on the influence of different climatic conditions or different construction standards on the service-life of building elements to adapt the devaluation curves. However, there is no obvious reason why the method itself could not be applied universally.

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Annex 1

Table of building elements used in the practical software application of the method Schroeder

(Stratus/Spectus)

No.	**Element**	**Specification**	**Expected service life in years**	**Portion of total building costs in %** [1)]
1	Load-bearing structure	light weight - massive	75-120	35
2	Pitched roof	type of roof covering	40-50	4
4	Flat roof	type of roof covering	25-30	4
5	Exterior walls, Facade	type of material	40-55	8
6	Windows	type of material, shading	30-40	8
7	Heat production	primary energy	15-25	1
8	Heat distribution	type of radiators	15-25	2
9	Sanitary facilities	cold, warm, wastewater	15-25	6
10	Electrical system	lightning and machines	15-25	6
11	Other building services	e.g. lifts	15-25	3
12	Interior walls and fittings	-	20-30	23
13	Other interior fittings	-	-	-
14-20	Disponible	-	-	-

[1)] Proposed standard values, depending on type of building and specification

Annex 2

Table of the 17 buildings simulated in Stratus

Scope of work: Comparison of methods Stratus / Bahr					
Data Bahr: 6 office buildings, 11 school buildings					
Building	*Type of use*	*GFA (m^2)*	*Year of construction*	*Technoglogy level (%)*	*Envelope / cubature (m^2/m^3)*
				T	E
AG FDS	Office	1'913	1952	20	0.29
AG PF	Office	4'424	1958	26	0.45
AKS PF	School	22'835	1950	30	0.25
GBS KA	School	11'950	1984	38	0.41
GS BA	School	797	1960	11	0.42
GS BB	School	14'523	1980	38	0.45
GS BŰ	School	829	1958	18	0.45
GS NE	School	1'244	1958	7	0.49
HE SCW	School	15'402	1965	27	0.34
HSL SBW	School	17'802	1963	24	0.40
LG FR	Office	8'146	1965	23	0.19
LG MA	Office	16'859	1970	23	0.16
LG OF	Office	5'823	1956	23	0.28
MORE HN	School	9'960	1979	24	0.41
RA BR	Office	6'153	1979	26	0.26
RWG BB	School	7'897	1980	27	0.49
STLA ET	School	16'595	1967	28	0.26
GFA: Gross Floor Area			min =	7	0.16
			max =	38	0.49
Source:	Bahr (2010)		average =	22.5	0.325

Annex 3

Questionnaire added to a letter asking portfolio managers for permission to use their Stratus data for scientific research (respondents: 27 out of 64; positive: 24; questionnaires: 18)

1. Ist das gesamte Portfolio in Stratus erfasst oder gibt es eine Erfassungsgrenze und wo liegt diese?
E: Do you manage the complete portfolio with Stratus or is there a limit/threshold and what would this limit be?
Answers:

- All buildings	10	(56%)
- Nearly all buildings	7	(39%)
- Majority of buildings	1	(6%)

2. Welche baulichen Massnahmen werden in Ihrem Stratus regelmässig nachgetragen?
E: Which construction measures are being updated in Stratus on a regular basis?
Answers:

- None yet, but planned	1	(6%)
-All projects	7	(39%)
- All large projects	4	(22%)
- Threshold dependent	2	(11%); (values from 3’000 to 50’000 CHF)
- Condition dependent	1	(6%)
- None 3 (17%)		

3. Wie werden laufende Aufwendungen (Instandhaltung) und aktivierbare Investitionen (Instandsetzung) unterschieden (z.B. durch einem bestimmten Betrag)?
E: How are regular maintenance expenses and investments in refurbishment separated (e.g. based on certain amount of the bill)?
Answers:

- Based on a threshold	7	(39%); (values from 5’000 to 100’000 CHF)
- Different budgets for each	2	(11%)
- No differentiation made	2	(11%)
- No suitable answer	5	(28%)
- No answer	2	(11%)

4. Stimmen die im Stratus prognostizierten Werte mit Ihren Ausgaben und Investitionen überein?
E: Do the prognosticated values for maintenance and refurbishment in Stratus correspond with the actual costs?
Answers:

- Yes	1	(6%)
- Partly yes	5	(28%)
- Applying a factor	3	(17%) *)
- No 5	(28%)	
- Don't know	3	(17%)
- No suitable answer	1	(6%)

*) Factors mentioned are: 0.8 and 1.25 for refurbishment, 1.5 for maintenance;
no correlation with answers to question 3 (threshold) was found

5. Haben Sie ein Ziel für einen minimalen oder einen anzustrebenden Zustandswert des gesamten Portfolios oder für einzelne Gebäude oder Gebäudegruppen definiert?
E: Did you set goals for the condition to be achieved, either for the whole portfolio or for a group of buildings or individual buildings?
Answers:

- Yes, numerical	5	(28%)
- Yes, qualitative	1	(6%);
- Not yet	2	(11%)
- No 9	(50%)	
- No suitable answer	1	(6%)

6. Wie oft werden die Gebäude neu bewertet? Haben Sie dabei systematische Abweichungen zu den Prognosen in Stratus festgestellt?
E: How often do you reassess the value of your buildings? Did you find systematic differences between the estimated values and the calculated values in Stratus?
Answers:

- Every ca. 10 years	1	(6%)
- Every ca. 5 years	8	(44%)
- Every ca. 2 years	4	(22%)
- No 3	(17%)	
- No answer	2	(11%)

7. Weitere Hinweise
E: Further comments?
Answers: 3 diverse comments e.g. inviting the authors to a personal discussion

6.1 Addendum Paper 3

This Paper 3 on the maintenance and refurbishment planning and budgeting method Schroeder was written approximately in the middle of the process of writing this thesis. In this section, some complementary information and a classification of the methods is provided as well answers to some questions which arose from the new position taken at the end of this work.

6.1.1 Method Schroeder – state-of-practice or state-of-the-art?

In Switzerland, the method Schroeder is state-of-practice for strategic planning and budgeting of MMs and RMs. Although the market is dominated by one product, there are other products promoting basically the same method. In Germany, the product EPIQR has found wider acceptance. It shows many similarities and shares partly the same roots. A significant difference between those two is the number of elements used (12-15 in Schroeder with 4 condition states each vs. 50 with up to 6 types of each element and 4 codes specifying the condition = up to 1200 choices in EPIQR, refer to section 2.3). Apart from a similar application in Norway, there are no other reports of the widespread use of such a method known.

Common maintenance management systems MMS (refer to Paper 3, as stand-alone application or included in CAFM systems) use fixed (short-term) periodical maintenance intervals (periodic maintenance tactic) based e.g. on maintenance specifications of mainly technical equipment (greasing of motors, changing of filters, etc.) instead of (long-term) condition deterioration curves (predictive maintenance tactic using mathematical algorithms). They do not calculate costs based on the value of assets. And, they do not calculate the overall condition of a system (building, portfolio) based on the condition of its elements.

The method Schroeder combines a standardised condition assessment (on-site audit of 12-15 building elements requiring approx. 1 hour per building) with an automated condition prognostication and time plan generation for the execution of measures over decades resulting in estimated maintenance and refurbishment costs for each year for budgeting purposes.

There are some reasons why the method Schroeder has found wide acceptance in the RE market and why practice has never gone beyond. These are listed in Table 10.

Table 10 *Main advantages of the method Schroeder*

Reason	**Explanation**
Low initial cost	According to the classification in section 5 and referring to Figure 5, the method uses the tactic of predictive maintenance. In its specific approach, uncertainty in service life prediction is narrowed considerably by one initial on-site inspection at low cost. However, detailed inspections before design of measures cannot be avoided.
Minimal data necessary	Apart from the initial on-site inspection, there is only the value of each building (e.g. insurance or reconstruction value) and an approximate figure for the surface area or the volume necessary. Both information is usually available and no handling of plans or detailed measuring is required.
Adequate accuracy	The evaluation with data of a real portfolio has shown a high accuracy of the prediction of service life of elements and a moderate accuracy of the prediction of cost and time of MMs and RMs. For strategic long-term planning, a moderate accuracy is usually sufficient.
Specific suitability	The method supports strategic decision making on a portfolio level at low cost and is strikingly easy-to-use. Everyone can understand exactly what is happening and start to create scenarios. It can be assumed that the resulting low cost/benefit-ratio is the main factor for its success.

6.1.2 Comparison with other methods

The Table 3 in Paper 3 shows limitations and possible applications of the method Schroeder and related methods found in literature. The table is complemented with the following Table 11 showing results of the methods and references to the supported process steps in the process matrix in Figure 1.

Table 11 *Methods presented In Paper 3 with references to process steps*

Method/Instrument	Focus	Results	Process steps
PABI (Bahr and Lennerts (2010))	Portfolio level; Budgeting without on-site assessment	Average annual budgets, no time plan	S3 und S5
Factor method ISO 15686-2000 (2008)	Building elements of a specific building	Service life calculation of single elements	O1
Method Schroeder (Stratus / Spectus (2012))	Portfolio level; Budgeting with on-site assessment	Annual budgets and time plan for MMs and RMs; Condition monitoring	O1, T1, S3, and S5
EPIQR (based on EU research project and IP Bau) (2012) www.epiqr.de	Single buildings; With on-site assessment (50 elements each); Includes portfolio functions and energy flow chart	Annual budgets and time plan for RMs; Condition monitoring of portfolio including sustainability criteria	O1, T1, S3, and S5 Similar in functionality to method Schroeder
TOBUS (based on EPIQR) Caccavelli (2002)	Module for commercial buildings	Now included in EPIQR	O1, T1, S3, and S5
INVESTIMMO (based on EPIQR) Caccavelli (2004)	Investment decisions (RMs or new constr.?)	Now included in EPIQR	O1, T1, S3, and S5
DUEGA Gredig (1997)	n/a	not supported anymore	n/a
SUREURO (2005) www.sureuro.com	n/a	not supported anymore	n/a
Building diagnosis idi-al (2012) www.bakaberlin.de	Single building of any type; design preparation with on-site assessment	Detailed analysis of one object including design proposal of RMs	O1, T2, and T3 (ev. T4)
Maintenance management systems MMS (different products available)	Systems with (technical) elements requiring periodic measures	Work program of MMs and RMS with estimated working time and costs of material	T2 and O2 (M&O)

The list of methods in Table 11 is not very diverse. If annual budgets and an indication of affected elements is required, the method Schroeder and its relative EPIQR are the only applicable ones on the strategic level. Both are based on average deterioration curves, which are approximated to the effective condition by an on-site inspection for more accurate prediction. Condition values for single elements are aggregated to a value that represents the whole building. Values for buildings are aggregated to represent the portfolio. From the results in Paper 3, it can be assumed that these two methods offer a good cost-benefit-ratio to portfolio managers.

The evaluation in Paper 3 also suggests, that there is room for improvement of such a strategic long-term planning and budgeting method due to the absence of enhancement measures. Some of the assumptions used in the method Schroeder, e.g. variable annual maintenance expenses based on condition (refer to Table 2 in Paper 3), could not have been validated and need further research.

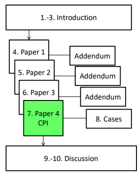
The defined split of costs between initial investment, maintenance, and refurbishment in the method Schroeder supports the goals of this thesis.

6.1.3 Conclusion

In RE practice where a large number of materially different and partly interrelated elements exists, published recommendations for service life times are not reliable and probably will never be without an enormous effort due to changing requirements and the large number of influencing factors and uncertainties, which need to be quantified. In this situation, methods, which look at a limited number of representative elements and which combine average service life times with on-site inspections resulting in approximated and sufficiently accurate predictions for strategic purposes with minimal effort, have been developed and found wide acceptance.

The method Schroeder was the first such method published in a journal. From the results of the evaluation in Paper 3, it can be assumed that it offers a good cost-benefit-ratio to portfolio managers. This is mainly due to its optimal relation between minimal effort for data gathering and application and - for strategic purposes - sufficiently detailed and accurate results. New methods that are fundamentally different than the method Schroeder and used for strategic planning have not been observed. Initially, it has been chosen for this thesis due to its widespread use in Switzerland and consequently the availability of data and due to an almost complete lack of actual research and publications about other methods for strategic planning and budgeting, which could be referenced.

A possibility for improvement of the method is seen in the fact that it does not support planning and budgeting of EMs in general and specifically of EEMs. This will be addressed in the following Paper 4. Newer research in service life times may help to improve the accuracy of the method but will not alter the method itself.



7 Paper 4 [P4]: On the usefulness of a Cost-Performance-Indicator curve at the strategic level for consideration of energy efficiency measures for building portfolios

The paper was accepted and published by the international journal Energy & Buildings in May 2016, (Impact Factor (2014): 2.884; 5-Year Impact Factor: 3.617)

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Connection to the title of the thesis

Following the definition of the RE strategy, including the maintenance strategy, planning methods are needed to determine the right time to execute measures based on the results of a portfolio analysis. Maintenance, refurbishment, and enhancement of EE are often combined when executed on existing buildings. Rarely, are buildings refurbished due to low energy efficiency only. Usually, EEMs are executed at the same time as RMs, which are initiated for technical reasons and/or changing user requirements, depending on the RE strategy.

This thesis proposes a new method for the consideration of energy efficiency measures within the refurbishment planning in building portfolios. To this end, the costs and time plans of maintenance and refurbishment measures, as well as measures to improve energy efficiency need to be known.

Paper 4 presents the cost performance indicator (CPI) method for considering additional EEMs when planning and budgeting MMs and RMs. The method is designed to complement existing planning methods and forms the central part of this thesis. The respective CPI curve is based on the law of increasing relative costs.

The paper is complemented by two cases based on real data showing the application of the CPI method in section 8. The section has been written from the new position taken near the end of this work. The paper is presented in its original, published form (including numbering of sections, tables, figures, and references).

The paper 4 indicates that the CPI is a suitable method to support consideration of energy efficiency measures in the process step S3 in the process matrix in Figure 1.

Abstract

There is an increasing desire by managers to reduce the amount of energy consumed by the buildings in their portfolio. Energy efficiency measures on existing buildings, however, are often economically feasible only if executed at the same time as the execution of necessary maintenance and refurbishment measures. At the strategic level it would be useful to be able to better plan the costs and benefits of energy efficiency measures so that decisions could be made to execute them when the opportunity arises.

In this paper, a Cost-Performance-Indicator (CPI) curve and the respective CPI method are proposed to indicate additional costs and benefits of energy efficiency measures at a strategic level, and evidence is given that corroborates the hypothesis that energy efficiency measures follow the law of increasing relative costs. The usefulness of the CPI curve is demonstrated through two case studies. An example is provided and the potential is discussed for using this curve for the planning and budgeting of refurbishment and energy efficiency measures, and as a tool to explain the relation between costs and benefits of measures enhancing building energy efficiency, including the production of renewable energy, to investors.

Keywords:

Strategic building portfolio management; sustainable construction; budgeting; refurbishment; energy efficiency measures; law of increasing relative costs; renewable energy; Cost-Performance-Indicator CPI

1 Introduction

As the existing building stock accounts for up to 40% of the total world energy consumption (World Business Council for Sustainable Development WBCSD [1]), and a large share of this energy is being produced from non-renewable fossil fuels, the existing building stock offers the single largest potential for energy conservation, and consequently reduction of CO_2 emissions. Example efforts to improve the technical-economic options of buildings owners are the development of passive (using less than 15 kWh/m².a), zero emission and plus energy buildings. An example effort to ensure that countries improve the energy efficiency of their buildings is the European Energy Performance of Buildings Directive (EPBD [2]), which requires in its article 9 that from 2020 all new buildings be nearly all zero-energy ones. A new study also shows considerable economic benefits of energy efficient building refurbishment (Ecofys [3]).

Refurbishment measures (RMs) and energy efficiency measures (EEMs), of which there are two types, energy conservation measures (ECMs) and energy production measures (EPMs), are closely linked and intertwined, yet they are often planned and treated separately. For example, painting an exterior wall of a building as a RM and adding insulation to that wall as an ECM both need scaffolding. If executed simultaneously synergies can be achieved resulting in lower combined costs. It follows that, in this case, since the scaffolding would already be available for the RM, that the additional cost of the ECM would be less than if it was executed alone. As the benefit of the ECM would remain the same, this reduction in cost would increase its net benefit, which would increase the chances that a building owner would execute it. In order to investigate the viability of executing EEMs at the same time as RMs, it is necessary to understand the costs of the RMs that would be incurred with or without the execution of the EEMs [4], which from a focus on the EEM are sometimes referred to as "anyway costs"[10] and "additional costs", respectively. In addition to ECMs, there are also measures that result in the production of energy from renewable sources. These EPMs are to be considered simultaneously with ECMs when determining how to modify the buildings within a building portfolio.

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[10] Defined as "Set of actions, products and services necessary to guarantee the regular, safe and legal functions and aesthetics of an existing building" in IEA Annex 56 [5]

The use of the proposed cost-performance indicator or CPI curve will help decision makers take into consideration the costs and benefits of RMs and EEMs, correctly at the strategic level, i.e. without the double counting of costs for both measures if they are executed together. Through its use, there will be an increased number of EEMs planned and executed, due to the increase in knowledge with respect to the costs and effectiveness of EEMs and, therefore, change in the actions of owners [6, 7, 8, 9]. It is based on the estimation of the additional costs of EEMs and their impact on performance.

The remainder of this paper is divided into seven sections. As there is a great variation in the terminology in this field, in section 2 the definitions used in the paper are explained. Section 3 identifies deficiencies of existing methods and the need for a new instrument. Section 4 contains the development and potential application of the CPI curve, which is illustrated with the data presented in the two case studies. Section 5 presents a planning process without and with the CPI method and contains an example of the usefulness of the CPI curve. Section 6 contains a discussion of the method and of the significance of the shape of the CPI curve. Section 7 contains the conclusions of the paper and the need for further studies, respectively.

2 Definitions

2.1 Functionality

In this work, it is considered that a building is constructed to meet an initial set of requirements, or in other words, to provide a certain level of service. If a building provides this level of service, it is considered to be 100% functional. A building can cease to meet initial requirements in two basic ways; 1) the building deteriorates, 2) the building requirements change. The latter can be subdivided into a) changes in building standards, e.g. increases in the expected energy efficiency, and b) changes because it is needed for another purpose, e.g. modification of a warehouse to be an apartment building. The amount of deterioration is expressed as a % loss of the initial functionality. The energy efficiency, generally measured by the energy performance indicator (EPI [10]), is an aspect of the functionality.

It is considered that the costs of RMs are directly proportional to the cost of reconstructing the building with the same functionality, today [11]. The costs of enhancement measures are, in general, not directly proportional to the accompanying change in functionality. There is, however, a relationship between them, at least for energy efficiency improvements, such as a more comfortable indoor environmental quality.

2.2 Value

The proposed method uses the reconstruction value, i.e. the expected cost of reconstruction of the building on a green-field site, as a base value. Costs of investigated measures are then expressed as a percentage of the reconstruction value. This facilitates the understanding of the method by normalising the costs of measures on buildings of different size and type, and by normalising costs over time. Estimates of this value can be obtained using either cost-indexed original construction costs, or the amount for which the building is insured, which is usually based on the so called reinstatement value, which reflects the reconstruction costs at a certain point in time (e.g. at the start of the insurance contract). Care must, however, be taken to account for deviations from these values, and the actual reconstruction costs, if a high level of detail is required. It is also noted, that these values are also not necessarily identical with the commercial market value, fair value or value of assets in the balance sheet also called the financial book value.

2.3 Measures

In order to ensure that a building continues to provide the desired level of service or functionality it is necessary to execute measures. In general, these can be classified as 1) maintenance measures (MMs), 2) refurbishment measures (RMs) and 3) enhancement measures (EMs) of which EEMs are a subset. MMs are relatively inexpensive measures that slow deterioration and, therefore, slow the loss of functionality of the building. The costs of such measures are normally included in expenses[11] and have no effect on the value of assets[12] in the balance sheet. RMs are relatively expensive measures that improve the functionality of the building up to and possibly beyond the initial functionality, e.g.to comply with new legal requirements. The costs of RMs are normally included in investments[13] and have an effect on the value of assets in the balance sheet. EMs are relatively expensive measures that improve the functionality of the building beyond the initial functionality, e.g. adding another floor on top of the building. The costs of EMs are also normally included in

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[11] Expenses - Operating expenditures (OPEX), in the context of this paper the amount of money spent or costs for maintenance and operation of a building

[12] Value of assets are the value entered on the balance sheet, which is used, for example, to help determine the amount of tax to be paid.

[13] Investment – Capital expenditure (CAPEX), in the context of this paper the amount of money spent or costs to improve the functionality of a building

investments and have an effect on the value of assets in the balance sheet. A description of each type of measure is given with respect to the reason for execution, the department responsible and budget request process, the effect that measure is expected to have on functionality, how the costs of the measure are taken into consideration by accounting and the effect on the balance sheet, and the normal source of funding in Table 1. The effect expected on the functionality of the building due to the execution of the measure is illustrated in Figure 1[14].

Table 1. Description of maintenance, refurbishment and enhancement measures (part 1)

No. and type of measure	Reason for execution	Department, budget request process	Effect on functionality	Accounting, effect on balance sheet	Common source of funding
1. Maintenance (MM)	Mainly based on technical considerations (e.g. spalling of concrete in an exterior wall)	Executed as part of the daily business; responsibility of technical staff within their budgets	Slows the loss of the initial functionality (by changing the speed of deterioration)	Cost included in expenses (often with a financial threshold upper limit); no influence on balance sheet	Annual income
2. Refurbishment (RM)	Often based on technical and legal considerations (e.g.to fix a roof to prevent leakage)	Treated as a project (construction department); forms part of multi-annual investment planning	Improves functionality, in general, up to the initial functionality and in some cases may improve the functionality beyond the initial functionality	Costs included in investments; They have an effect on the value of assets in the balance sheet (restoring the original value)	Capital set aside from past income or capital made available through depreciation of assets

[14] It is noted that the exact definitions of a measure may vary from organization to organization, and even between persons within the same organisation. This decision depends on multiple factors such as internal accounting and/or taxation principles, legislation of the rental market, the actual condition vs. advances in building technology, standards and regulations, types of requirements, financing of the measures, and responsibility for planning and execution. The explanations we have given here, are, however, exact enough to demonstrate the proposed method and can easily be adapted to a specific organisation if desired.

Table 1. Description of maintenance, refurbishment and enhancement measures (part 2)

No. and type of measure	Reason for execution	Department, budget request process	Effect on functionality	Accounting, effect on balance sheet	Common source of funding
3. Enhancement (EM)	Based mainly on financial considerations (e.g. to raise comfort with a modern kitchen or additional floor in order to earn more rent)	Treated as a project (construction department); forms part of multi-annual investment planning; often together with refurbishment	Improves the functionality beyond the initial functionality	Costs included in investments; They have an effect on the value of assets in the balance sheet (higher values due to higher functionality)	Capital invested in the anticipation of additional future income

To execute measures on buildings in an optimal way, it is necessary to analyse and plan all measures together [12]. Unfortunately due to organisational structures and internal regulations this is not always done.

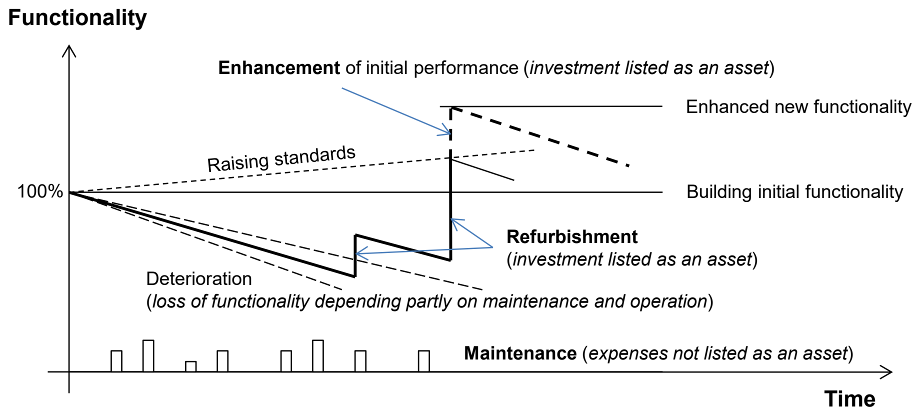

Figure 1. Illustration of the terms maintenance, refurbishment and enhancement (adapted from EN 15221-1 [13])

2.4 Costs and benefits

Costs, in this paper, are defined as the impacts that are incurred during the execution of measures by the owner of the building. They are grouped as shown in Table 2, where if a measure is executed the costs for the lowest category are counted first, then the costs for the second, etc..

Table 2 Cost categories per type of measure

No.	Types of measures and cost categories	Description
1	Maintenance	All costs are normally reported as expenses. They are not subdivided into further categories.
2	Refurbishment	All costs are normally reported as investments. These are referred to in this paper as "anyway" costs. They are subdivided into two sub-categories.
2.1	Costs to improve the physical parts of the building	The costs related to restoring the original functionality of the building, e.g. replace a heating system with the same heating system as the original one RMs executed to improve the physical parts of the building often result in a higher level of functionality due to technological advances [14].
2.2	Costs to achieve legal requirements	The additional costs related to modifying a building to fulfil legal requirements beyond what has been required to improve the physical parts of the building, e.g. the additional costs to replace a heating systems with a heating system that pollutes less than the original heating systems due to new regulatory requirements. RMs executed to achieve legal requirements often result in an increased level of functionality. Indeed, that is why the new laws were made.
3	Enhancement	All costs are normally reported as investments. They are subdivided into three sub-categories.
3.1	Costs to execute direct economic measures	The additional costs related to modifications that are principally done to earn more money or to spend less in the future, e.g. the additional costs to replace a heating system with a heating systems that is more efficient than that required by regulations.
3.2	Costs to achieve a rating label	The additional costs related to achieving a rating label[15] once costs to improve the physical parts of the building, to achieve legal requirements, and the costs to implement direct economic measures, are subtracted, e.g. the additional costs to replace an oil fired heating system with a heat pump. EMs executed to achieve a rating label tend to improve the functionality of a building. These improvements may only be indirectly related to economic gain.
3.3	Costs to achieve a pioneering level or excellence	The additional costs related to trying to achieve a pioneering level in building technology once all other costs mentioned above are subtracted, e.g. the additional costs to substitute better insulation for the heating system altogether and thus to convert the building into a zero emission or plus energy house [2]. EMs executed to achieve a pioneering level of excellence tend to improve the functionality of a building. These improvements may only be indirectly related to economic gain. .

Benefits are defined as the impacts that are incurred both during and following the execution of measures that are not directly related to the execution of measures. They are grouped as shown in Table 3. Both are measured in monetary units with respect to a "do nothing" scenario and, for the method, expressed in

[15] There are numerous rating labels on the market, either specific to energy consumption or covering other aspects of sustainability. As part of their corporate identity and responsibility, organisations often demand a certain rating of the buildings they occupy. The rating may result in a higher value of the labelled building in the market [24] and thus enhances its functionality.

percentage of the reconstruction value. Each group can consist of things that are relatively certain, and things that are less certain. The latter of which can be referred to as risks[16].

Table 3. Benefit categories from an investor's point of view with exemplary indicators

Main category of benefits	**Subcategory and type of benefits**	**Direct measures (1.) or exemplary indicators of future income (2.)**	**Indirect results (future income)**
1. Direct monetary measurable	1.1 Increased income	Rent, charges, subsidies	Less administrative costs and less lost income due to fewer changes in occupants
	1.2 Decreased expenses/costs	Expenses (e.g. for cost of energy, maintenance, tax, insurances), capital cost, investment costs (e.g. of other measures), tax optimisation	- -
	1.3 Optimised values, equity, assets	Book value (balance sheet), market value [17], equity optimisation, e.g. improving factors which lead to an increased Economic Sustainability Indicator ESI [18]	Better price if building is to be sold; Reduced interest rates, if money is to be borrowed due to higher credit worthiness
2. Indirect monetary measurable	2.1 Achieved legal compliance	Allowances for required expenses related to legal issues (e.g. removing asbestos from a building when legally required or the payment of lawyer fees) or insurance fees	Increased income due to use of capital that no longer needs to be set aside for required allowances or used for insurance fees
	2.2 Sensorial, behavioural benefits	Higher tenant satisfaction, better tenant productivity	More income (owner-user situation) or rent [16]
	2.3 Better image, PR, Branding	Higher sales, easier recruiting, better lettability	More income through higher rents, and lower costs due to, for example, marketing

[16] Risk (R) is the estimated probability (P) of occurrence of an event multiplied by the potential costs/benefits (loss/gain of value (V)) it incurs, formulated as $R = P \times V$. In addition to these costs and benefits that are likely to happen with respect to relatively certain scenarios, there is also a reduction in the probability of other scenarios, or in other words in the reduction of negative risks. Newer initiatives like the Economic Sustainability Indicator ESI [18] are trying to quantify specific risks in the RE sector.

[17] Popescu et.al. [17] have found evidence that EEMs are indeed enhancing the market value of a building

Unlike the initial or up-front cost, a major problem with estimating costs and benefits in the future is that they depend on many factors that are difficult to predict, e.g. future energy prices, inflation and average interest rates, or changing user requirements. A large number of researchers have described various methods for the calculation of long-term benefits, e.g. in form of life cycle costing (LCC) [10, 19] or using indicators to measure systems performance to ensure appropriate consideration of non-monetary benefits (e.g. using a Balanced Scorecard). None of these methods are currently common practice in the strategic planning of the measures in building portfolios.

The defined relation in Table 1 between the types of measures, the cost categories and their effects on the value of assets, i.e. the amount that could be obtained if the building was sold under the assumption of a constant market, and benefits is illustrated in Figure 2. As can be seen there is no defined relation between the type of measure and the types of benefit. To be clear, multiple types of benefits are possible for each type of measure.

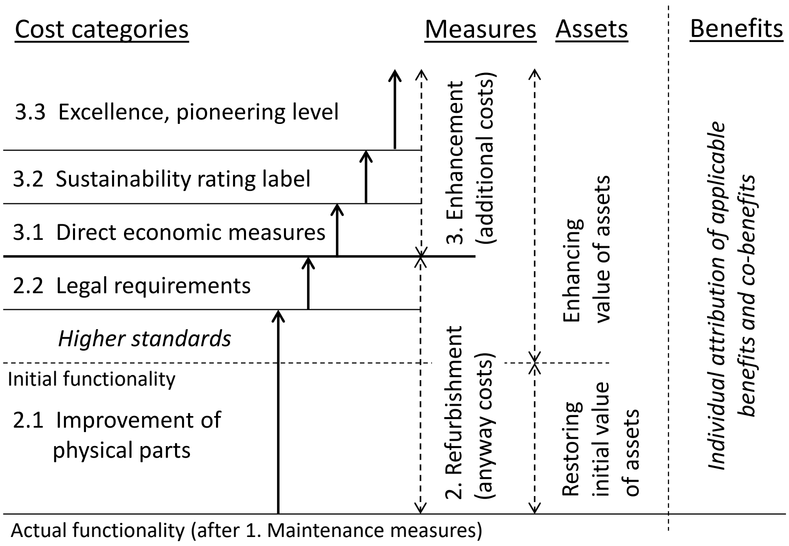

Figure 2. Cost categories, their relation to refurbishment and enhancement measures, and their effect on value of assets (numbering in accordance with Table 2)

3 Problems with using existing methods and instruments in strategic planning

Around the turn of the millennium, some research on developing methods and instruments to help plan measures to improve the sustainability of buildings - mainly concentrating on reducing energy consumption - was undertaken. However, this has not resulted in a widely used method or instrument, specifically not on a strategic portfolio level in combination with refurbishment planning. The reasons for this may be found in the random nature of some of the influencing factors[18], and the lack of sufficient data to find regularities and to identify relationships between costs and the ability to reduce energy consumption. Recently, a number of authors have published articles in this field which shows a renewed interest [20-25].

The found methods and instruments designed, or currently used to help plan measures to improve the sustainability of buildings or related purposes (Annex 2) all have deficiencies if to be used for strategic planning purposes. These deficiencies can be grouped as shown in Table 4 along with brief descriptions of the consequences, exemplary methods or tools and the benefits of the use of CPI curves with respect to alleviating the deficiency.

[18] Factors influencing cost and time of maintenance may include building type, size, age, construction materials, usage, wear and tear, strategy, user requirements, etc.

Table 4. Identified deficiencies for strategic planning purposes of existing methods and instruments and the respective benefits of the CPI curve (part 1)

Deficiencies	Consequences	Exemplary methods	Benefit of using the CPI curve
1. Too much detailed object level information required	They are on an operational level. As they are designed for operational duties; the costs of acquiring the required amount of precise and accurate detailed information are high.	Energy analysis / energy audit: EN 16427-2 [26], Simulation of thermal building loads using heat balance techniques: e.g. DIN V 18599 [27], Virtual energy analysis (no-touch audits or rapid energy modelling [28])	Use of a relatively small amount of widely accessible data, e.g. reinstatement values and values of the EPI in conjunction with own experience keeps the costs of acquiring the required amount of information low.
2. Not enough detailed object level information possible	They are above the strategic planning level. They are focused on a very large number of buildings, e.g. the whole building stock of a region or country, and therefore do not have information that can be meaningfully used	Top-Down building stock modelling: Kavgic [30]; Bottom-up building stock modelling: Kavgic [30], Kesicki [31], Heeren et al. [32]; SLABE (samples for building categories) [33]	Equally useable irrespective of the number of buildings being considered, e.g. from one building up to the whole building stock.
3. Insufficient available data	They require the collection and interpretation of a large amount of data - which is currently not available and would require a large effort to obtain.	Assignment of buildings to archetypes and modelling of savings from typical EEMs per archetype: Chidiac [34], IEA [35] (see also EPBD [2], Definition of reference buildings and general EEMs: EPBD [2], Calculation of a reference project and marginal costs of element specific ECMs: Jakob et.al [29]	Use only requires the experience of experts. As additional information is required it can be added.
4. Too much information on the alternative measures with costs and benefits required	They require substantial information on multiple alternatives so that the optimal alternative can be selected. The development of the specifics of the alternatives is coupled with high costs.	Incremental cost benefit analysis, often based on an energy analysis: e.g. INSPIRE in Eracobuild and IEA Annexe 56 [36, 5], Decision making methods for multi-objective optimisation between alternative measures: Menassa [37], Juan [38], Kaklauskas [39], Diakaki [40], Fawcett [41], Girmscheid [42], Wu [43]	Use only requires an acknowledgement that alternative measures exist. The specifics of the alternative measures can be done during a later phase.
5. Algorithms not publically available	They have been developed by private persons or companies and any further development requires the developers consent or participation.	Process based refurbishment strategy and measures optimisation like 4-step model and tool IMMOWIN in Pichler [44]	Use of only publically available algorithms.

Table 4. Identified deficiencies for strategic planning purposes of existing methods and instruments and the respective benefits of the CPI curve (part 2)

Deficiencies	**Consequences**	**Exemplary methods**	**Benefit of using the CPI curve**
6. Too little detailed information provided	They provide too little detailed information regarding the costs of RMs and EEMs, or it would be too much effort to convert them in to a form, to facilitate portfolio level decisions.	Indicators or benchmarking figures like the energy performance indicator EPI (kWh/m^2.a)	Use involves the development of sufficient detailed information with respect to both costs of RMs and EEMs to facilitate portfolio level decisions. This information is presented in easily interpretable charts, which is a substantial improvement of methods or tools that provide only single values.
7. Designed for related purposes	They are designed for a purpose that is related to strategic planning but does not entirely cover strategic planning, e.g. a method that has been designed to evaluate only RMs.	Decision making between refurbishment and new construction like Retrofit advisor [45], risk quantification like Economic Sustainability Indicator ESI [18])	The CPI curve is specifically developed for the strategic planning.

All methods found have at least one of these deficiencies, which is perhaps why none are used widely in the strategic planning of buildings at the portfolio level. The CPI curve has been specifically designed for strategic planning with these deficiencies in mind.

With respect to the deficiencies 1 “Too much detailed object level information required” and 2 “Not enough detailed object level information possible” in Table 4, it is worthwhile mentioning that the CPI curve can be used with a range of the amount of data required and can deliver a range of accuracy in the results. At one extreme it can be used with only minimal often available data and on the other extreme it can be used with detailed object level data that can only be collected with substantial effort. This makes it ideal for use at a strategic planning level as the costs related to its use and the desired accuracy of its results can be optimised from case to case. A qualitative illustration of the level of effort vs. use perspective for typical methods and where it is expected that the methods using the CPI curve would normally be located is given in Figure 3.

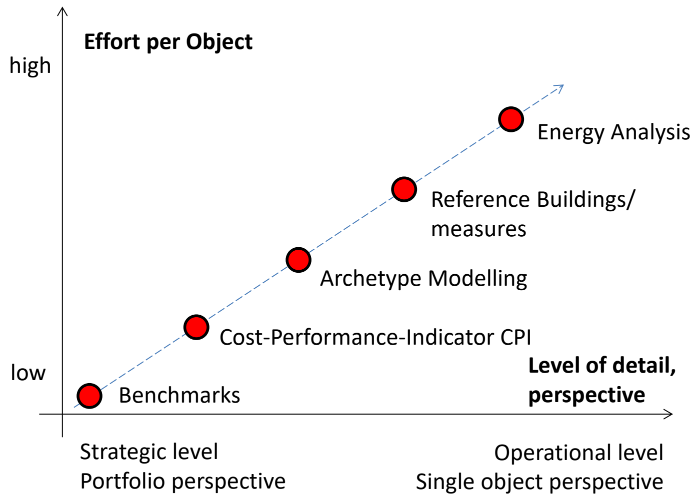

Figure 3. Qualitative illustration of the level of effort vs. use perspective for typical methods

4 The Cost Performance Indicator curve

4.1 General

Budgeting of MMs, of RMs and of EMs on a strategic portfolio level is a regular task for building owners and portfolio managers. This is often a challenging task, which can be made easier by the use of cost-performance-indicator (CPI) curves[19]. A general CPI curve is the curve that results from plotting the cost of EMs against the performance of the building, which can be measured using one or more indicators. When discussing EEMs as a sub-type of EMs, a CPI curve (Figure 4) is the curve that results from plotting the cost of EEMs against, for example, the energy efficiency of the building, for which the EPI, measured in units of energy consumption per m^2 of building energy reference area and year, abbreviated as kWh/m^2.a as defined in EN 15459 [10] can be used. The development of a CPI curve is only possible if it can be assumed that there is a relatively well defined relationship between the performance, in this case the current energy efficiency of buildings, and the

[19] One way to make the estimates of the future costs of MMs and RMs is the method Schroeder described in Schroeder [46] and evaluated in Christen [11]. In this method the loss of functionality of single buildings is estimated, based on the performance of small subsets of elements. The functionality of single buildings is then aggregated to give an indication of the loss of functionality of a selected group of buildings and used to estimate the time at which measures should be executed to stop the functionality from falling below an acceptable level, and then their costs. Once aggregated the costs to restore the functionality are represented as a function of the reconstruction values of the buildings. Once it is clear when and what type of RMs are to be executed, and how much they will cost, the CPI curve can be used to estimate the additional costs for EEMs (Figure 9).

additional costs to execute EMs to increase this performance (in conjunction with RMs), in this case EEMs to increase the energy efficiency. The method proposed to do this is given in the following sections. It is presented only referring to EEMs, but is generally applicable for all types of performance and EMs. The uses of the CPI curve to estimate the optimal EEMs and the total costs of measures are then explained in subsequent sections.

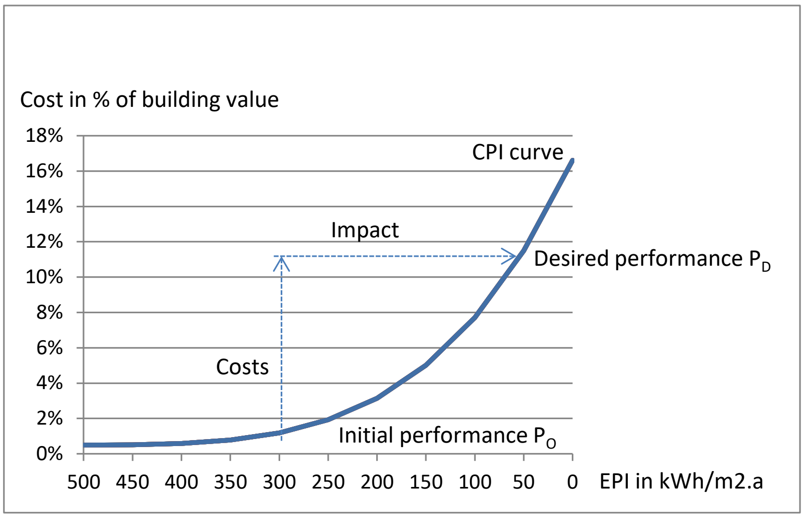

Figure 4. An example CPI curve

4.2 Development of the CPI curve

EEMs influence the energy performance of buildings in a positive way and thus save energy costs as a direct monetary measurable benefit and possibly achieve other benefits as well. As such, the cost of EEMs can be expressed as a function of the energy performance in a curve, showing the additional costs required to improve performance up to a desired level. The steps to convert an additional cost – additional benefit curve to a CPI curve are given in Table 5.

Table 5. Steps to convert an additional cost – additional benefit curve to a CPI curve

No.	Description
1	Determine the intervals in the CPI curve coordinates to be used to represent costs and improvements in efficiency per cost interval as a function of total improvement to be used
2	Convert the benefits of all measures in each step into energy saved either using the actual numbers per measure or the average of multiple measures and then divide by the total energy reference area to calculate the effect of each interval on the value of the EPI
3	Divide the cost of all measures in these intervals by the total value of buildings to convert costs into the CPI curve coordinates
4	Start the curve(s) at the initial performance P_0 of each building separately or of the average of all buildings

In the development of this CPI curve there are basically two cases to be considered:

1) the case where there is detailed information available on multiple EEMs for a few buildings, and

2) the case where there is general information available on multiple EEMs for a large number of buildings.

In both cases the measures are plotted in ascending order of the cost/benefit ratio and table 5 is used. For the former, this is done using the exact costs and improvements in efficiency and for the latter, this is done using the average costs and improvements in efficiency. Additionally for the former case CPI curves can also be generated per building. These two cases are illustrated in the next sections, where the CPI curves are developed for two real world situations, respectively.

4.2.1 Example of case 1

4.2.1.1 Buildings and measures

In the first case study, 168 ECMs in five major buildings at Zurich airport are used. The types of buildings range from passenger terminals, of which there were three (68% of total area) to administration of which there was one (11% of total area) to freight handling buildings of which there were one (21% of the total area) (for the underlying data refer to Annex 1). The ECMs were designed in the late nineties by three engineering companies specialising in energy matters as part of a large project to reduce energy consumption and its associated costs and emissions [47]. Some of the measures were executed on their own while others were executed alongside large RMs and EMs to meet new user requirements.

The costs and benefits of all measures were calculated within the same framework and using the same parameters and costs divided into those for RMs und those for additional ECMs. The additional costs and benefits of the ECMs are plotted in Figure 5. It can be seen that the relationship is convex.

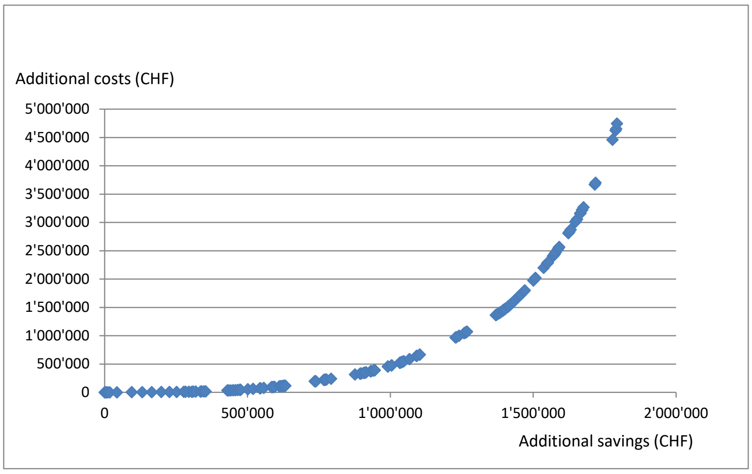

Figure 5. Additional costs versus additional savings of 168 ECMs at Zürich airport [47] in the increasing order of their cost/benefit ratio

The CPI curve of the five analysed buildings together is given by dividing the additional costs by the total value and normalising the savings by the achieved improvement of EPI (Figure 6).

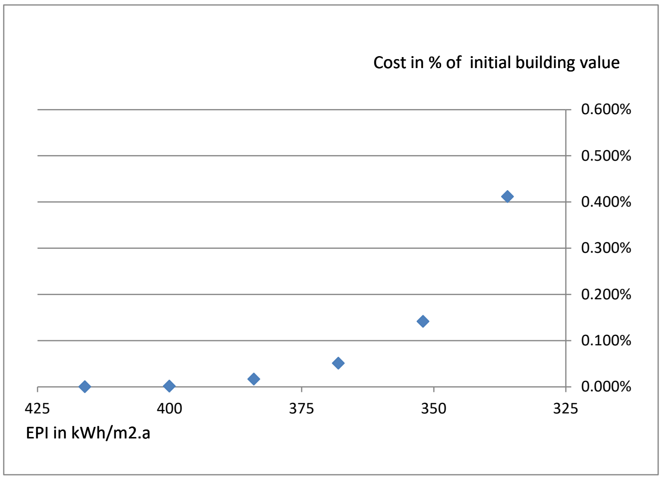

Figure 6. CPI curve of all proposed ECMs in example 1

In total, approximately 20% of the energy consumption could be saved at additional costs for ECMs of approximately 0.4% of the value of the buildings if 1.1% of the initial building value was spent on RMs (total 1.5% or 17.4 million CHF). In this case, the resulting cost/benefit ratio (also referred to as pay-back time or factor by which up-front costs exceed (constant) annual benefits in years) of all ECMs as a package is, a relatively short, 2.7 years (Annex 1) while the least economic ECMs which were considered in the project have a ratio of approximately 15 years (Figure 5). Not included in the benefits is an avoided increase of central heating capacity to serve additional new buildings.

4.2.1.2 Development

Cumulative costs and benefits for all ECMs for each individual building are shown in Figure 6.

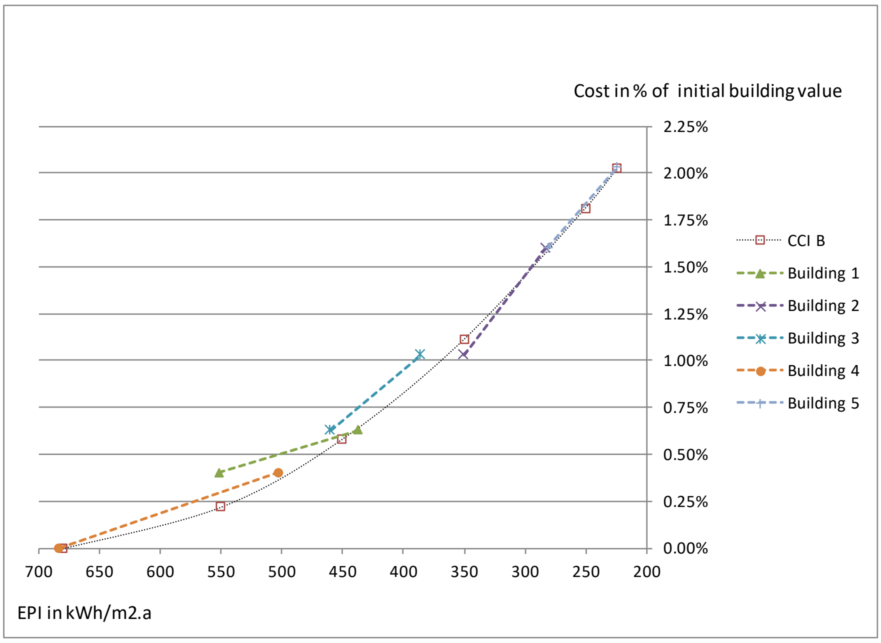

Figure 7. CPI curve for all buildings in example 1

Once the data shown in Figure 7 has been plotted the CPI curve itself can be determined as a curve that fits best to the data by selecting multiple possible forms using standard methods to determine the appropriate values of the parameters. A good fit for the data in this case was determined using the summation of a linear function ($b*x$) and a power function ($c*x^R$). While the initially prevailing linear term can be explained by a certain type of measures (e.g. improving the lighting), the origin and character of the power-law relation needs to be explained yet given the mix of different measures from cheap to expensive, linear to non-linear (e.g. insulation), and scalable to incremental ones (e.g. installing a heat pump). For this example, the form of the best fit curve was:

$$MC_{ev} = a + b*x + c*x^R \qquad (1)$$

MC_{ev}	Additional cost of improvement of a building element in percentage of total reinstatement value of building (in %)
a, b, c	Variables
R	Exponent
x	Performance (P) measured as Energy Performance Indicator (EPI) in $kWh/m^2.a$

To calibrate with the effective numbers in the x-axis the following adaption of formula (1) was necessary, which resulted in:

$$MC_{ev} = a + b*(x_0-x)+c*(x_0-x)^R \quad (2)$$

x_0 Initial performance P_0 of the least efficient building

The values of the parameters that gave the best fit with the data by using approximation were: a = 0 (RMs or anyway costs, not represented); $b = 6*10^{-6}$; $c = 8.4*10^{-8}$; R = 2; x_0 = 680.

4.2.2 Example of case 2

4.2.2.1 Buildings and measures

In the second example, the additional costs for improving energy efficiency of 280 single family houses going beyond the legal requirements (Energieeinsparverordnung (EnEV)/Energy Saving regulation) in Germany [48] form the basis. The levels of energy efficiency and the additional costs of RMs and ECMs for each standard are shown in Table 6.

Table 6. Varying levels of energy efficiency and the respective marginal costs [48]

Criteria	**Efficiency standard**			
	ENEV (legal requirement)	**Low Energy house 85**	**Low Energy house 70**	**Low Energy house 55**
Average energy consumption EPI in kWh/m^2.a	95	82	68	48
Cost of RMs in EUR/m^2	400	400	400	400
Additional costs of ECMs in EUR/m^2	--	30	70	140

4.2.2.2 Development

The CPI curve is shown in Figure 8. The data shows the typical behaviour of increasing relative costs.

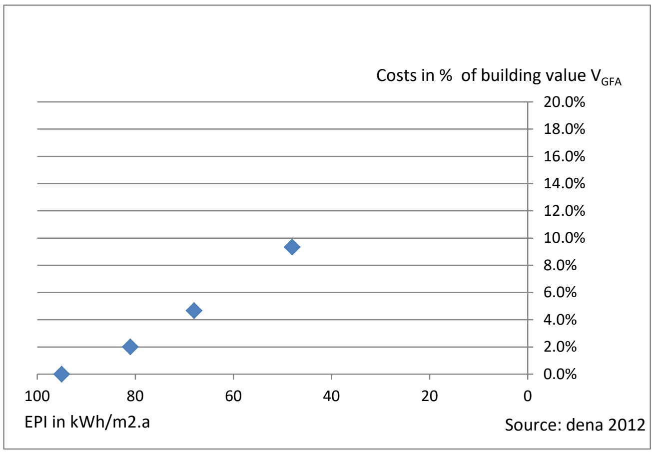

Figure 8. CPI curve for single-family homes in Germany

The form of the CPI curve is given in equation (2). The approximated values of the parameters are: a = 0 (RMs or anyway costs, not represented); $b = 0.11*10^{-2}$; $c = 0.19*10^{-4}$; R = 2; $x_0 = 95$. It can be seen that in this example, as in the last, the linear and cubic terms ($c*x^2$) are part of the best fit equation. The curve is valid between an EPI of 95 (the legal requirement in Germany) to 50.

4.3 Estimation of total costs of measures using the CPI curve

The total costs of measures are the sum of costs of the RMs and the additional costs due to the EEMs. Once the costs of the RMs are known the CPI curve can be used to estimate the total project costs. This is illustrated in Figure 8, where the costs of the RMs are assumed to be directly proportional to the loss of functionality and the loss of functionality is assumed to have a defined, in this case linear relationship with time. The steps to do this are outlined in Table 7.

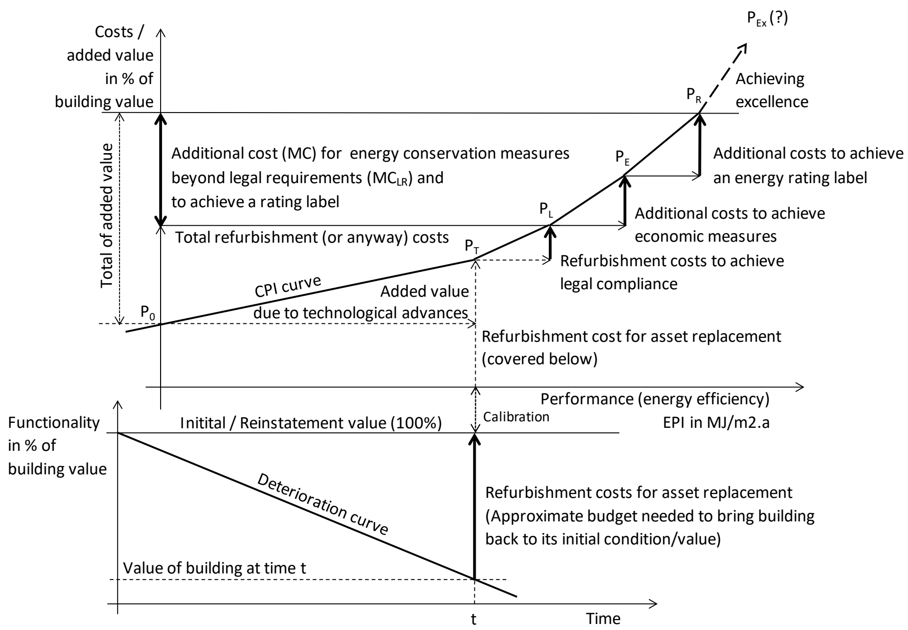

Figure 9. CPI curve (top) together with refurbishment cost curve (bottom)

In Figure 9, the following notation is used:

P_T Energy performance after measures executed to improve the physical parts of the building (RMs),

P_L Energy performance after measures executed to achieve legal requirements,

P_E Energy performance after measures executed to achieve direct economic gain;

P_R Energy performance after measures executed to achieve a rating label,

P_{Ex} Energy performance after measures executed to achieve a pioneering level of excellence.

Table 7. Steps to use a CPI curve to determine total costs

No.	**Description**
1	Estimate functionality of buildings in the portfolio and determine buildings to have RMs and the respective costs at time t
2	Estimate improvement of the energy performance of buildings following execution of RMs to determine P_T on the CPI and calibrate the x axes of the two charts so that the time of the RMs in the refurbishment cost curve lines up with P_T in the CPI curve
3	If applicable, determine additional costs to achieve legal compliance in terms of energy efficiency using the CPI curve
4	Determine additional costs to achieve optimal performance P_{PE} or P_{PP} (chapter 4.4) or the desired performance P_D in accordance with strategy (chapter 5)
5	Add the respective costs of RMs and EEMs (bold arrows in Figure 9, in %) together and multiply with the value of buildings involved to calculate total costs of measures

It can be seen that the total cost would be the costs to restore the functionality or the physical parts of the building at time t, (shown by the RM cost curves), plus the additional costs to improve energy performance, (shown by the CPI curves), i.e. the difference between P_T and the respective desired performance.

4.4 Estimation of the optimal ECM

When doing strategic planning of ECMs it is useful to estimate and illustrate their benefits. There are many well-known and defined methods to estimate these, e.g. the net present value (NPV) method or the internal rate of return (IRR) [10, 19]. These methods will allow the determination of the maximal gradient or cost/benefit ratio in which ECMs are still considered economical. The line that gives the optimal ECMs is called the economic gradient (EG in %.a.m^2/kWh). The steps to estimate the optimal ECMs are given in Table 8.

Table 8. Steps to estimate the optimal ECMs

No.	Description
1	Define basic parameters like expected service life of measures, energy price, indirect benefits, and feasibility requirements e.g. using the internal rate of return (IRR) or the net-present-value (NPV) method
2	Calculate maximal up-front costs which fulfil the above parameters e.g. using the IRR method and an assumed annual benefit
3	Divide the calculated maximal up-front costs by the annual benefit to determine the maximal cost/benefit ratio
4	Multiply the cost/benefit ratio from step 3 with the assumed price of 1 kWh energy (€/kWh) including indirect benefits. This results in the maximum up-front costs for 1 kWh/a saved which still fulfil the defined parameters (€.a/kWh)
5	Divide these maximum up-front costs by the building value per unit area (€/m^2) to determine the cost expressed in % of the building value per kWh/m^2.a saved which equates to the economic gradient (EG) in the CPI chart coordinates. The EG is normally considered to be linear in the range of a CPI curve
6	Determine optimal additional costs for ECMs in % of building value with the help of the CPI curve and the EG (P_0 -> P_{PE} where the EG becomes the tangent to the CPI curve in Figure 10 or where the EG meets the CPI as a diagonal through P_0 in Figure 11)
7	Calculate the total cost of optimal measures in a specific building by multiplying the optimal additional costs for ECMs in % of building value with the total value (€)

For example, to achieve an expected IRR (derived from the NPV) of 10% over the next 15 years, the ECMs can cost no more than approximately 8.5 times the annual savings. Taking this result and a unit value of the buildings of 3000 €/m^2 and unit energy costs including indirect benefits of 0.15 €/kWh, then the economic gradient is 0.043 %/(kWh/m^2.a).

A graphic illustration of the determination of the minimal economically viable EPI is shown in Figure 10. The threshold indicating the optimal ECMs, i.e. the ones that will result in the minimal economically viable EPI, is given by the point P_{PE} where the economic gradient becomes the tangent to the CPI curve on its right hand side. This means that all ECMs that have a cost/benefit ratio of less than 0.043 % of the building value per unit EPI are economical and the rest are uneconomical. In this case, around 115 €/m^2 or 22’000 € in a house of 200 m^2 can be spent additionally to half the EPI from 300 to 150 kWh/m^2.a in conjunction with conventional RMs. It also indicates that it costs increasingly more to decrease the value of the EPI the lower its value.

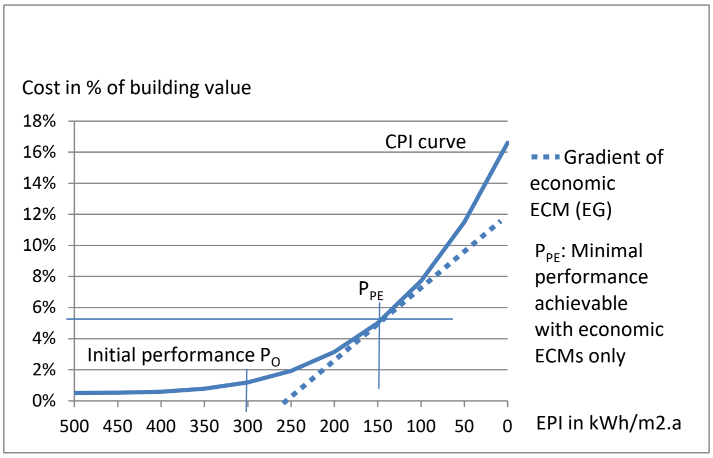

Figure 10. Illustration of the optimal EPI achievable when considering each ECM separately

If ECMs are combined, however, it is possible that ECMs with an even higher cost/benefit ratio can be executed, as the relatively inexpensive measures will, in a sense, subsidise the more expensive ECMs [49]. For example, if two ECMs were combined, and measure M1 reduced the value of EPI from initially 300 to 150 kWh/m^2.a for 4% of the building value and M2 from 150 to 50 kWh/m^2.a for an additional 6% of the building values, than together their gradient is equal to the EG, but in actuality M2 would be substantially above the economical threshold. In the example, measures up to a gradient of 0.075% would still be executed. This is illustrated in Figure 11.

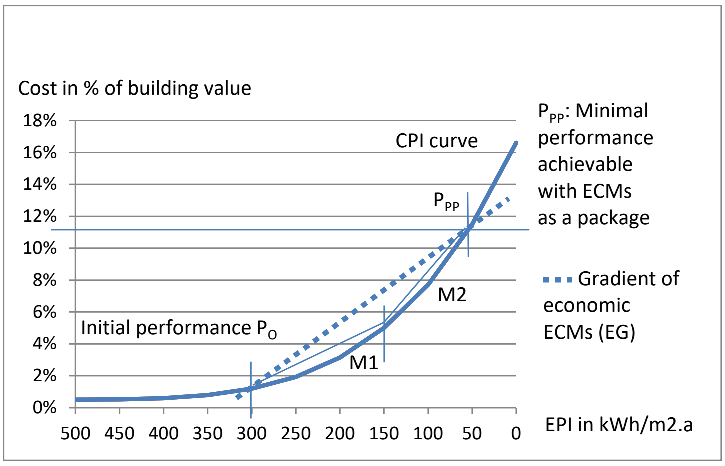

Figure 11. Illustration of the optimal EPI achievable when considering ECMs combined in a package

This also indicates that less improvement in the energy efficiency of buildings would be considered economically viable if ECMs are considered individually, than if they are considered in packages.

4.5 Estimation of optimal energy production measures

When doing strategic planning of EEMs it is often desired to not only determine the optimal ECMs. Often there is a desire to enhance efficiency (EPI) by EPMs using renewable sources, for example, by harnessing low-exergy heat [50] or by producing electricity from photovoltaic cells (PV)[20]. The execution of EPMs will have a similar effect on the efficiency as ECMs due to the definition of the EPI which measures the input of final energy from outside the system.

In order to estimate the optimal combination of conventional ECMs and EPMs using the CPI curve, a quantitative indicator similar to the EG has to be used that indicates how much one is willing to spend on EPMs, which is referred to as the renewable energy gradient. This is done by following the steps in Table 9. For example, at a building value of 3'000 EUR/m^2 and costs of PV-production of 1.3 EUR for 1 kWh.a the resulting

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[20] Considering the steep learning curve of PV with annual cost reduction in the range of 15%, this technology is becoming a big game changer, especially if feed-in tariffs (FIT) generating a guaranteed income are taken into account. Tariffs today reflecting production costs in Germany with maximum solar radiation of 1200 W/m^2 are between 10 and 15 Euro Cents/kWh for small PV units and are still falling while the price of grid electricity is considerably above 20 Euro Cents/kWh for households. Even without FIT's, it could soon become more economical to replace traditional building materials such as tiles (20-50 EUR/m^2) and sheet metal or natural stone facades with active photovoltaic panels (currently 200-300 EUR/m^2, but generating a constant income) which are already available in different colours (including white) and shapes (including transparent).

renewable energy gradient to improve efficiency by 1 kWh/m^2.a using PV is around 0.036 % of the building value which is below the EG in section 4.4 with 0.043%.

Table 9. Steps to estimate the optimal combination of ECMs and EPMs

No.	Description
1	Evaluate the cost of production of one unit of renewable energy per year (€/kWh/a) taking into account the effects of feed-in tariffs (FIT) or applicable, indirect benefits.
2	Divide this cost by the building value per unit area (€/m^2) which results in the cost expressed in % of the building value per kWh/m^2.a produced. This equates to the renewable energy gradient (in %.a.m^2/kWh) in the CPI curve coordinates.
3	Compare the EG and the renewable energy gradient: if slope of the renewable energy gradient is lower than the slope of the EG (or of the least economic measure when considering packages), then production of renewable energy is - in a certain range - seen as better than conserving more energy. This happens to the right of the point where the renewable energy gradient becomes the tangent to the CPI curve. From there, the new combined CPI curve changes from convex ascending (ECMs) to linear ascending (EPMs).
4	Multiply the value of the renewable energy gradient with the required reduction of the EPI (kWh/m^2.a) to calculate the specific costs to reach the efficiency goals per area in percentage of the value.
5	Calculate the total costs in a building by multiplying the specific costs with the total area and with the total value of it and add costs of previous ECMs.
6	Optional: Define the total amount of energy to be produced from renewable resources: Because these are scalable, the amount to be produced is only limited by the willingness to invest, availability of FIT's or space for installation once the energy efficiency goals are met.

In the example, it is optimal to execute ECMs to reduce energy consumption up to the point P_{RE} (150 kWh/m^2.a, refer to Figure 12) when the additional costs of the EPMs to produce energy from renewable sources are equal to the additional costs to conserve the same amount. Afterwards, any increase in the amount of energy produced from renewable resources would be worth it[21].

[21] The production of energy from renewable sources is scalable. Therefore and depending on the availability of FITs, the production of a surplus resulting in a plus-energy building can become an interesting option for a building owner. To simplify matters, effects of economy of scale in the installation have not been taken into account in this paper, the renewable energy gradient is also assumed to be linear

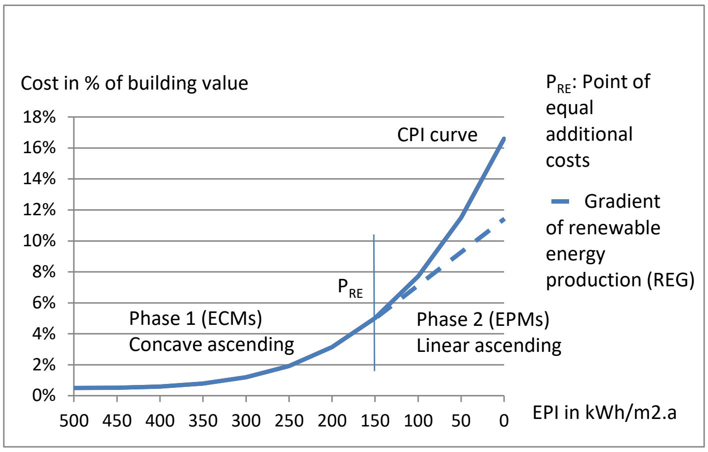

Figure 12. Illustration of the optimal combination of ECMs and EPMs

5 Strategic planning using the CPI curve

5.1 Steps

The steps to be used for strategic planning with a CPI curve are given in Table 10. Underlying these steps, is a controlling cycle with the elements planning, execution, controlling and continuous improvement. For each step, a description of the strategic planning process is given along with the improvements to the step when a CPI curve is used.

Table10. Steps for strategic planning without and with the CPI curve (part 1)

Step No.	Step Name	A) Description without CPI curve	B) Description with CPI curve	Results and potential improvement of method B over method A
1	**Analyse portfolio**	Analyse the ability of the portfolio to meet requirements, e.g. to have the expected value, functionality, and physical condition. This includes the determination of the expected values of key performance indicators. The data used varies from organisation to organisation.	Analyse the ability of the portfolio to meet requirements, e.g. to have the expected value, functionality, and physical condition. This includes the determination of the expected values of key performance indicators. The data used varies from organisation to organisation, but always includes the data as outlined in section 3 and 4.2 of this paper, when available.	A+B) Basic information about the ability of the portfolio to meet requirements

Table10. Steps for strategic planning without and with the CPI curve (part 2)

Step No.	Step Name	A) Description without CPI curve	B) Description with CPI curve	Results and potential improvement of method B over method A
1.1	Analyse energy efficiency options	Analyse energy efficiency options using normal methods (deficiencies are described in Table 4 in section 3.)	Analyse energy efficiency options by drawing the initial CPI curve and determining the optimal cost/benefit ratio (including direct and indirect monetary measurable benefits) using the benefit structure in section 2.4. Step 1.1 provides useful information for step 2.	Information on all identified energy options. Comment: It is expected that method B will either provide more information than method A or it will be easier to provide the same information
2	**Set goals and constraints**	Set goals, such as the adaptation of existing buildings to accommodate 10% more students and constraints, such as the amount of money available. These goals are to be made to support the overarching business goals, e.g. to be the best technical university in the world.	Set goals, such as the adaptation of existing buildings to accommodate 10% more students and constraints, such as the amount of money available. These goals are to be made to support the overarching business goals, e.g. to be the best technical university in the world. Additionally, use the CPI curve to support the definition of reasonable goals and constraints ,	Clear goals and constraints, which are used to develop the real estate/portfolio strategy Comment: It is expected that method B will be able to help ensure that more realistic goals and matching budgets be determined
2.1	Set energy efficiency goals and constraints	Set energy efficiency goals and, constraints, based on detailed energy analysis of a large number of buildings or a rating system.	Set energy efficiency goals, constraints and priorities, using the CPI curve to determine energy efficiency goals within matching (budgetary) constraints, taking into account packages of measures (section 4.4), optimising between energy conservation and energy production (section 4.5), and possibly rating systems (benefits)	Clear energy efficiency goals and constraints Comment: Because the relation between costs (constraints) and performance are unknown, this step contains many uncertainties. It is expected that the use of method B will result in more realistic goals and constraints, especially with respect to the relationship between costs and performance

Table10. Steps for strategic planning without and with the CPI curve (part 3)

Step No.	Step Name	A) Description without CPI curve	B) Description with CPI curve	Results and potential improvement of method B over method A
3	**Determine and evaluate portfolio strategy**	Determine how the goals are to be achieved within the constraints, e.g. which buildings are to be renovated.	Determine how the goals are to be achieved within the constraints, e.g. under which conditions buildings are to be renovated. Check the possible ways to meet the energy efficiency goals and constraints using the CPI curve, and if necessary adjust goals and constraints, e.g. obtain more funding	A portfolio strategy to be followed that will likely achieve the set goals within the set constraints. Comment It is expected that the use of method B will result in a strategy that will be more likely to achieve the goals within the constraints than with method A.
4	**Set priorities**	Compare functionality with requirements to determine buildings to have RMs in each budgeting period and set priorities considering desired enhancements. Use detailed analysis to take into consideration energy efficiency goals, or make rough estimates.	Compare functionality with requirements to determine buildings to have RMs in each budgeting period and set priorities considering desired enhancements. Use the CPI curve to take into consideration energy efficiency goals.	A list of prioritised buildings to have measures in each budgeting period Comment: It is expected that the use of method B will save substantial time in setting priorities, or result in a better setting of priorities.
5	**Develop detailed work program**	Initiate, supervise and control design of RMs and EEMs on project level (steps 3.1-3.4, per building)	Initiate, supervise and control design of RMs and EEMs on project level (steps 3.1-3.4, per building)	Detailed work program and basic project plans for all measures Comment: Once these are approved detailed project plans can be developed.
5.1	Plan RMs	Plan RMs in selected buildings and calculate their costs (refer to section 4.1) and benefits	Plan RMs in selected buildings and calculate their costs (refer to section 4.1) and benefits	Plans and estimates of costs and benefits for all RMs in work program
5.2	Identify candidate EEMs and estimate costs	Identify the candidate EEMs, estimate their costs and split these in refurbishment and enhancement costs as described in section 2.4 *)	Identify the candidate EEMs, estimate their costs and split these in refurbishment and enhancement costs as described in section 2.4	List of EEMs and estimates of their costs for each building

Table10. Steps for strategic planning without and with the CPI curve (part 4)

Step No.	Step Name	A) Description without CPI curve	B) Description with CPI curve	Results and potential improvement of method B over method A
5.3	Estimate benefits of candidate EEMs, and calculate their cost/benefit ratios	Estimate benefits of EEMs and calculate cost/benefit ratio. Take into consideration using indirect monetary measureable benefits, make rough estimates, or neglect. *)	Estimate benefits of EEMs considering direct and indirect monetary measurable benefits as described in section 2.4 and calculate cost/benefit ratio	List of EEMs with ascending cost/benefit ratios Comment: The use of method B is expected to result in considerable improved estimates of the benefits, with respect to the use of method A.
5.4	Select the measures to be executed	Determine the measures to be executed by choosing the ECMs and the EPMs with the lowest cost/benefit ratios using the costs and benefits as calculated above until no more measure can be added without exceeding the constraints and integrate them into the list of prioritised buildings to obtain the work program.	Determine the candidate measures to be executed by choosing the most expensive economically viable ECMs and EPMs and, within the constraints, optimise between the two as described in section 4.4 and 4.5, and integrate them with the list of prioritised buildings to obtain the work program.	A work program that achieves the goals within the constraints. Comment It is expected that the use of method B will result in improved work programs that will have a lower probability of needing to be adjusted in the future because it is discovered when implemented that they do not satisfy constraints. It is also expected that the use of method B will result in work programs that will better achieve the goals than those developed using method A.
5.5	Determine total costs and benefits of work program	Estimate the total costs of measures by summing the costs and benefits of the RMs and of the EEMs - eventually using individual cost and benefit structures	Estimate the total costs of measures by summing the costs and benefits of the RMs and of the EEMs - additionally use cost and benefit structures described in sections 2.4 for more transparency and to be comparable with other portfolios	Estimates of the total costs and benefits of the work program Comment If method B is used systematically than there will also be improved transparency and comparability over the years and between work programs developed for different portfolios.

Table10. Steps for strategic planning without and with the CPI curve (part 5)

Step No.	Step Name	A) Description without CPI curve	B) Description with CPI curve	Results and potential improvement of method B over method A
6	**Execute measures in work program**	Initiate, supervise and control execution of RMs and EEMs	Initiate, supervise and control execution of RMs and EEMs	Executed measures in work program
7	**Evaluate measures and portfolio strategy**	Evaluate the actual costs and benefits of the measures and how well the work program achieved the goals within the constraints using existing methods and instruments, with those predicted. (Deficiencies of existing methods and instruments to do this have been described in Table 4 in section 3) Initiate adjustment of portfolio strategy if necessary	Evaluate the actual costs and benefits of the measures and how well the work program achieved the goals within the constraints using existing methods and instruments, with those predicted. Update the CPI curve by updating variables with effective costs and benefits. Initiate adjustment of portfolio strategy if necessary	Updated values of the costs and benefits of measures. Updated portfolio strategy Comment For method B, this includes an updated CPI curve

*) Neither the splitting of costs nor the consideration of indirect measurable benefits are common practice today. To be better comparable, the application of both is assumed in methods A and B.

Comment to Table 10: The seven steps follow a controlling cycle with the phases Plan (steps 1-5), Do (step 6), and Check and Act (step 7 leading back to step 2)

5.2 Example

5.2.1 General

To illustrate the practical application and the benefits of using a CPI curve, measures are planned for two buildings at a public university. The buildings are identical except for the fact that building 1 can be used for PV production, whereas building 2 cannot e.g. because the roof space is used for research facilities. The optimal measures are planned using both the approaches A) and B) outlined in Table 10 (details are provided in Annex 3).

5.2.2 Steps

Step 1: Before any portfolio strategy is determined, an analysis of the actual situation is necessary. In both cases, general indicators characterising the portfolio are collected. Step 1.1: In case A, the university starts a costly project to gather and analyse detailed data to draw the energy balance of all major buildings which requires 1-3 days of work per building (refer to point 1 in Table 4). In case B, the university follows the proposed CPI method and relies mainly on available data and only minimal new data is selectively assessed which requires less than 1-2 hours per building. This data is then used to draw an initial CPI curve as an input for step 2.

Step 2: The real estate/portfolio strategy is partly determined by the government strategy (university buildings often belong to the state, but are managed by the universities) which often includes sustainability goals (e.g. to be a role model) based e.g. on a certain sustainability rating system.

Step 2.1: In case A, the sustainability goals in such a political environment are set without knowing the costs for execution of measures. In case B, the CPI curve was used to determine the goals. In both cases, the target is set at an EPI of 50 kWh/m^2.a with the restriction of a cost/benefit ratio of 7.5.

Step 3: In case A, the achievement of the target within the restrictions remains uncertain (refer to Table 4). In case B, the additional costs to reduce the current EPI of the entire building portfolio of 300 to the target EPI of 50 was estimated, by using the CPI, at 10% of the building value or less depending on execution of RMs and EEMs. Following this estimation, the efficiency target can be met within the cost/benefit ratio restrictions. The necessary funds are applied for in the annual construction budgets and the strategy does not need to be reconsidered.

Step 4: In case A and B, the university uses a strategic refurbishment planning method to trace condition of buildings and to estimate future refurbishment costs. Considering stated user needs and strategy, this allows in both cases to designate buildings which are due for refurbishment with high priority. Additionally, in case B, the cost and benefits of EEMs are considered. The two buildings mentioned above are selected in both cases.

Step 5: In this step, the work program is developed by designing RMs and EEMs on project level for the designated buildings. To be better comparable, costs have been split to separate anyway costs in both cases although this is not common practice. In building A1, measures are included in the work program until there are none left with a ratio below 7.5. An EPI of 150 is reached with this so called ‘picking of the low hanging fruit’ and the target is missed. In building A1, the target is not achieved and so the portfolio strategy needs to be reconsidered and some steps eventually be repeated. In case B, the CPI curve approach proves itself useful on project level as well: In building B1, measures are viewed as a package and so more measures are executed. Therefore, the target EPI of 50 is reached within restrictions. In building A2, the same approach as in A1 is driven and the remaining efficiency gains to meet the target are reached by production of renewable energy. The target is achieved, but, because some of the executed conservation measures are more expensive than energy production, the optimal cost/benefit ratio is missed. In building B2, with the help of the CPI curve, the optimal trade off point between conservation and production is calculated and the target is reached with less costs.

Step 6: Execution of the work program on project level is initiated and supervised.

Step 7: Results are checked and controlled and adjustments initiated. In case A, the target is not reached in building A1 while in building A2 more is spent than optimal. The consequence is that goals are set at a lower level. In case B, the goals based on the CPI curve proofed themselves as realistic and are achieved at slightly higher total costs than in case A. The experience gained is built into the CPI curve and so the curve is available for the next cycle in a more precise and accurate form.
Without the splitting of costs and consideration of not directly measurable benefits in case A - these are not common practice today but are demanded in the CPI curve method which is applied in case B - results would be even more distinctive.

5.3 Comparison

Comparison of the results in the two cases A and B show that there is an improvement in the strategic planning and in the execution if the CPI curve is used than if it is not. This is shown as building owners would be able to better take into consideration at the strategic level the reduction in costs that are optimally possible when ECMs and EPMs are combined with RMs then they otherwise would be able to do. Furthermore, this is achieved with much less costly analysis. During execution, the CPI curve approach leads to optimised cost/benefit ratios and a higher probability of fulfilment of targets. This in turn will lead to improvements in today’s building stock as more and more buildings become in need of RMs.

6 Discussion

6.1 Summary

In this paper, the Cost-Performance-Indicator curve or CPI curve method to estimate and budget costs for EEMs in conjunction with RMs for strategic planning purposes is proposed, and related, new definitions in this field are provided. This proposed method is an improvement on the state-of-the-art as no such method currently exists. It is shown in two practical cases that the CPI, which is convex in both cases, can be constructed and used to make predictions. It is suspected that no generally applicable curve exists and that curves must be calculated for each portfolio individually. The use and benefits of the method are illustrated by planning measures on a strategic level for a realistic but fictional example.

6.2 Appraisal

The advantages of applying the proposed CPI curve to strategic planning are:

- It is an easy to use method designed for application by strategic portfolio managers which is adaptable to individual portfolios, requirements, and goals
- It requires a relatively small amount of building information that is often readily available at little cost
- It is a complementing method for existing strategic planning and refurbishment budgeting methods which presents a graphical representation of results
- It is based on a holistic view which incorporates maintenance measures, refurbishment measures and enhancement measures, of both energy conservation and energy production nature.
- It can be used in many different situations, e.g. for building portfolios in different climates, types of buildings, legislation, and technologies
- It is scalable to be used for building elements, single buildings, entire portfolios or a whole economies or countries (the CPI method could be used to estimate total costs to reduce CO_2 consumption of buildings in an economy by considering the whole building stock of the country)

Its disadvantages are:

- There is currently little experience with its use in practice

- The inherent uncertainties and unknown variables in the combination of building refurbishment and associated EEMs reduce potential applications and accuracy has not been extensively explored
- It is unclear as to which variables defining the CPI curves should be used for which types of buildings

With such a method there is always a contradiction of sorts between the necessity to gain reliable and detailed results and the additional effort to collect the necessary data. Sustainable refurbishment of the stock of existing buildings, especially if commercial buildings are included, is a complex and diverse task due to the random nature of characteristics like condition, location, construction, building technique and materials involved. It still needs to be proven that this task can be modelled and standardised in a supporting tool in such a way that the effort is justified by the accuracy of the results.

Although great care was taken in the development of new terminology e.g. to structure costs and benefits, they are just proposed new definitions and other definitions are imaginable. It is in the general interest that such structures are being discussed by the stakeholders and eventually adopted and standardised in order to generate a common language, enable comparable data collection, benchmarking, and experience accumulation.

6.3 Significance of the shape of the CPI curve in strategic planning

Although the method works principally with every shape of CPI curve, the shape of the curve drastically effects decision making. If the CPI curve is

- linear, then all measures have the same additional cost/benefit ratio (static indicator) and a decision maker should spend all of his budget until there are no EEMs left if he wants to save as much energy as possible, i.e. each EEM provides the same return on investment. As an example, EPMs can have a linear shape.
- convex, then the more expensive the measure the greater the improvement in energy efficiency and a decision maker should, therefore, spend all of his budget until there are no EEMs left if he wants to save as much energy as possible.
- concave, then the more expensive the measure the lesser the improvement in energy efficiency and a decision maker must determine the optimal number of EEMs, i.e. the EEMs that provide him with

desired improvement in energy efficiency for the least cost. A concave curve is supported by the work of Jakob [29], the US EPA [51], Jones et.al [52], the IEA [35], the WEC [53], Kost [54], Fraunhofer [55], and the cases provided in this paper, i.e. it is easier and less costly to improve a building with a low energy efficiency than it is to improve a building that has already a high energy efficiency resulting in a concave curve for EEMs. A concave curve implies that the law of increasing relative costs is applicable on EEMs. This has some practical implications: a) There is a need of optimisation of EEM's in relation to costs and benefits, b) The concave shape can be used as an approximation to start drawing a CPI curve if there is still little data available, c) Static indicators have a linear shape and are therefore insufficient for the given task.

7 Conclusion

7.1 Summary

The proposed Cost-Performance-Indicator curve or CPI method complements conventional strategic planning methods for budgeting maintenance and refurbishment with a method for budgeting additional costs to improve energy performance. No other method is known on portfolio level that indicates the costs in function of the current functionality and the desired energy performance or provides a comparable function and has found acceptance in the market.

For strategic decision making, low cost for data acquisition is more essential than the accuracy of the results for each building within the portfolio. The CPI curve is based on the assumption that the law of increasing relative costs is applicable for EEM's and can be mathematically formulated. Unfortunately, there is still a chance that the random nature of different aspects concerning the refurbishment and enhancement of a specific building stock may make it inherently impossible to predict costs for additional EEMs accurately enough to justify the expenditure for such an instrument. Irrespective of this question, the CPI curve is a useful model to explain interested building owners the relations between refurbishment and new requirements, associated costs and benefits, and the role of renewable energy.

Without this or a comparable method, decision makers need either to rely more on personal experience or more on costly and detailed analyses of buildings assigned for potential refurbishment projects and may end up with less energy efficient buildings because potential benefits are not realised.

7.2 Further research

The CPI curve and its combination with refurbishment budgeting tools is a new method for strategic planning. Therefore, the need for additional research appeared at several points. First of all, additional effective data to gain more experience in constructing and using the CPI curve needs to be collected. The proposed definitions in this paper could support this task. Based on additional data, a reconfirmation of the CPI curve on an elemental basis (bottom-up approach) should be undertaken in order to find an explanation of the steep power-law relation in the single measures curve, better algorithms to calculate the variables and construct the CPI curve, and to explore the limits of the curve and the possibility of extrapolation towards zero energy houses. Also recommended is research concerning influencing factors like the number of buildings with similar characteristics that are needed in a mixed portfolio in order to obtain sufficiently accurate results. A constant task will be the incorporation of the effects of the constant evolution of costs and the advancement of technology concerning EEMs on the CPI curve. For international application, conditions in specific countries (e.g. regarding building standards, climate or legislation) and the resulting factors and variables in the CPI curve need to be evaluated. Finally, an expansion of the CPI curve in order to encompass sustainability in its entirety can be aspired to.

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Annex 1. Table of buildings at Zurich Airport with relevant data

Building	Area (energy reference) m²	EPI before ECMs MJ/ m².a	EPI after ECMs MJ/ m².a	Cost of RMs CHF	Additional cost of ECMs CHF	Number of ECMs	Energy saved MWh/a	Energy saved %
1	45'130	551	438	5'447'795	495'608	37	5'135	20.6%
2	35'698	350	283	235'500	1'335'900	36	2'400	19.2%
3	57'468	460	386	5'787'000	1'336'530	34	4'264	16.1%
4	6'285	683	503	0	113'850	18	1'131	26.4%
5	59'156	281	224	1'221'800	1'461'400	43	3'399	20.4%
Total	203‘737	416	336	12'692'095	4'743'288	168	16'329	19.3%

Cost / benefit ratio of all proposed measures in all buildings: 2,7 years

Annex 2. Methods and tools to help plan measures to improve the sustainability of buildings with exemplary references part 1

Methods	Exemplary references
1) Energy analysis / energy audit; based on on-site inspections and detailed calculations	EN 16427-2 [26]
2) Virtual energy analysis (no-touch audits or rapid energy modelling, data mining); based on building management systems with a large number of data points	Reference [28]
3) Simulation of thermal building loads using heat balance techniques; based on detailed construction data and surface areas of effective buildings and used for design purposes	DIN V 18599 [27]
4) Incremental cost benefit analysis; often based on an energy analysis employing a split of cost of RMs and additional cost for EEMs, refurbishment planning using service life considerations, and considerations of constraints based on the other interventions	INSPIRE in Eracobuild [36] and IEA Annexe 56 [5]
5) Top-Down building stock modelling; based on past data like energy use in an economy and related variables like gross domestic product GDP for modelling	Kavgic [30]
6) Bottom-up building stock modelling (see also simulation of thermal loads or archetype modelling); based on data of archetypes, their distribution, and the impact of changes in variables like different energy technologies and policies for modelling	Kavgic [30], Kesicki [31], Heeren et al. [32]
7) Assignment of buildings to archetypes and modelling of savings from typical EEMs per archetype; based on a proposed database of reference buildings for archetypes with a list of applicable EEMs per archetype and their cost and benefits (e.g. from list of 500 EEMs in [22])	Chidiac [34], IEA [35] (see also EPBD [2] and SLABE [33])
8) Definition of reference buildings or samples and general EEMs; based on proposed representative (for functionality, climate, etc.) reference buildings and fitting EEMs with costs and benefits	EPBD [2], SLABE [33]
9) Calculation of a reference project and marginal costs of element specific EEMs; based on the estimation of marginal costs for improvement of common building elements including associated benefits	Jakob et.al [29]
10) Multi-objective optimisation between alternative measures; based on a list of measures with calculated costs and benefits as well as relations between alternatives; listed exemplary tools are using different mathematical descriptions to find optimal solutions	Menassa [37], Juan [38], Kaklauskas [39], Diakaki [40], Fawcett [41], Girmscheid [42], Wu [43]

Annex 2. Methods and tools to help plan measures to improve the sustainability of buildings with exemplary references part 2

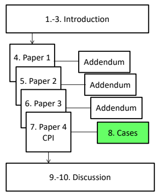
Methods	Exemplary references
11) Process based refurbishment strategy and measures optimisation; based on costs and benefits and inter-dependencies of EEMs in relation to alternative strategies, the exemplary method takes a process approach and gives answers for a small number of empirical variables	4-step model and tool IMMOWIN in Pichler [44]
12) Specific decision making methods or tools; the given example is a decision making tool to decide between refurbishment and new construction)	Retrofit advisor [45]
13) Element based addition to such methods for refurbishment planning (e.g. method Schroeder [11, 46]); Based on (dynamic) indicators for additional costs and benefits of ECMs per building element in addition to conventional refurbishment planning	(no references available, method not published yet)
14) Energy performance based addition to element based methods for refurbishment planning; based on a dynamic indicator to model additional costs and benefits of ECMs in addition to conventional refurbishment	Proposed CPI presented in this paper
15) Risk quantification; based on values placed on risks as part of the valuation resulting in an incentive to reduce them	Economic Sustainability Indicator ESI [18]
16) Indicators or benchmarking figures; usually one static figure based on common structures and definitions and a large number of similar cases	Energy performance indicator EPI (kWh/m^2.a)

Annex 3: Example

Quantitative example of benefits achieved with using a CPI curve approach (refer to chapter 5.2).

		Case A			Case B	
		Without using the CPI curve			With using the CPI curve	
Building name		A1	A2		B1	B2
Suitability for energy production		no	yes		no	yes
Basic values						
Value of building (reconstruction)	€	30'000'000	30'000'000		30'000'000	30'000'000
Area	m2	10'000	10'000		10'000	10'000
Specific value	€/m2	3'000	3'000		3'000	3'000
Energy consumption	kWh/a	3'000'000	3'000'000		3'000'000	3'000'000
Initial EPI	kWh/m2.a	300	300		300	300
Price of Energy	€/kWh	0.10	0.10		0.10	0.10
Indirect measurable benefits per kWh	€/kWh	0.05	0.05		0.05	0.05
Energy costs (direct)	€/a	300'000	300'000		300'000	300'000
Costs of photovoltaic installation	€/kW	1'300	1'300.00		1'300.00	1'300.00
Costs of photovoltaic production	€/kWh/a	1.10	1.10		1.10	1.10
Costs of photovoltaic energy	€/kWh	0.14	0.14		0.14	0.14
Savings						
Target EPI	kWh/m2.a	50	50		50	50
Target cost/benefit ratio (restriction)	-	7.5	7.5		7.5	7.5
Target savings	%	85%	85%		85%	85%
Target benefits	€/a	382'500	382'500		382'500	382'500
Achieved EPI within restrictions per measure	kWh/m2.a	150	150		n/a	n/a
Achieved EPI considering packages, EPMs	kWh/m2.a	n/a	n/a		50	180
Achieved EPI	% of target	60%	60%		100%	48%
Achieved savings	€	229'500	229'500		382'500	183'600
Costs (in % of value) according to CPI curve	%	4%	4%		10%	3%
ECMs						
Costs of ECMs	€	1'200'000	1'200'000		2'850'000	750'000
Cost/benefit ratio ECMs (excl. EPMs)	-	5.2	5.2		7.5	4.1
EPMs						
PV production required for target EPI	kWh/a	n/a	1'000'000		n/a	1'300'000
Costs of PV production	€	n/a	1'100'000		n/a	1'430'000
Benefits	€/a	n/a	150'000		n/a	195'000
Cost/benefit ratio EPMs	-	n/a	7.3		n/a	7.3
EEMs						
Costs EEMs (ECMs and EPMs)	€	1'200'000	2'300'000		2'850'000	2'180'000
Costs of RMs (in % of value)	%	50%	50%		50%	50%
Costs of RMs	€	15'000'000	15'000'000		15'000'000	15'000'000
Costs of measures	€	16'200'000	17'300'000		17'850'000	17'180'000
Benefits	€	229'500	379'500		382'500	378'600
Cost/benefit ratio of EEMs per building	-	5.2	6.1		7.5	5.8
Final EPI	kWh/m2.a	150	50		50	50
Target achieved per building		no	yes		yes	yes
Total buildings 1+2						
Total costs of measures both buildings	€	->	33'500'000		->	35'030'000
Total costs ECMs incl. EPMs	€	->	3'500'000		->	5'030'000
Total benefits	€	->	609'000		->	761'100
Total cost/benefit ratio	-	->	5.7		->	6.6
Additional cost in % of building value	%		5.8%			8.4%
Achieved EPI average of buildings	kWh/m2.a		100			50
Target achieved average of buildings			no			yes
Differences case A to case B						
Additional funds applied due to CPI	€		n/a			1'530'000
Additional benefits	€		n/a			152'100
Cost/benefit ratio of additional funds	-		n/a			10.1

8 Examples



In the first part of this section, a real portfolio is presented and analysed. Based on this real data and some assumptions, two cases of an application of the CPI method are provided, one on portfolio level and one on building level. The first case follows the steps in the CPI method where applicable. The cases show how this method can be initially introduced and what the potential problems and benefits of the two separate applications are. Further, the sensitivity of different parameters is discussed and the sensitivity of the most influential parameter analysed with the additional instrument of the CPI benefits matrix. Finally, the differences between conventional planning and the application of the CPI method are summarised and discussed.

8.1 The portfolio

The chosen example is the real estate portfolio of the canton (or state of) Zürich. It is the state with the largest city (Zürich) and the largest population (1.45 million people) In Switzerland. The example was chosen due to the availability of data (public buildings) and the relative uniformity and larger size of the portfolio[22].

It contains around 2’000 buildings with a reconstruction value of 15 billion CHF (book value 8.5 billion CHF). There are four main categories of buildings (Table A1):

- Administrative buildings
- Educational buildings, starting at the postsecondary level (primary and secondary schools belong to the cities or communities) including universities and further vocational education
- Justice and military buildings, including police stations, courts and detention facilities
- Health care related buildings, i.e. state hospitals

Most of these usages are comparable to the usage of a standard office building, therefore, the portfolio is considered as being relatively uniform. Exceptions are e.g. the state hospital, university laboratories, sports

[22] The original data is available for the reviewers so that any numbers can be reproduced. Further availability of data requires the written consent of the owner.

facilities within schools, agricultural research facilities or heritage listed buildings (e.g. castles). There are no industrial or production facilities nor are indoor or outdoor swimming pools included. Every building has a unique number referring to the land register and differentiating each building on each parcel of land.

Around 50% or 950 buildings with a reconstruction value of 9.6 billion CHF have been assessed on-site and recorded in the software application STRATUS (refer to section 6; Paper 3) for maintenance and refurbishment planning reasons. The assessment includes information about age, size (area or volume), value and physical condition. A minor part of these – 95 buildings or groups of – are measured and monitored with respect to energy consumption on a regular basis. The monitoring of this sample of buildings includes recording of consumption and costs of electricity, of different forms of heating, and of water – around 400 data sets - in a stand-alone energy database (Excel). Unfortunately, energy reference areas and building volumes in STRATUS do no always match as in some cases, whole groups of buildings – e.g. the majority of buildings belonging to a post-secondary school campus - are measured together. Such groups have been given a different number that also relates to the parcel of land but unfortunately complicates the match between the two databases. 73 buildings or groups in the energy database could have been matched successfully with the STRATUS database. This means that the energy reference area and calculated gross floor area (calculated based on volumes using fixed floor heights) do not differ by more than 20%. In total, considering groups of buildings, the energy database covers around 340 buildings in the STRATUS application (35% of assessed buildings, on average 6 buildings per group with two groups of hospitals including more than 30 buildings).

Of the other 50% of mainly minor buildings in the portfolio, such detailed information is not available.

8.2 Analysis of portfolio

This is step 1 in the CPI method. The available data of the portfolio has been analysed from different angles. Much effort was previously needed to match the STRATUS data with the separate data from the energy database due to the partially different building numbering used.

8.2.1 Age

Figure 6 shows the distribution of age of the buildings in the assessed portfolio. The oldest building dates back to 1250. The average age of all the assessed buildings is around 90 years, even when weighted with the value or the volume. In the 1970s, new construction boomed. Naturally, during world war I and II construction stood at a standstill. A distinct peak of 21 buildings in 1866 could be historically interesting (e.g.it was the same year as the introduction of the law of justice). The twin peaks in 1976 and 1979 of 27 buildings each are probably just that, a coincidence. A regular pattern such as a peak every tenth year (e.g. estimated construction date at a round figure) cannot be observed.

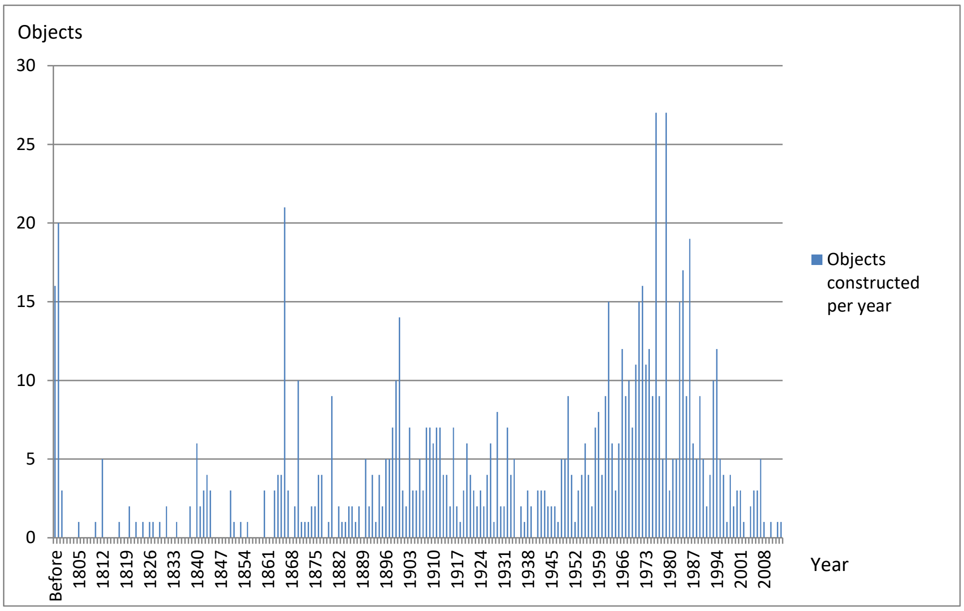


Figure 6 *Distribution of age of buildings in the assessed portfolio (number of objects constructed per year)*

8.2.2 Size

Figure 7 shows the distribution of volumes (in m^3) of assessed buildings. At the top, the distribution is very uneven with a few very large objects. Two of the largest buildings belong to the university hospital, one is the university underground parking. Total volume of assessed buildings is 10.4 million m^3. The average size is 11’050 m^3 or, using an average height per floor of 4m, 3650 m^2 of gross floor area GFA. The total volume of monitored buildings is 70% of that volume or 7.1 million m^3. In this instance, the monitored sample is not fully representative and seems to cover more of the larger buildings. The average size in the monitored sample is much larger because it contains groups of buildings that count as one object.

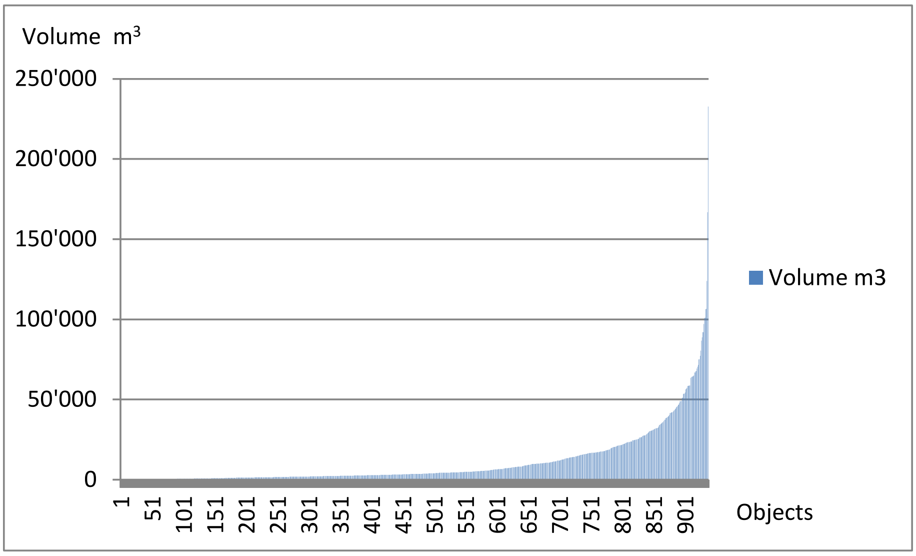


Figure 7 *Distribution of volumes in m³ of assessed buildings*

Figure 8 shows the volume built in a specific period. Here, the peak in the seventies is even more evident.

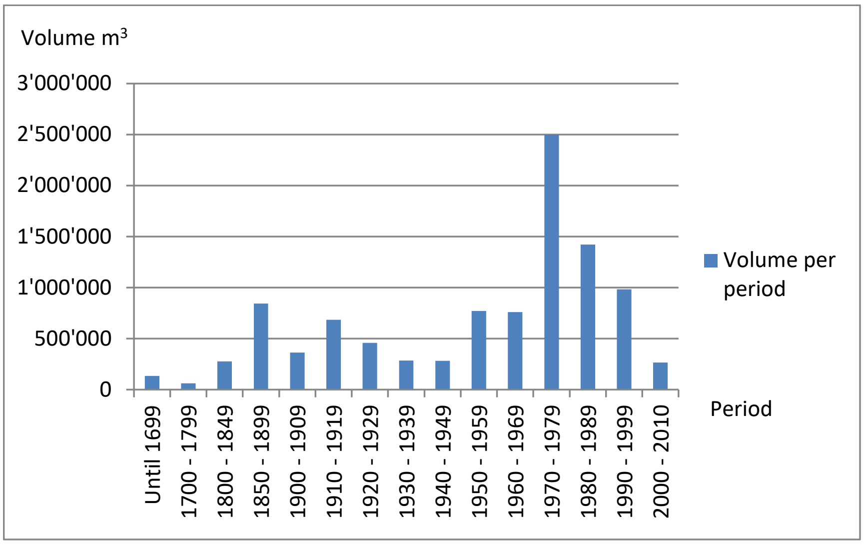


Figure 8 *Volume in m³ constructed in a specific period (after 1900: 10 years in each period)*

8.2.3 Energy reference area (Ger.: Energiebezugsfläche EBF)

Figure 9 shows the distribution of EBF in the monitored buildings. The measuring of the EBF is defined in standards like SIA 416/1 and usually differs from the GFA. The EBF have been compared with the volumes (assumed average floor height of 4m which includes a factor for different measuring of GFA and EBF) to check if buildings in the two databases match. In some cases, groups of buildings on a large parcel of land needed to be confined to the monitored group of buildings (e.g. having the same address). The totals of EBF and GFA of the monitored portfolio differ less than 5% and less than 20% in individual buildings. The picture in Figure 9 looks similar as the one in Figure 7. The monitored buildings seem to be a representative part of the assessed buildings where the distribution of size is concerned.

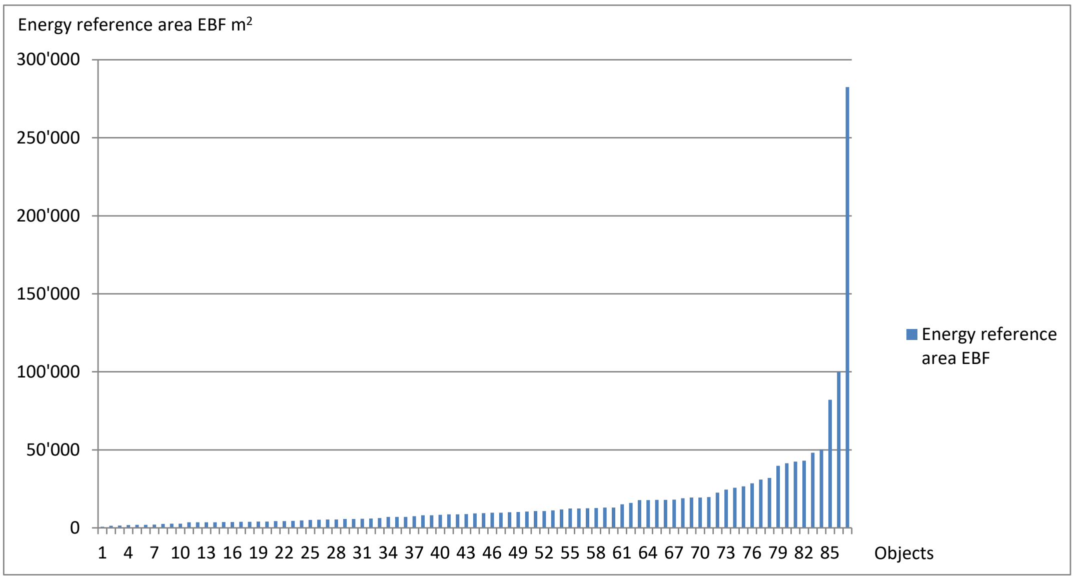


Figure 9 *Distribution of energy reference area EBF in m^2 in the monitored buildings*

8.2.4 Absolute value

Figure 10 shows the distribution of reconstruction values of the assessed buildings. The picture is very similar to the one of the distribution of size. Around 80% of the assessed buildings are worth more than 1 million CHF. The total assessed portfolio value is 9.6 billion CHF and the average building value is 10.05 million CHF.

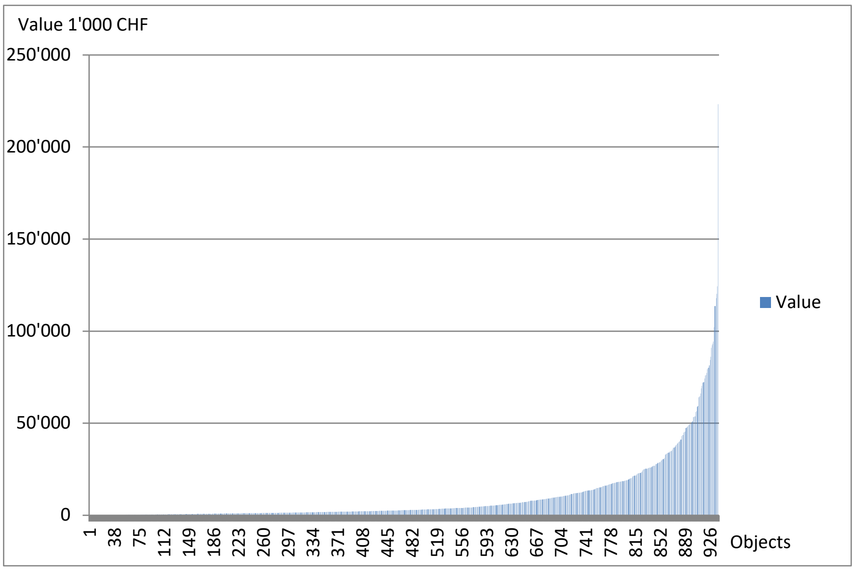


Figure 10 *Distribution of (reconstruction) values in CHF of the assessed buildings*

8.2.5 Relative value

Figure 11 shows the distribution of specific reconstruction values of the buildings per volume expressed in CHF/m^3. The average is around 900 CHF/m^3. All buildings with an exceptionally high relative value above 2’500 CHF/m^3 belong to smallest buildings in size. They were found to be irrelevant and have been left out of the figure (in total 10 buildings).

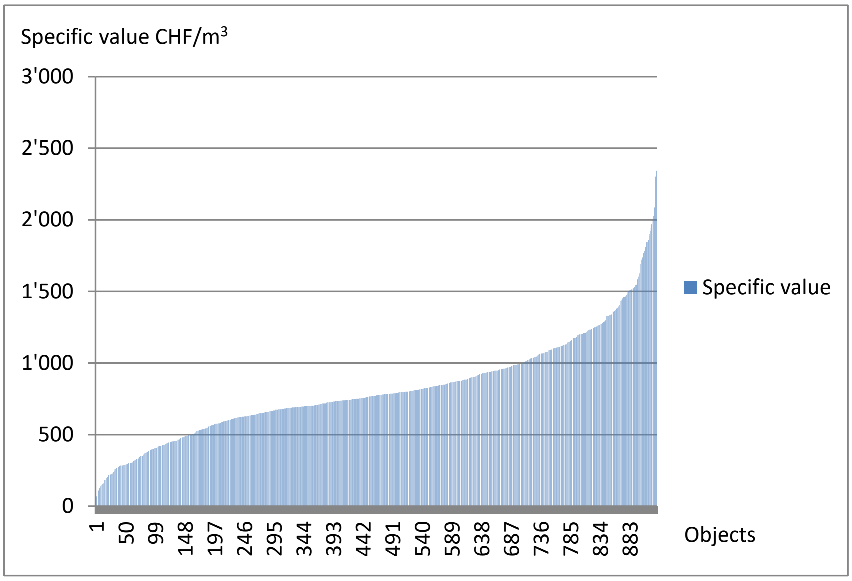


Figure 11 *Distribution of specific reconstruction values of the buildings per volume in CHF/m^3*

8.2.6 Relation between size and relative value

Figure 12 shows the relation between size and specific value. Interestingly, the linear trend line is ascending, there is no economy of scale to be observed in this portfolio. This can be explained by the fact that rather complex and expensive buildings, like hospitals or university laboratory buildings, are usually very large in size as well.

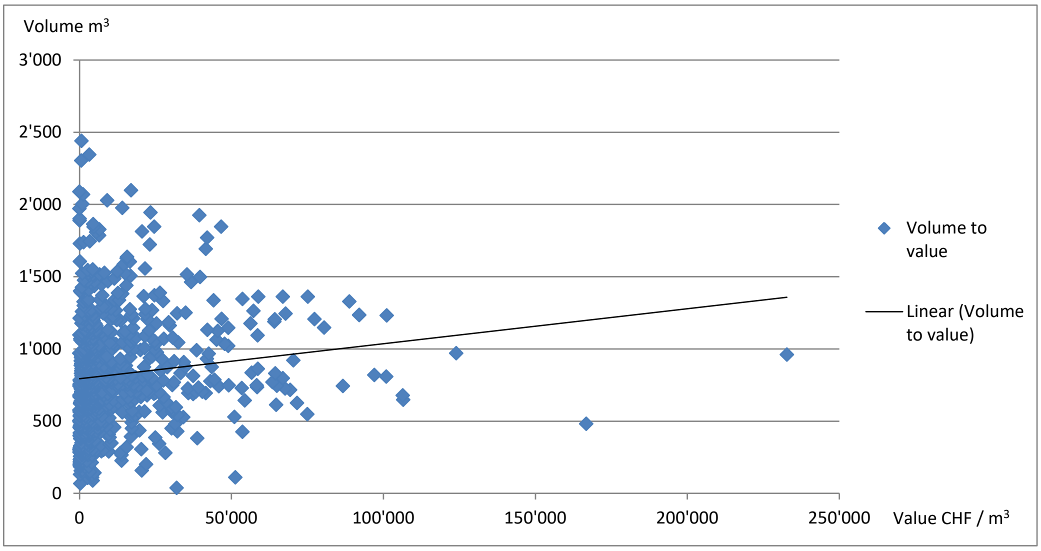


Figure 12 *Relation between volume in m^3 and specific value per volume in CHF/m^3 with linear trend line*

8.2.7 Physical condition

Figure 13 shows the distribution of physical condition of the assessed buildings. It is defined as the quotient of the current, condition based (deteriorated) value divided by the reconstruction value. The current value is calculated by the application STRATUS from the assessed condition of around 15 elements by (annually) following individual deterioration curves. Forming the sum of such curves, the distribution of the portfolio also resembles a deterioration curve with a sharp decline in the first few years, a longer period of consolidation and then an ever stronger deterioration towards the end of the projected service life. The average quotient is 0.73. If this value continues to fall over time, it may indicate a potential maintenance backlog in the future.

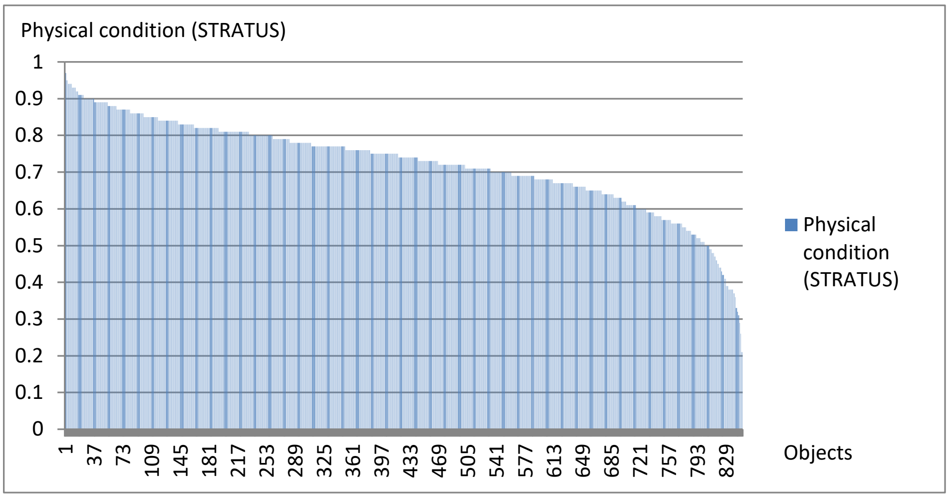


Figure 13 *Distribution of physical condition of the assessed buildings (STRATUS)*

The average condition of the monitored sample of buildings is higher with 0.78. In this instance, the sample is not fully representative of the portfolio. One reason for this may be that energy measuring is partly used to control the effectiveness of executed refurbishment measures.

8.2.8 Energy Performance Indicator EPI (thermic and electric)

Figure 14 shows the distribution of the EPI in the monitored part of the portfolio. The EPI is measured in kWh/m^2.a (area used = EBF). The measure is not repeated each time in this section when a value for the EPI is given. Each value is subdivided into the EPI thermic (i.e. oil, gas, district heating) and EPI electric (including electricity for heat pumps or resistance heating, lighting, and user appliances or processes). Figure 15 shows the relation between EPI thermic and EPI electric with a trend line. The linear trend indicates that high consumers of heating have also a large consumption of electricity (b=0.2). This is surprising as a large consumption of electricity usually facilitates heating in winter in the form of rejected heat.

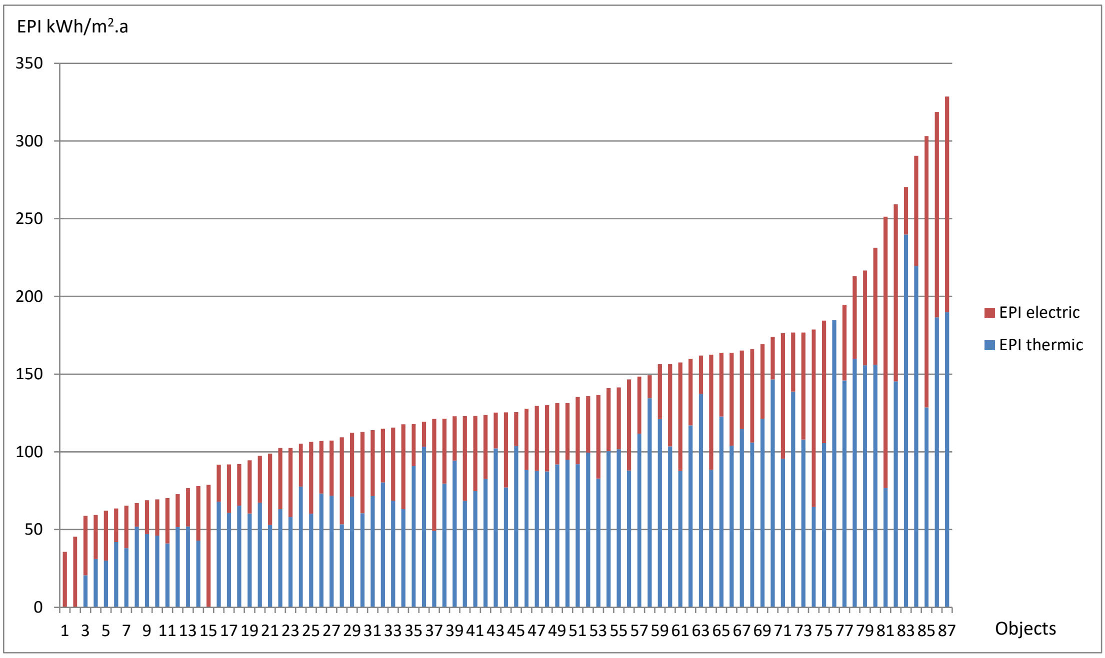


Figure 14 *Distribution of the EPI in the monitored part of the portfolio (EPI thermic and EPI electric)*

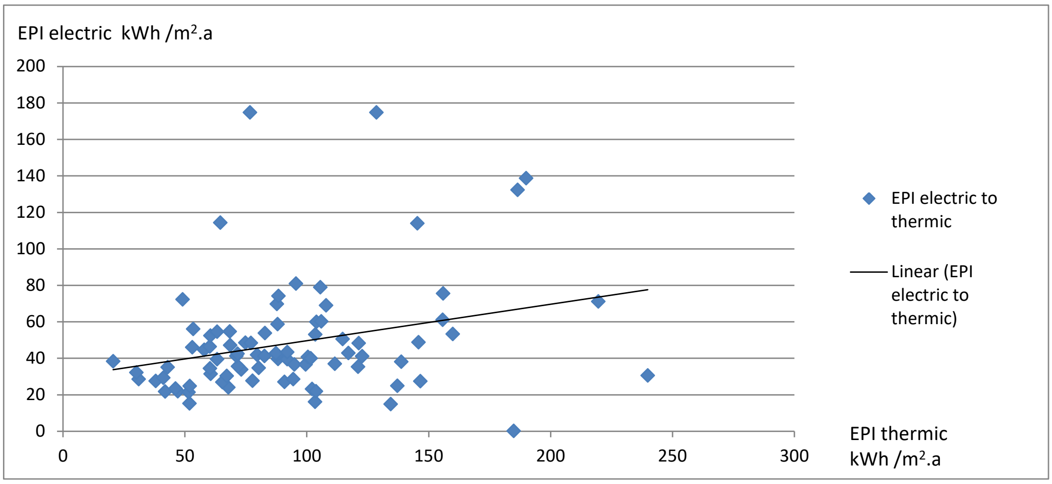


Figure 15 *Relation between EPI thermic and EPI electric with linear trend line*

The EPI thermic can be more or less fully attributed to heating and domestic hot water (there are no industrial processes in the portfolio) except for some gas used for cooking. The EPI electric, on the other hand, includes user related energy such as lighting and user appliances or processes and cannot be fully attributed to the building technique (heating, ventilation, air conditioning HVAC). The measured EPI is therefore not fully comparable with the mandated minimum EPI. Thermic energy accounts for around 2/3 of total energy and electricity for the remaining 1/3. The split of electricity between HVAC and user related energy is not known. It is assumed to be 1/3 and 2/3 again, i.e. around 15-20% of total energy is user related energy. This fixed share ignores the fact that the share of user related energy rises the more efficient the building itself becomes.

The largest consumers are the five hospitals or health care related groups of buildings. They consume 50% of the monitored energy on only 30% of the area. In Table 12 the number of buildings and the different shares on consumption and volume of different usages are listed. The measured average EPI of all monitored buildings is 181 and excluding the hospitals, 125. The Minergie target value for refurbished office buildings is 55. For this example, the health care related buildings haven been left out because they cannot be compared with the rest of the portfolio where energy efficiency is concerned. Compared to the average EPI thermic in residential buildings (built between 1920 to 1980) of 175 to 225 [72], the overall EPI of 125 is already fairly low. However, as previously mentioned, the monitored buildings have been partly included in this sample due to previous ECMs executed on them to control the outcome. Therefore, the sample is most likely not representative for the whole portfolio where energy efficiency is concerned.

Table 12 *Number of buildings and different shares on consumption and area EBF per usage*

Category of use	Number of buildings	Energy kWh/a	EBF m2	EPI kWh/m2.a	Share of energy %	Share of EBF %
Health care, hospitals	5	136'384'841	459'586	297	53.6%	32.8%
Education, high schools	11	32'578'392	280'276	116	12.8%	20.0%
Education, vocational	27	27'589'318	234'540	118	10.8%	16.7%
Administration, offices	16	19'606'340	155'918	126	7.7%	11.1%
Education, university	4	15'506'999	118'899	130	6.1%	8.5%
Military, offices and baracks	3	6'638'799	47'872	139	2.6%	3.4%
Justice, detention centers	2	11'681'804	57'395	204	4.6%	4.1%
Police and traffic	5	4'609'405	48'467	177	1.8%	3.5%
Total	73	254'595'898	1'402'952	181.5	100.0%	100.0%
Cost of energy CHF / CHF per m2		28'569'698	20.4			

The correlation between age and EPI did not yield a clear result in the sample. The reason may be that buildings older than 30-50 years have already been refurbished and energetically improved and are therefore not reflected in the original construction date.

8.3 Assumptions

Most figures in the two cases presented in this section are based on the figures in the real portfolio (Table E1). However, some assumptions have been necessary.

In most buildings, low-cost ECMs do exist. There are companies which have specialised in these, like e.g. Energho [78]. The following decreasing low-cost EE gains in function of the EPI are assumed: for EPIs > 200 -> 20%, for EPIs 150-200 -> 15%, for EPIs 100-150 -> 10%, and for EPIs < 100 -> 5%.

Following a study [71] which found that additional costs to achieve Minergie standard in new construction (55 kWh/m^2.a) are maximal 10%, it is assumed as a first estimate that the additional costs to achieve Minergie standard in refurbished buildings are also 10%.

It is further assumed that every building is refurbished on average every 40 years (e.g. windows every 15-30 years and roof covering every 50-60 years) except for the load bearing structure which lasts for several such refurbishment cycles. The load bearing structure counts for 35% of the building value in the software STRATUS. Under these assumptions, average annual refurbishment cost is 1.6% of the value. Taking into account that some buildings are not refurbished at all but replaced with new construction, average refurbishment cost of 1.3% is assumed for a portfolio.

The assumed amortisation period of 20 years for ECMs is derived from a mix of building technique measures (15 years) and structural measures (30 or more years).

For the production of renewable energy with photovoltaic, costs of 1’800 CHF per kW, a production of 1’500 kWh/kW.a, 20 years amortisation and 5% for maintenance and interest (e.g. with a contracting model) are assumed. With these assumptions a fixed production price of 0.12 CHF/kWh for the next 20 years results.

8.4 Case 1 application on portfolio level

This case shows the application on portfolio level and follows the steps in the CPI method.

8.4.1 Energy efficiency options - first draft CPI curve

Step 1.1 of the CPI method is the analysis of energy efficiency options. This includes the drawing of an initial CPI curve for the (monitored) portfolio. No on-site inspection or planning of measures was conducted for this example.

Based on the experience with the Zürich airport and the DENA examples with the form of the curve, a preliminary, first draft of a CPI curve for this portfolio has been drawn (Figure 16). Following the assumptions made in section 8.3, the curve was calibrated so that the additional costs in order to achieve Minergie standard are 10% [71, 75]. It is part of the CPI method to continuously evaluate and improve this first draft CPI curve based on the results of refurbished objects.

The draft CPI curve shows the initial and the target condition as well as the legal requirement of 75.

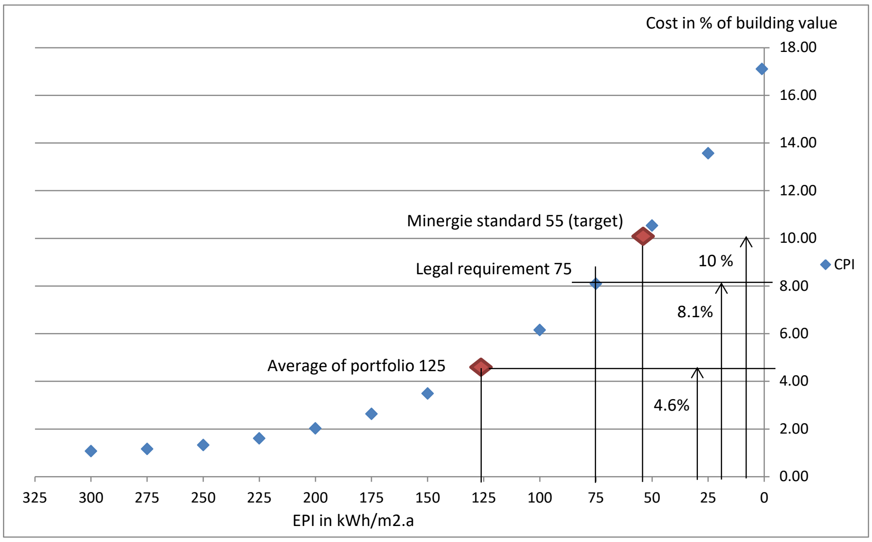


Figure 16 *First draft of the CPI curve*

The formula used is: $y=a+b*(fx)^4$ (a=1 so that the curve does not start at zero and leaves room for higher EPIs; the variable a could also be interpreted as initial planning costs; b calibrates the curve within the coordinates; $fx=x_0-x$ with x_0=start of the curve/highest EPI).

From this first draft CPI curve (Figure 16 and Figure 17), the following information can be extracted:

- In order to attain Minergie standard, two thirds of the additional costs for ECMs are needed for the legal requirements in this example (this is not a general statement)
- The gradient of the tangent of the average EPI of 126 is around 0.052
- The gradient of all measures as a group to achieve Minergie standard is around 0.077

8.4.2 Portfolio strategy

Steps 2 and 3 in the CPI method are to set goals and constraints and determine the RE portfolio strategy.

The Canton of Zürich is presently working on a new RE strategy in which all three aspects of sustainability will be considered. In its energy planning report 2013 [72, next report planned for 2017] and sustainability standard [73] the Canton expressed its wish to achieve the Minergie [23] standard in new and refurbished buildings as its target. This label is supported and aspired to by federal, state, and communal authorities for their public buildings in order to become role models for private investors. This target was chosen without previous cost/benefits considerations. The costs of being a role model are unknown. In practice, cost/benefit considerations are demanded for each refurbishment project before constructions starts and then the target is sometimes disregarded based on cost constraints.

The Minergie standard requires a weighted EPI of 55 $kWh/m^2.a$ or less in refurbished office buildings and even less in new buildings. It includes heating, ventilation, and air conditioning (HVAC, including domestic hot water) without user related energy (lighting and user appliances or processes). The weighting factor for electricity is higher than for oil and gas due to the higher energetic value of electricity. In the example, the reduction from

[23] Minergie is a Swiss born label for different types of buildings concentrating on low energy consumption and user comfort. Around 50% of all newly constructed buildings (public and private) in canton Zürich are compliant to this standard today.

considering user related energy and the increase from the weighting factors are assumed to be nearly equal and are therefore disregarded for the calculation of the EPI in order to reduce complexity.

Current legislation in Switzerland requires an EPI between approximately 60 and 90 (assumed average: 75) for refurbished office buildings. This is no longer state-of-the-art. The next step planned in legislation is to lower the required EPI to levels near or below Minergie (section 8.6 [74]). This step is in line with the European Energy Performance of Buildings Directive, EBPD [2] which talks about 'nearly zero energy buildings', and like the EBPD, will take effect around the year 2020.

Table 13 *Comparison of planned legislation and Minergie / Minergie-P*

Threshold values Category of buildings		EPI (HVAC) kWh/m² New / Refurb. buildings	Comparison with Minergie kWh/m² New / Refurb. b.	Comparison with Minergie-P kWh/m² New buildings
I	Residential single-family	35 / 53	38 / 60	30
II	Residential multi-family	35 / 53	38 / 60	30
III	Office	40 / 60	40 / 55	25
IV	Schools	35 / 53	40 / 55	25
	…			

From [74] and [71]

With the new legislation, the current level to suffice as a role model will become the future mandated standard. In order for the Canton to remain a role model past 2020, a step towards effective 'zero energy buildings' would have to be taken.

At the moment, the authorities of the Canton do not know what its energy target or other scenarios cost or even what the benefits are. In the following sections, an attempt is made to answer these questions based on effective figures, the draft CPI curve, and some necessary assumptions.

8.4.3 Anyway cost for refurbishment

Under the assumptions listed in section 8.3, annual refurbishment cost is 1.3% of the value of the assessed portfolio (value 9.6 billion CHF) or around 155 million CHF/a. This does not include enhancement measures like EEMs or adaptations to changed user requirements. Effective annual investments in RE are 300 million CHF/a. If

50% is spent on new construction/enhancement and the other 50% on refurbishment, these investments are more than likely sufficient in preventing a maintenance backlog which would result in a deterioration of the portfolio's average condition over time.

8.4.4 Anyway and additional cost for EEMs

For the estimation of anyway cost for EEMs needed to achieve legal requirements and additional cost for EEMs beyond legal requirements and their split, the CPI curve is necessary. The average CPI of the monitored portfolio (without hospitals) is 125. Applying the current legislation (e.g. minimal insulation standards), a CPI between 60 and 90 (assumed average 75) results with costs around 3,5% of building value.

The strategy defines the Minergie standard with a CPI of 55 (refer to section 8.4.2) as the target. Additional costs to achieve the Minergie standard beyond legal requirements are around 2,9% of building value. If looking at single measures as in regard to conventional methods, these costs are then independent of the initial EPI for buildings with an EPI higher than 75. Conventional methods follow the CPI curve at relatively low gradients (the low hanging fruit) until legal compliance is achieved. In this case from an EPI of 125 down to 75 with gradients starting at 0.053% (Figure 17). Further improvements of the EPI follow the CPI at higher gradients. In this case from 75 down to 55 with gradients up to 0.104%. There, the measures are more expensive and, therefore, harder to justify economically on their own. If looking at all measures as a group as in the CPI method, this percentage becomes lower the higher the initial EPI is. Consequently, more costs can be attributed to the anyway costs, i.e. more additional EEMs are economically feasible. In this case, this effect accounts to around 15% of the costs to achieve the target EPI.

8.4.5 Benefits – direct energy cost savings

Energy costs for the monitored sample of buildings excluding (in brackets: including) hospitals are 12.2 (26.8) million CHF, of which 7.0 (14.3) is thermic energy for 0.09 CHF/kWh and 5.2 (12.5) electric energy for 0.13 CHF/kWh. If the average EPI of 125 (181) is lowered to 55 by ECMs, then direct energy savings of around 66.3 million kWh/a or 6.9 million CHF (177.4 million kWh/a or 18.7 million CHF) result annually.

As the sample covers 50% of the building volume and possibly the same share of the energy consumption of all assessed buildings, potential savings could be double in the assessed portfolio.

8.4.6 Additional benefits

Direct energy costs saved are often not sufficient to finance all ECMs. To place a value on additional benefits like those mentioned in section 7 (Paper 4) could be a solution to this problem which can be economically justified. In this case, a relatively high value was placed on the desire to be a role model in energy efficient construction and refurbishment. The price of energy was doubled to 0.210 CHF/kWh. With this factor of 2 the economic gradient is 0.089 (20 years amortisation period) and is thus above the gradient of ECMs as a group with 0.077 (Figure 17).

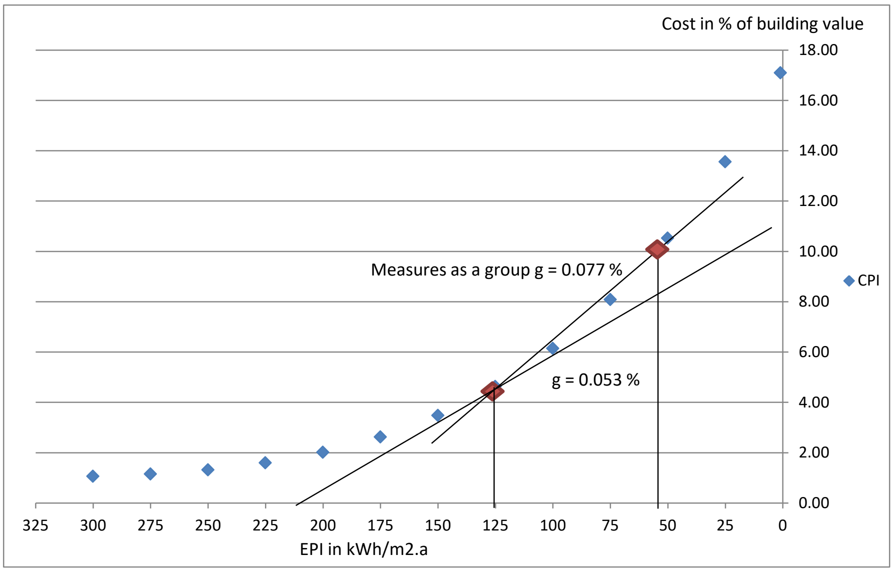


Figure 17 *CPI curve with gradient of EPI 125 and of ECMs as a group down to 55*

8.4.7 Investment cost for ECMs

According to the draft CPI curve, it requires 5.4% of the value to improve the EPI in the monitored portfolio down to the target of 55. This adds up to 162.7 million CHF. Assuming an average amortisation over 20 years, this accounts to annual costs of around 13.6 million CHF. Considering the potential energy savings of 66 million kWh/a, this means an investment of 0.205 CHF/kWh. This is above the direct price of energy without additional benefits of 0.105 CHF/kWh. A consideration of additional benefits is needed in order to achieve the target. The gradient of all measures as a group is 0.077.

8.4.8 Renewable energy production:

Following the assumptions made in section 8.3, a price for photovoltaic energy production of 0.12 CHF/kWh results. This price is close to the average price of energy of 0.105 CHF/kWh and is likely to come down even further in the near future. Considering a common electricity tariff structure with a daytime high tariff and an average production profile with maximum production at midday, photovoltaic energy replaces electricity mainly charged at the higher daytime tariff and not at the average price. Consequently, the price of self-produced photovoltaic energy may be already below the effective price of energy delivered from the electricity utility.

Investment in RE production can replace higher investment in ECMs per unit of energy saved. Theoretically (refer to section 8.3), with an investment of 80 million CHF (50 MW installed capacity) it would be possible to produce 66 million kWh/a and consequently to reach the target EPI in the portfolio. However, this replacement is possible for only around 50% of electricity consumption because the production profile and the demand profile do not match all the time. For the remaining 50% of production, a form of storage (e.g. batteries), demand shifting, or feeding the surplus energy into the grid at much lower feed-in tariffs would be necessary. Consequently, an optimisation based on tariffs and demand profiles is necessary. The gradient of renewable energy production is 0.039%. In Figure 18 the gradient of the combination of ECMs (50% of EPI reduction) and EPMs is around 0.048. As can be seen, the execution of a combination of ECMs and EPMs is less expensive than the execution of ECMs alone with a gradient of 0,077% (Figure 17).

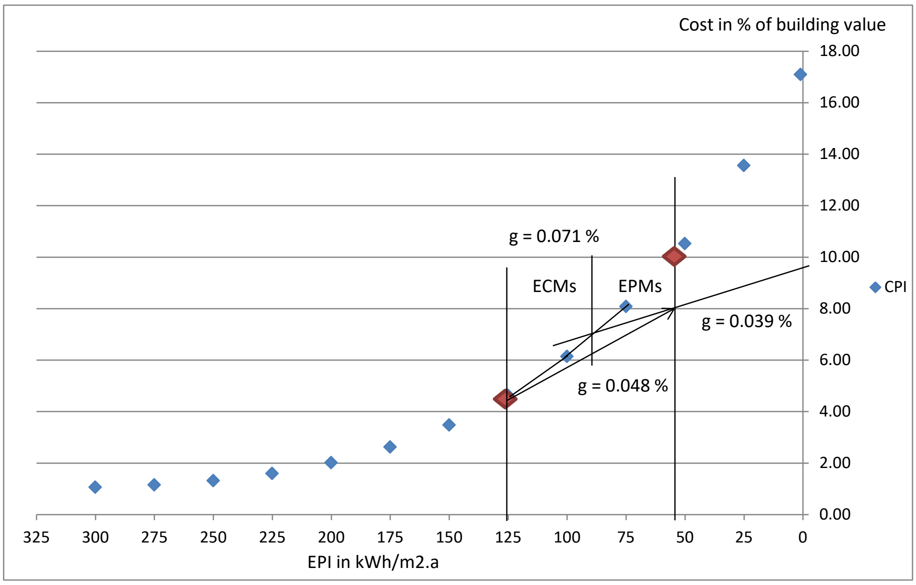


Figure 18 *CPI with a combination of ECMs and EPMs (50% each) resulting in lower costs*

8.4.9 Conclusions from steps 3 and 4

Under the given assumptions, aiming to reach the target EPI of 55 and starting at an EPI of 125, ECMs as a group are economically feasible for the portfolio. ECMs from an EPI of 75 (legal compliance) down to 55 would not be economical in this case if it were considered separately due to the convex shape of the CPI curve and the relatively low average EPI of the portfolio. An optimal combination with energy production is recommended in order to minimise costs. Considering grouping and optimal combinations of ECMs and EPMs, more measures are feasible within financial constraints or even lower targets seem achievable. To gain more transparency regarding these questions, the CPI method is a useful tool.

8.4.10 Set priorities

For step 4 to set priorities - the relation between physical condition and EPI was analysed.

Figure 19 shows the relation between physical condition and EPI and the linear trend line. The trend line shows a negative correlation between condition and energy consumption, i.e. a building in poor condition is more likely to have a high EPI than a building in better condition. This is an important finding regarding the postulated interconnection between RMs and EEMs.

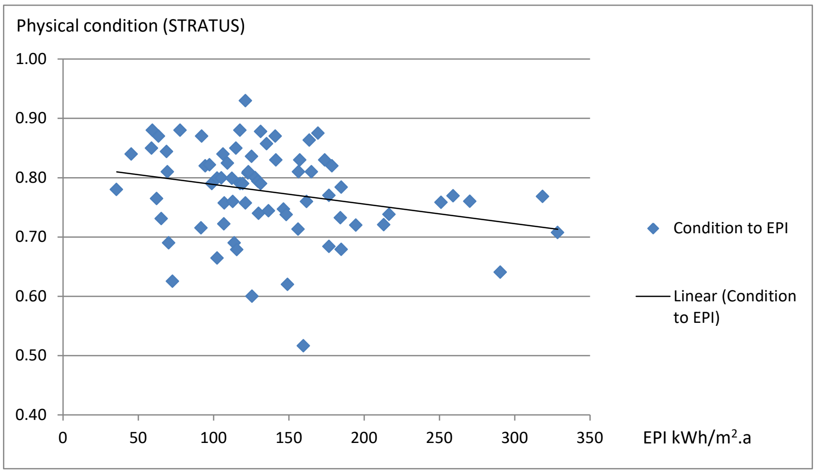


Figure 19 *Relation between physical condition (STRATUS) and EPI in kWh/m^2.a with linear trend line*

Figure 20 shows the distribution of physical condition and EPI in four quadrants (monitored buildings without the hospitals). Only 10-15% of the buildings already reach the target EPI of 55, even when taking away 20% for user related energy. Also, only a few buildings are below the condition of 0.75 and need RMs to be planned in the near future. However, within the next 30 years, nearly all buildings will reach this stage. Refurbished buildings will start a new life cycle at a higher condition and, following legislation and the target, with a lower EPI.

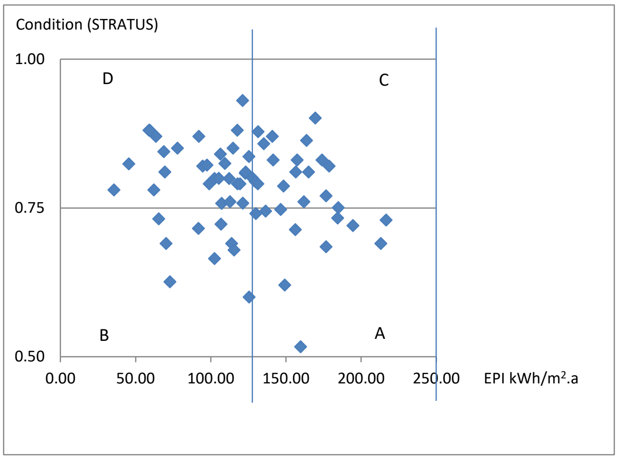


Figure 20 *Quadrants (A-D) of physical condition (STRATUS) and energy efficiency in kWh/m²*.*a*

As the monitored buildings are not fully representative of the whole portfolio, the overall picture may be somewhat different for the whole portfolio.

Refurbishment decisions in regards to this portfolio are mainly based on changing user requirements and rarely on physical condition alone. For these decisions, the results of this analysis is a valuable tool in supporting decision making and to help allocate funds where they are of most benefit. It is, however, not directly part of the CPI method.

8.4.11 Work program

Developing a work program is step 5 in the CPI method. This step requires considerable engineering and design effort as each building is individual. Due to the high costs involved and ever changing requirements, this step is only performed for those buildings which are next due for refurbishment. Furthermore, this is a well-known operational task for a respective contractor and therefore outside the scope of this research work. A list of possible measures which, when implemented in optimal combination, are sufficient to reach ambitious targets for the EPI, is provided in Annex E (Table E2). Depending on the target EPI, measures can be implemented in different numbers and depths. For example insulation can vary between 5 and 30 cm and consist of different materials with specific costs and physical properties.

8.4.12 Execution and evaluation of measures

Execution and evaluation of measures are steps 6 and 7 in the CPI method. Like step 5, the execution of measures is outside the scope of this case. For the evaluation of measures, a sensitivity analysis of the relevant parameters is provided in section 8.6 instead. For the evaluation of the strategy please refer to the following section about the consequences of an application of the method.

8.4.13 Consequences of application on portfolio level

The Canton of Zurich has its own set of relatively strict rules based on the fact that it is a role model for society. As well, it is embedded in a well regulated environment [74]. In this case, the CPI method is most valuable in bringing more transparency to the strategic RE decision making and budgeting process. The authorities can control the cost and value of the Canton being a role model and decide if even more measures would be feasible for this task.

For a more generic discussion in a less regulated environment, a private company with a similar portfolio is assumed. The company has various decision alternatives in respect to the energy efficiency of its portfolio (refer also to Paper 4):

a) Do nothing (executing only MMs, RMs and EMs other than EEMs)
   Due to technological advances (e.g. better efficiency of new windows) a minimal efficiency gain will be achieved

b) Execute measures in order to achieve legal compliance.
   Legal compliance depends e.g. on national legislation or regional building codes. For this example, it is assumed that regulations for existing buildings have not changed since the construction of the buildings in the portfolio and that choosing alternative a) alone would be possible.

c) Execute low-cost EEMs (e.g. energy optimisation like adjusting operating times / temperature settings of building technique or installing movement sensors for lighting)
   Based on the authors own experience, an efficiency gain of 5-10% can be expected in most buildings prior to any energy optimisation.

d) Execute economic measures.

The range of measures depends on economic decisions of the company such as interest rates, pay-back period, and additional benefits to be incorporated.

e) Execute measures to achieve a rating label.

A rating label may enhance the value of a portfolio through better lettability and testified quality or may be demanded by a corporate responsibility strategy.

f) Execute measures to achieve excellence.

Various authors show that many building owners tend to choose alternatives a), b), or c) and propose measures to overcome the hurdles towards more energy efficiency (so that building owners consider alternatives d) to e) as well) they have identified [references 6,7,8,9 in Paper 4/section 7]. One such hurdle identified in this thesis is the lack of adequate budgeting methods for additional energy efficiency on strategic portfolio level.

Once the example company is willing to consider economic EEMs as in alternative d), the proposed CPI method comes into play. It provides a clear structure to decide the costs and benefits which are to be considered in the cost benefit calculation. As well, it can be used in order to discuss the consequences and may therefore influence the decisions towards more energy efficiency. Even the willingness to consider EEMs may be influenced by the existence of such a method on strategic decision making level.

There may be the case where there is only a minimal difference in costs between economic measures d) and measures to achieve a rating label e). If this were to happen, the company may choose to profit from the additional benefits of a rating label at little additional cost if it sees the consequences after applying the method.

For a company to choose the excellence alternative f), a special economic environment is required. This could be a very high social responsibility awareness in the company or a core business in the field of energy efficiency itself using the portfolio as a test case. This alternative is therefore not further discussed.

In summary, from the CPI curve or the associated benefit matrix in Table 17 in section 8.6.2, the example company sees the effect of its respective decisions. If, for example, the initial EPI is 150 and the energy price is 0.10 Fr./kWh, a target EPI of 140 is indicated as being economical which is only a minor improvement. Failing to look at all measures as a group as postulated in the CPI method, the achievable target EPI would be even worse. If a factor for additional benefits of 0.5 is applied (total 0.15 Fr./kWh), then a target EPI of 67 is indicated as being economical. This already low EPI would certainly start the discussion, if not, the additional benefits of a certified sustainability rating like Minergie (with an EPI of 55) should be aspired to at little additional cost. Consequently, decision alternatives d) and even e) become feasible for this exemplary company. The example shows that raising the benefits by 50% from 0.10 to 0.15 Fr./kWh can make a considerable difference. This underlines the importance of such strategic decisions based on a strategic planning and budgeting method.

The CPI method is the only method known which supports the specific strategic decisions which need to be taken when budgeting EMs considering energy efficiency in conjunction with RMs. There is a good chance that these decisions will be influenced towards more energy efficiency investments by the method in that:

- All potential benefits are considered in a structured way (not just direct energy cost savings alone)
- Only the additional costs are considered (anyway costs are attributed to RMs or legal compliance)
- A comprehensive view is supported (short-term measures help to pay for long-term measures when looking at measures as a group; EPMs are also being considered)
- The method asks for active strategic decision making about the economic framework
- Easy-to-understand graphics support the discussion of the decisions consequences

It is assumed that through the use of the new CPI method there will be an increased number of EEMs planned and executed. This is mainly due to the increase in knowledge with respect to the cost and effectiveness of EEMs and their impact on energy performance [Paper 4] as well with respect to additional benefits.

8.5 Case 2 application on building level

The available data enables a modelling on individual building level. To this end, two scenarios were calculated in a second case using the 73 buildings mentioned before (Table 14).

The first scenario is called conventional. The company in the example applies decision alternative a) and c) which means efficiency gains as a result of RMs plus efficiency gains from execution of low-cost EEMs. The calculation follows the assumptions taken in section 8.3. The following decreasing gains are assumed: EPI > 200 -> 20%; EPI 150-200 -> 15%; EPI 100-150 -> 10%; EPI < 100 -> 5%. When these gains are applied to the whole portfolio, the EPI improves by 16% from 181 to 153. Benefits considering direct energy cost savings are around 4.3 million CHF per annum. Due to the nature of the measures, there are only small costs involved and the measures are highly profitable. These profits will be absent in the calculation if the condition is improved further at a later stage.

In the second scenario, called CPI, the company applies the CPI method. In its RE strategy (steps 2 and 3), it chooses alternative d) which means the execution of economic measures. Additionally, it decides in the strategy to use a moderate factor of 0.5 for the consideration of additional benefits in the cost benefit calculation. The decisions used in this example equate to the benefit scenario C) in the CPI benefit matrix (Table 17). The respective EPIs after execution of measures are taken from this matrix.

The two scenarios are presented and compared in Table 18. The five columns Value, EBF, EPI effective, Condition, and Energy effective refer to the real data of these buildings. The column Quadrants refers to Figure 20. The values in the columns EPI conventional and EPI scenario CPI are described above. The two columns Energy conventional and Energy scenario CPI show the energy consumed after execution of measures and are a multiplication of EBF and applicable EPI. The two columns Benefits conventional and Benefits scenario CPI are a multiplication of energy consumed and the applicable price of energy (without and with additional benefits).

Table 14 *Example on building level (effective values, conventional scenario, and scenario C with CPI)*

Code	No.	Value 1'000 CHF	EBF m2	EPI eff. kWh/m2.a	Condition %	Quadrant	EPI convent.	EPI scen. C (CPI)	Energy effective kWh/a	Energy convent. kWh/a	Energy scen. C kWh/a	Benefits convent. CHF/a	Benefits scen. C CHF/a
10050	1	16'887	6'242	270	0.50	A	216	55	1'687'587	1'350'070	343'310	35'439	211'724
10183	2	112'972	39'826	160	0.52	A	136	55	6'364'671	5'409'971	2'190'430	100'244	657'443
10192	3	15'093	5'704	126	0.60	A	113	70	716'333	644'700	399'280	7'521	49'936
10067	4	15'333	5'340	149	0.62	A	134	70	796'701	717'031	373'800	8'365	66'607
10335	5	178'504	32'005	291	0.64	A	232	55	9'298'449	7'438'759	1'760'275	195'267	1'187'262
10232	6	205'331	42'504	177	0.68	A	150	55	7'515'048	6'387'791	2'337'720	118'362	815'429
10254	7	32'049	8'473	213	0.69	A	170	55	1'805'546	1'444'437	466'003	37'916	210'978
10051	8	1'413'134	282'438	329	0.71	A	263	55	92'803'511	74'242'809	15'534'090	1'948'874	12'169'934
10203	9	118'947	25'813	156	0.71	A	133	55	4'035'525	3'430'196	1'419'715	63'560	411'990
10038	10	25'283	5'750	195	0.72	A	165	55	1'118'762	950'947	316'250	17'620	126'396
10081	11	362'967	41'395	217	0.73	A	173	55	8'969'744	7'175'795	2'276'725	188'365	1'054'150
10168	12	43'574	19'000	184	0.73	A	157	55	3'503'878	2'978'296	1'045'000	55'186	387'273
10120	13	25'871	9'266	130	0.74	A	117	70	1'204'613	1'084'151	648'620	12'648	87'569
10202	14	128'869	43'062	137	0.74	A	123	70	5'881'544	5'293'389	3'014'340	61'756	451'585
10144	15	64'399	19'540	147	0.75	A	132	70	2'864'020	2'577'618	1'367'800	30'072	235'655
10141	16	32'520	7'000	185	0.75	A	157	55	1'294'400	1'100'240	385'000	20'387	143'231
10046	17	13'492	3'608	162	0.76	C	138	55	584'303	496'657	198'440	9'203	60'773
10245	18	22'668	2'763	319	0.76	C	255	55	880'486	704'389	151'965	18'490	114'742
10228	19	465'838	99'876	259	0.77	C	207	55	25'887'347	20'709'878	5'493'180	543'634	3'212'081
10199	20	25'721	9'388	177	0.77	C	150	55	1'659'762	1'410'798	516'340	26'141	180'089
10244	21	14'290	3'658	251	0.77	C	201	55	919'064	735'251	201'169	19'300	113'068
10119	22	95'664	31'032	148	0.79	C	134	70	4'605'663	4'145'097	2'172'240	48'359	383'264
10196	23	12'136	3'872	131	0.79	C	118	70	508'673	457'806	271'040	5'341	37'427
10089	24	24'167	12'395	130	0.79	C	117	70	1'606'187	1'445'568	867'650	16'865	116'320
10101	25	28'456	9'820	128	0.80	C	115	70	1'254'162	1'128'746	687'400	13'169	89'265
10043	26	26'946	5'149	157	0.81	C	133	55	805'970	685'075	283'195	12'694	82'337
10084	27	13'287	4'461	165	0.81	C	140	55	736'578	626'091	245'355	11'601	77'368
10103	28	32'682	1'750	179	0.82	C	152	55	312'780	265'863	96'250	4'926	34'104
10198	29	53'408	8'913	141	0.83	C	127	70	1'261'046	1'134'941	623'910	13'241	100'349
10193	30	47'948	8'760	157	0.83	C	134	55	1'379'310	1'172'413	481'800	21'724	141'358
10096	31	5'149	1'465	174	0.83	C	148	55	254'879	216'647	80'575	4'014	27'453
10186	32	48'851	13'020	125	0.84	C	113	70	1'632'135	1'468'921	911'400	17'137	113'516
10044	33	12'361	4'419	135	0.86	C	122	70	598'033	538'230	309'330	6'279	45'471
10045	34	34'820	8'734	164	0.86	C	139	55	1'430'240	1'215'704	480'370	22'526	149'605
10188	35	49'055	11'873	141	0.87	C	127	70	1'674'604	1'507'144	831'110	17'583	132'850
10039	36	10'902	5'923	131	0.88	C	118	70	778'678	700'810	414'610	8'176	57'341
10085	37	39'611	16'000	170	0.90	C	144	55	2'712'060	2'305'251	880'000	42'715	288'549
10206	38	138'994	48'174	73	0.63	B	69	69	3'508'021	3'332'620	3'332'620	18'417	27'626
10054	39	54'967	24'566	102	0.66	B	92	90	2'517'707	2'265'937	2'210'940	26'436	48'316
10165	40	206'170	82'104	116	0.68	B	104	90	9'491'051	8'541'946	7'389'360	99'656	331'016
10197	41	10'263	3'759	70	0.69	B	67	67	264'166	250'957	250'957	1'387	2'080
10116	42	7'643	2'700	114	0.69	B	103	90	307'560	276'804	243'000	3'229	10'168
10095	43	73'653	28'662	92	0.72	B	87	87	2'631'185	2'499'626	2'499'626	13'814	20'721
10118	44	20'386	13'000	107	0.72	B	96	90	1'389'995	1'250'996	1'170'000	14'595	34'649
10088	45	45'181	22'581	65	0.73	B	62	62	1'476'259	1'402'446	1'402'446	7'750	11'626
10063	46	82'792	26'585	107	0.76	D	97	90	2'851'526	2'566'373	2'392'650	29'941	72'273
10047	47	57'671	12'635	121	0.76	D	109	90	1'533'336	1'380'002	1'137'150	16'100	62'399
10166	48	41'119	10'795	113	0.76	D	102	90	1'217'671	1'095'904	971'550	12'786	38'764
10056	49	2'848	762	36	0.78	D	34	34	27'165	25'807	25'807	143	214
10062	50	13'449	6'000	62	0.78	D	59	59	373'505	354'830	354'830	1'961	2'941
10209	51	38'945	12'756	99	0.79	D	94	94	1'262'248	1'199'136	1'199'136	6'627	9'940
10205	52	33'370	11'234	118	0.79	D	106	90	1'323'371	1'191'034	1'011'060	13'895	49'189
10195	53	7'202	2'195	119	0.79	D	107	90	262'078	235'870	197'550	2'752	10'163
10117	54	46'364	19'767	112	0.80	D	101	90	2'220'079	1'998'071	1'779'030	23'311	69'465
10340	55	24'991	10'000	103	0.80	D	92	90	1'025'088	922'579	900'000	10'763	19'701
10076	56	35'004	10'200	105	0.80	D	95	90	1'074'417	966'975	918'000	11'281	24'636
10210	57	255'447	50'201	123	0.81	D	111	90	6'176'951	5'559'256	4'518'090	64'858	261'271
10042	58	12'052	3'727	69	0.81	D	66	66	258'898	245'954	245'954	1'359	2'039
10181	59	9'035	3'989	123	0.81	D	111	90	491'428	442'285	359'010	5'160	20'856
10064	60	10'006	4'758	95	0.82	D	90	90	450'182	427'673	427'673	2'363	3'545
10204	61	46'670	17'897	97	0.82	D	93	93	1'744'286	1'657'071	1'657'071	9'158	13'736
10072	62	4'412	7'000	45	0.82	D	43	43	318'265	302'352	302'352	1'671	2'506
10055	63	25'461	7'574	109	0.82	D	98	90	828'523	745'671	681'660	8'699	23'131
10191	64	68'899	17'900	106	0.84	D	96	90	1'905'805	1'715'224	1'611'000	20'011	46'432
10187	65	18'547	8'076	69	0.84	D	65	65	556'205	528'395	528'395	2'920	4'380
10194	66	48'921	15'070	78	0.85	D	74	74	1'173'874	1'115'180	1'115'180	6'163	9'244
10182	67	6'575	1'971	115	0.85	D	103	90	226'495	203'846	177'390	2'378	7'734
10102	68	13'453	5'270	64	0.87	D	60	60	334'933	318'187	318'187	1'758	2'638
10083	69	17'200	8'088	92	0.87	D	88	88	745'394	708'124	708'124	3'913	5'870
10194	70	48'351	17'940	59	0.88	D	56	56	1'056'347	1'003'530	1'003'530	5'546	8'319
10185	71	53'300	12'391	59	0.88	D	56	56	736'479	699'655	699'655	3'867	5'800
10180	72	8'179	2'623	118	0.88	D	106	90	308'682	277'814	236'070	3'241	11'436
10041	73	53'682	9'766	121	0.93	D	109	90	1'184'431	1'065'988	878'940	12'437	48'115
	Total		**1'402'952**	**181**					**254'595'898**	**214'071'597**	**94'929'679**	**4'255'052**	**25'147'430**
	EPI								181.5	152.6	68	0.105	0.1575
	%									84.1%	44.3%		

In the benefits matrix (Table 17) it is stated that down to an EPI of 100, economic EEMs exist. For buildings below that EPI, low-cost gains as in the conventional scenario are assumed. For buildings above that EPI, a specific characteristic of the CPI curve can be observed. The worse the initial EPI, the better the achievable EPI is as the second point where the economic gradient cuts the CPI curve as a secant moves upwards. In the theory of the CPI curve, looking at measures as a group means that low cost measures help to pay for costlier measures. Therefore, the worse the initial efficiency of a building is, the more low cost measures exist (flat part of the CPI curve) and the more costly measures can be executed economically. In the benefits matrix, EPIs below 10 have been excluded as being outside the range of such a curve. When these economic restrictions are applied on the whole portfolio, the EPI improves by 44% from 181 to 68. Benefits considering direct energy cost savings and additional benefits are around 25.1 million CHF per annum (Figure 21).

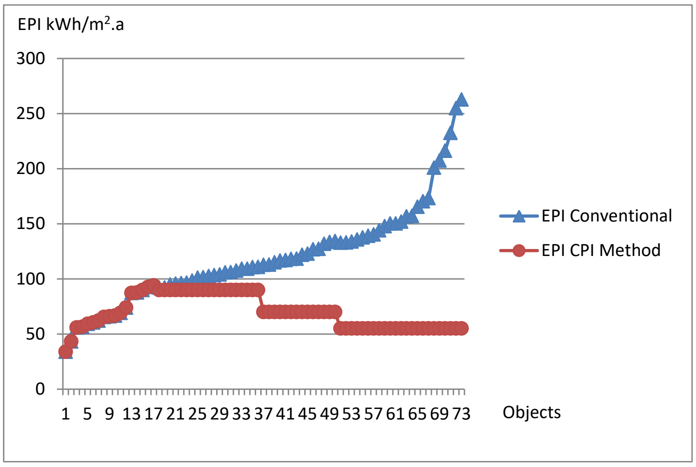


Figure 21 *Achieved EPIs per building with conventional scenario and application of CPI method*

8.5.1 Consequences of application on building level

From this example on building level, two lessons can be learned for the use of the CPI method. Firstly, if the spread of EPIs in a non-homogenous portfolio is too large, then the achievable target EPI is higher (= less energy efficiency) than stated in the benefits matrix as not all EPIs of objects outside the range of the CPI curve can be compensated for. Secondly, an adaptation of the CPI curve on building level needs to be done with caution as there are low-cost measures to be found in almost every building, as it is not clear if every building has the potential to reach a very low EPI (e.g. in the case of heritage listed buildings), and as the lower and upper limits of the CPI curve are not yet defined. The last point requires further research on building level.

Again, on building level, it is assumed that through the use of the new method, there will be an increased number of EEMs planned and executed. The example also exemplifies the danger of executing low cost measures in a first stage because it will be much harder to justify more costly measures in a second stage later. This is a consequence of the CPI curve being concave.

8.6 Sensitivity

In this section, parameters with an influence on the CPI method are discussed and a sensitivity analysis of a relevant parameter is provided in form of the CPI benefits matrix.

8.6.1 Discussion of parameters with an influence

The Table 15 lists and comments a number of parameters which have an influence on the outcome of the CPI method.

Table 15 *List of parameters with an influence part 1*

Parameter	**Comment**	**Sensitivity / influence on**
1. Goals and restrictions (strategy)	The goals and restrictions have no influence on the shape of the CPI curve (refer to parameter 5), but, define the gradient of economic ECMs (economic gradient EG, refer to Paper 4). The CPI curve then shows if ECMs are feasible and if goals are achievable under the set restrictions or if goals and restrictions eventually need to be revised (Figure 17). -> The CPI curve may have an influence on strategic decisions	High Economic gradient
2. Price of energy, tariff	Benefits of ECMs are very energy price sensitive (refer to section 8.6.2). It is different if electricity can be bought on the open market as a large consumer or if it is supplied at fixed tariffs by the local electricity utility. Also, expected development of fossil fuel prices in the future may vary considerably. -> Assumed tariffs have a large influence on outcome	High Economic gradient
3. Benefits	The value placed on additional benefits above direct energy cost savings is equally important as the energy tariff. In the CPI method this value is considered by the multiplication of energy tariffs with a factor. So, it is possible to e.g. double the benefits. -> The definition of the value of additional benefits is central	High Economic gradient
4. Economic framework	Assumptions such as the amortisation period, interest rates for annuity, and energy price increases are required for the calculation of feasibility. To reduce complexity, it is e.g. possible to assume interest rates and price increase as being equal and, consequently, to neglect both. -> Assumed economic framework has a large influence on outcome	High Economic gradient

Table 16 *List of parameters with an influence part 2*

5. Variables in formula $y=a+bx+cx^R$	The variables in the formula behind the CPI curve determine its shape. The variables a, b, and c are needed to calibrate the shape within the coordinates. The exponent R has the most influence in the power function. In the first draft, these variables have a large influence on the outcome. Later, they will be determined by experience gained from real projects. -> The shape of the CPI curve needs to be corrected and constantly improved based on experience	High to low (with time and experience) CPI curve
6. Value of buildings	The specific value of buildings (per area in m^2) determines the costs of RMs and ECMs as they are calculated in % of the value. This seems to be justified for RMs (refer to section 6 Paper 3). For ECMs, however, this could be questioned as the specific values are up to a factor of 10 away from each other in the real portfolio. -> It is an open question if the relative calculation of ECM costs is justified or if a calculation based on predefined average building values or on cost per area or volume is preferable	Portfolio level: Medium Object level: High CPI curve
7. Split between anyway and additional costs	Exact definitions on how to split costs are missing, which results in uncertainties. Due to this and the additional effort needed for the calculation, this split is not being done per default in refurbishment projects. -> This split yet needs to be better defined and more investors need to be motivated to contribute data in order to enlarge the experience base	Medium to high CPI curve
8. Cost of renewable energy production	As with utility energy prices, the economic gradient is sensitive to the price of self-produced energy. Combinations of ECMs and EPMs are likely to be economically more feasible than ECMs alone (refer to Figure 17). -> Considering combinations of ECMs and EPMs can make a difference in the feasibility of additional measures above legal compliance	Medium to high Economic gradient
9. Measures as a group	The average EPI of 125 in the monitored part of the real portfolio is fairly low. Nevertheless, the split of costs between measures to achieve legal requirement and those for strategy achievement, changes from 63%/37% to more than 72%/28% when looking at all measures as a group. For higher initial EPIs this change is even larger. -> Looking at the measures as a group can make a difference in the feasibility of additional measures above legal compliance	Medium Cost/benefits

From this list, the most influencing parameters have been extracted and consolidated. Five of the nine parameters covered in the table have an influence on the economic gradient and cover the benefits side (numbers 1-4 and 8). Three parameters influence the CPI curve and cover the cost side (numbers 5-7). One parameter covers the application of the method and influences the cost benefit calculation (number 9).

The benefits side is mainly decided upon by the portfolio owner with his strategy and his future energy price expectations while the cost side is more often decided by measurable facts like building values and costs of executed measures. Thus, the sensitivity analysis concentrates on the benefits side.

To analyse the sensitivity and consequences of different decisions on the benefits side, the following CPI benefit matrix has been developed with the benefit scenarios A-E. The parameters on the cost side can be analysed in the same way. They are kept invariable in this analysis.

8.6.2 CPI benefit matrix

The CPI benefit matrix complements the CPI curve and acts as sensitivity analysis at the same time. It shows, starting from various initial conditions (initial EPI), what improvement can be achieved (target EPI) under different economic settings. Mathematically, the economic gradient cuts the CPI curve at two points as a secant, once at the initial condition x_I and once at the economically achievable condition x_T. The additional cost is given by the difference in the y-axis between the two meeting points of the CPI curve ($y = a + bx^4$) and the economic gradient ($y = c + dx$).

As the variables a and b are known from the CPI curve and the variable d has to be decided by the owner, c can be determined for a given x_i.

$c = a + bx^4 – dx$

For b<d the second meeting point is above the initial condition and can be determined using approximation. This is then repeated for different economic gradients, starting from the effective energy price, to represent various factors for additional benefits. The results are listed in the CPI benefit matrix (Table 17). This new matrix complements the CPI method in section 7.

Table 17 *CPI benefit matrix*

Benefits CHF/kWh		**0.100**	**0.125**	**0.150**	**0.175**	**0.200**
Economic gradient g		**0.043**	**0.054**	**0.064**	**0.075**	**0.086**
Benefit scenario		**A**	**B**	**C**	**D**	**E**
EPI initial	Gradient CPI	Achievable EPI				
		Costs %				
				Renewable energy gradient		
300	0.0025	33	- -	- -	- -	- -
		11.46				
275	0.0050	46	14	- -	- -	- -
		9.82	13.94			
250	0.0086	60	27	- -	- -	- -
		8.16	11.97			
225	0.0136	77	42	13	- -	- -
		6.32	9.83	13.65		
200	0.0203	93	59	30	- -	- -
		4.62	7.57	10.88		
175	0.0289	115	77	48	20	- -
		2.56	5.28	8.12	11.61	
150	0.0397	140	100	67	38	13
		0.42	2.66	5.33	8.42	11.76
125	0.0528	- -	125	90	60	32
			0.00	2.23	4.85	8.01
100	0.0686	- -	- -	- -	82	54
					1.35	3.96

An achievable target EPI meets the condition EPI target < EPI initial. Target EPIs below 10 are assumed as being outside the range of the CPI curve (symbolised with: - -). The upper limit is where the EPI target becomes higher than the EPI initial. Outside these limits, measures are usually uneconomic apart from energy optimisations at little or no cost.

The red line in the matrix shows where the production of renewable energy would become less expensive than additional measures under the assumed costs and benefits.

The following conclusions can be drawn from this CPI benefit matrix:

- The higher the initial EPI is, the lower the target EPI becomes due to the effect of looking at all measures as a group (cheap measures help to pay for more expensive ones).
- The sensitivity of the decisions concerning the benefit scenarios is very high. This means that these decisions (e.g. concerning the future energy prices) have to be made carefully.
- Under the assumptions taken, very low target EPIs seem possible. This needs to be reconfirmed in practice.

The CPI benefit matrix can also be depicted in a graphic (Figure 22).

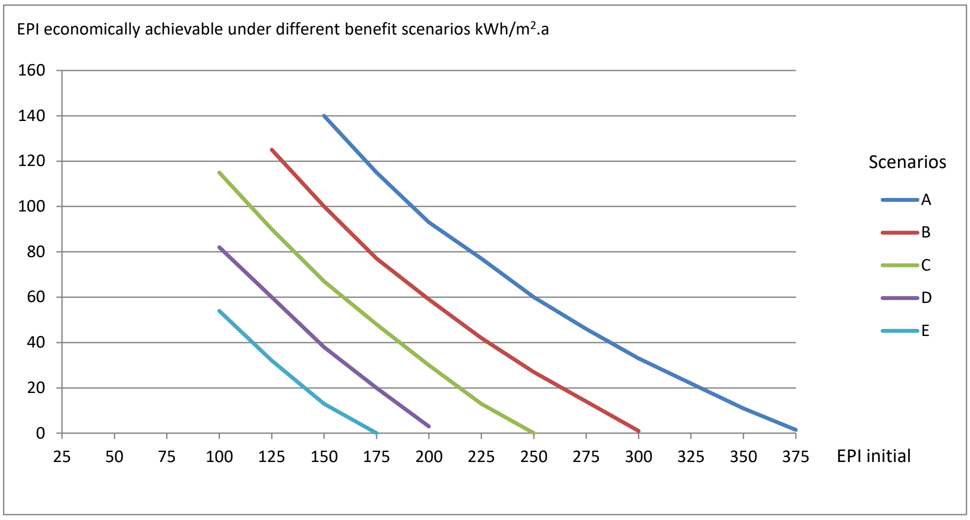


Figure 22 *Economically achievable target EPIs in function of the initial EPI for different benefit scenarios A-E*

Using this benefit matrix or graphic, the building owner sees the consequences of his decision alternatives at a glance. As a consequence, the interpretation of the CPI curve becomes easier and more comprehensible.

The values in the benefit matrix depend on the shape of the assumed CPI curve. It is also imaginable to calculate e.g. two different matrix in order to show the band width of the measures. One matrix for a more optimistic scenario and one for a more pessimistic scenario.

8.7 Discussion

The two cases with real life data presented in this section complement the theory and examples in Paper 4 (section 7). They highlight the benefits of the new method and point to some restrictions at the same time. In general, they show that it is possible to apply the new method for a given portfolio with little initial assumptions and effort. Based on different assumptions, scenarios can be created and compared.

In the monitored part of the portfolio of the Canton of Zurich, the average EPI of 125 (without hospitals) is already in the lower range for existing buildings, especially as it includes user related energy. This limits the potential savings and, according to the concave shape of the CPI curve, relative costs of measures are higher than for a portfolio starting at a higher EPI (=lower energy efficiency).

Additional benefits such as being a role model, were given a high value that is equal to 100% of the direct price of energy. As the target of the canton is set in a standard, this could be seen as the cost and additional benefits to reach the target. For buildings with a higher EPI the costs are lower. Combinations of ECMs and EPMs can also lower the costs. To gain transparency in such questions, the CPI method is a useful tool.

A restriction of the application of the method was found in the spread of EPIs in a portfolio as objects with extreme values reach some limits and as higher EPIs need to be compensated for with lower EPIs in other objects. Another restriction are the potentially very low target EPIs which result from very high initial EPIs due to the concave shape of the CPI curve. The practicality or the limits of this behaviour of the CPI curve need to be confirmed with further research.

The cases also show that there are considerable differences between conventional planning and the application of the CPI method in the achieved energy efficiency possible. A part of these differences is due to the higher transparency in costs and benefits of EEMs while another part is due to strategic decisions which may also be influenced by the method towards more investments into energy efficiency.

The sensitivity analysis has shown a number of parameters with medium to high influence on the outcome. Given the inherent uncertainties and small experience base, this new method must be applied carefully in the first place.

Advantages of the CPI method compared to conventional planning according to the cases:

- More transparent costs and benefits of EEMs with relatively little effort
- Better assessment of strategy or support of strategy making and evaluation of goals based on scenarios
- Easier optimisation between ECMs and EPMs as this forms part of the method
- Provision of a long-term perspective for single buildings or a whole portfolio that works against the short-term picking of the low hanging fruit (as a consequence of the concave shape of the CPI the ECMs above legal requirements are relatively more expensive and therefore less attractive - looking at all measures as a group may reduce this problem)
- More accurate calculation of the share of costs to achieve legal requirements and of the share of additional costs for ECMs

Disadvantages of the CPI method compared to conventional planning according to the cases:

- Little experience available with this new method
- Variables of the CPI curve need to be defined or assumed individually for each portfolio
- Splitting of costs is not well defined and requires additional effort (very few published figures)
- Swiss building regulation does not result in a clearly defined EPI for refurbishment which makes a comparison with the target EPI difficult

Additional questions for further research have arisen from the cases:

- What is an adequate basis for the first draft of the CPI curve (e.g. 10% of building reconstruction value or 10% of project cost (refurbishment cost); starting from which point; individual for each portfolio or fixed recommendation)
- What are the limits of the CPI curve especially when considering the application on building level
- Is there a relation between the spread of individual EPIs in a portfolio and the achievable target EPI

A more generic discussion is provided in section 10.

8.8 Excursus – whole economy

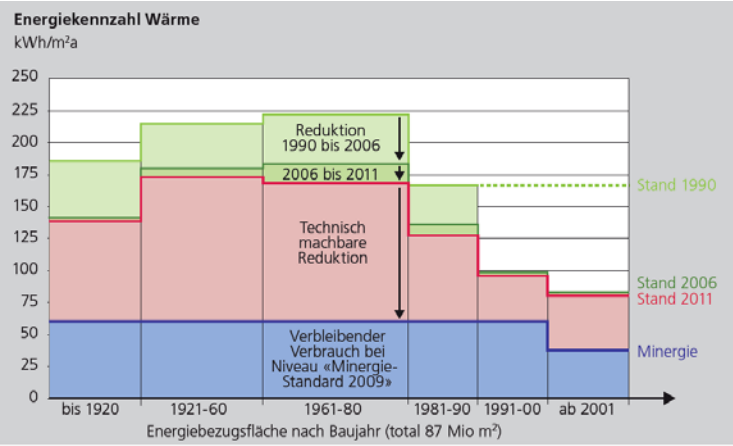
In this section, a short discussion is added about the application of the CPI for the whole buildings stock of an economy to demonstrate its scalability.

At least three different authors have drawn a diagram showing the EPI in function of the construction period and the existing constructed area from each period [38, 75]. Provided as an example (Figure 23) is the version from the energy report of the canton of Zürich [72]. It refers to the residential buildings in the state. The initial EPI is compared to the current standards or the Minergie standard.

Total area (EBF) covered is 87 million m^2. Buildings constructed between 1920 and 1980 have an initial EPI of 220 which has been reduced by refurbishments to 175 on average. Buildings before 1920 and between 1980 and 1990 have a reduced EPI of around 135. All buildings before 1980 cover around 80% of total constructed area with an average EPI of around 155.

If the EPI in this stock of buildings is reduced to 55, around 65% or 7 billion kWh/a from 13.5 billion can be saved. Resulting annual cost savings are close to 1 billion CHF. According to the draft CPI, 6,7% of building value needs to be invested. At a specific value of 3’000 CHF/m^2 this means 17.5 billion CHF of investment.

Considering these large figures, it is evident that adequate planning methods and sufficient experience based data are necessary on this high level of a whole economy as well.



EPI thermic

Reduction (by RMs) 1990 - 2006

2006 – 2011; Situtation 1990

Technically feasible reduction

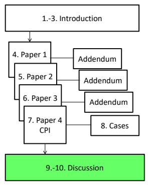
Situation 2006 / 2011

Reduced consumption according to ‘Minergie standard 2009’

EBF per construction year

Figure 23 *EPI thermic for residential buildings and built EBF per construction year in the Kanton Zürich [72]*

9 Discussion



In this section, a discussion of some aspects of the work and specifically of the CPI method, other research paths followed, and miscellaneous questions is provided.

9.1 Method

9.1.1 EPI as measure for performance

The EPI is the defined measure for performance in the CPI method. This poses the question why another measure such as CO_2 emissions has not been used for this method (reduction of CO_2 emissions, for example, has become more of a target of late). The answer is that the EPI (measured in units of energy consumption per m^2 of building energy reference area and year, abbreviated as $kWh/m^2.a$) as defined in EN 15459 [44][24] is a well-defined and standardised measure and its calculation is well understood. It is often readily available as it is used to compare buildings with similar buildings and, in some countries, it is even mandatory to provide it, e.g. when selling or renting out an object. However, it does not differentiate between different qualities of energy used apart from the production of renewable energies in the buildings itself, which has a positive effect on the EPI.

The EPI is measured as final energy at the gate of the building (also termed delivered energy). It is the amount of energy charged for by the utility. The other form of energy often referred to is primary energy, which includes production and transmission losses. The factor between them (primary energy factor) for example for electricity from fossil fueled power stations (efficiency of the steam generator) is around 3 and for hydro power stations (efficiency of the turbine) close to 1.2. The EPI does not reflect the type of energy consumed and its emissions produced during production. By knowing the type of energy and its primary energy factor, the respective CO2 emissions can be calculated. However, this needs to be done individually for each building as building emissions depend greatly on the mix of electricity delivered by the specific electricity utility (or

[24] In some publications, the term EPI is used for a class of indicators and $kWh/m^2.a$ is specifically termed energy used indicator (EUI)

ordered by the customer). To enable such calculations, the utilities are now mandated to document and publish the origin of their products (which is subject to change). Utilities reacted to this by offering various products with different production mixes to the customers.

For example, an efficient heat pump can produce as many CO2 emissions as an oil fired heating system if the electricity for the heat pump originates from a coal fired power station. As a consequence, the EPI needs to be complemented with environmental indicators if such considerations are to be taken into account. A change from final energy to primary energy as the basis for the EPI is not scheduled. This is because data on final energy is easily accessible (utility bill) without further calculations (which are based on constantly changing factors) and because primary energy is often user related (i.e. depending on willingness of a customer to pay more for a cleaner product) and not a building specific characteristic. Furthermore, measuring final energy puts the focus on reducing the demand before substituting one source of energy with another.

9.1.2 Generalisation of split between anyway costs and additional costs

The promoted split (in Paper 4) of costs into anyway costs and additional cost for ECMs is not a generally applied approach in RE. This may be due to the fact that this split requires knowhow plus additional effort and that there are no standards or recommendations as to where to make the split because this is often not straight forward. An organisation interested in optimal solutions and more energy efficiency in their buildings will gladly make this effort while an organisation interested in the cheapest solution will probably not.

9.1.3 The use of m^2 in the CPI method

The CPI curve is defined on a per m^2 base of building area. Often, the net floor area (NFA), which excludes interior and exterior walls, is known and used for such purposes. On such a universal base, the indicator becomes comparable and scalable for the large share of buildings. Also, it can build on existing refurbishment planning methods that use the same base. As has been discussed in Paper 4, some building specific variables such as climate zone or type of usage might need to be incorporated yet for the CPI curve to become more specific and more accurate.

9.1.4 The use of % of value in the CPI method

The CPI curve is defined as the relation between the EPI in kWh/m^2 and the costs in % of the building (reconstruction, reinstatement or insurance) value. In literature, the costs to improve EE are sometimes given in €/m^2 [56].

Reasons for the use of % of the building value are:

- Use of the same measures as in the method Schroeder to directly complement such a method that is based on empirical data on average portion of elements on total building value (%)
- Assumption that a building with a high value is more expensive to refurbish and enhance than a building with a low value

Construction costs of buildings per m^2 can vary considerably. These differences are very likely to have an effect on refurbishment costs (e.g. through materials used, complex forms and structures/architectural design employed, building technique installed, etc.). However, the assumption that they have the same effect on costs of ECMs (for example that a complicated façade is more costly to insulate) has not been validated.

To change from one measure to another is an easy task: the % value just needs to be multiplied with the value of the building per m^2. Example:

Building value =	3’000 €/m^2 x 1’000 m^2 = 3’000’000 €
Cost for EEMs in % of building value =	2% (to reach a defined enhancement)
Cost for EEMs in €/m^2 =	3’000 €/m^2 x 0.02 = 60 €/m^2

9.1.5 Mathematical model for the CPI curve

In the two cases in Paper 4, the CPI curve is matched with the real life data by approximation using a common quadratic equation. There are many different methods to achieve this match. Paper 4 does not particularly recommend any of them. Any recommendation should, however, consider the more managerial and less technical orientation of the target audience.

9.1.6 Limits of the CPI curve

Naturally, the CPI curve is limited by the availability of data to draw it. Based on experience with energy conservation projects, the limits could be at around 50% reduction of energy consumption and 20% additional costs. An extrapolation beyond these limits for prognostication towards zero or plus energy houses is tempting but not covered by this work. Furthermore, production of renewable energies need to be considered in this context. As proposed in Paper 4 they may change the form of the CPI curve for ECMs beyond or even before these limits.

9.1.7 Use of the method Schroeder as a reference

The method Schroeder [6] was chosen as a reference for maintenance and refurbishment planning methods because it is the only method known that fulfils the following criteria found to be important for this work. It is based on a small number of elements, it distinguishes between maintenance and refurbishment, it uses costs per area (CHF/m^2) as the basis, and it uses generally available data. Furthermore, it does not cover EMs and specifically EEMs. Despite its widespread use in practice, there was no research paper found out validating this or a comparable method in the course of this work. The CPI method builds on and complements such a method and it was therefore necessary to validate one as a reference beforehand. This gap was successfully closed with Paper 3 of this thesis.

9.1.8 Extensions to other performance indicators

The EPI is a well-known indicator which is often used to define efficiency goals. EEMs have a direct measurable impact on it that can be calculated. Therefore there is a relatively simple relation between this performance indicator and additional costs to improve it. Looking at other performance indicators, this relation is less clear. Most environmental rating systems provide simple ratings but require complex calculations based on many variables beforehand. Due to the diversity of possible measures to improve such a rating, a (convex) relation to additional costs is imaginable, but this has not been researched to date. Other known indicators are related e.g. to workplaces, rental income or operating costs. While the rental income may be improved proportionally to an expansion of the area, the relation to qualitative improvements (e.g. better indoor air quality) are less clear. Ideas to relate materials, surfaces, the intensity of installed building techniques or other variables to operating costs are still in their infancy. In that case, other such relations are imaginable but it is assumed that the EPI is better suited to be used this way than other indicators.

9.2 Optimisation of measures to improve sustainability - building element oriented method

There are numerous sustainability rating methods and labels available on the market (Annex G). However, none of them give the user advice on the necessary costs to achieve such a label or an indication of how these costs and the benefits can be optimised. What would be needed in regards to the objective of this work is a method to facilitate an early decision on whether a label is economically feasible and to answer the question of what the most cost effective measures would be.

In the framework of this thesis, an element based method has been developed covering energy efficiency only. The idea of this method is to provide a very simple and low-cost way to estimate costs and benefits of EEMs in a building. The method builds on available statistical data on costs of building elements and on the share of overall energy consumption that can be attributed to these elements. Then, it requires the experience of an energy conservation engineer to estimate additional costs for EEMs and potential savings per element. If used regularly and results are evaluated, it has the potential to develop a self-learning effect. The idea was originally presented in the annexes of Paper 3, but didn't make into the published version (Table 18).

Table 18 Example of building element oriented estimation method for energy savings

No.	Building elements (according to method Schroeder)	Expected service life in years	Portion of total building value	Common energy efficiency measures ECM	Marginal costs of ECM	Costs of ECM weighted according to value	Portion of total energy consumption affected	Estimated reduction of consumption (savings)	Reduction weighted according to consumption
1	Load-bearing structure	75-120	35.0%	none	0%	0.0%	0%	0%	0.0%
2	Pitched roof	40-50	4.0%	additional insulation	20%	0.8%	10%	80%	8.0%
3	*Flat roof*	*25-30*	*4.0%*	*see above*	*20%*	*0.8%*	*10%*	*80%*	8.0%
4	Exterior walls, Facade	40-55	8.0%	additional insulation	20%	1.6%	15%	80%	12.0%
5	Windows	30-40	8.0%	better windows	30%	2.4%	20%	80%	16.0%
6	Heat production	15-25	2.0%	optimised operation	5%	0.1%	5%	10%	0.5%
7	Heat distribution	15-25	2.0%	additional insulation	1%	0.0%	5%	5%	0.3%
8	Sanitary facilities	15-25	6.0%	solar or heat pump	20%	1.2%	15%	50%	7.5%
9	Electrical system	15-25	6.0%	better ligthing	20%	1.2%	10%	50%	5.0%
10	Other building services	15-25	3.0%	better efficiency	30%	0.9%	10%	30%	3.0%
11	Interior walls and fittings	20-30	22.0%	none	0%	0.0%	0%	0%	0.0%
12	Other interior fittings	-	-						
13 - 20	Disponible	-	-						
Sub-total			100.0%			9.0%	100%		60.3%
Additional ECM (cumulative after measures above have been implemented):									
6	More efficient heat production		2.0%	solar or heat pump	100%	2.0%	80%	60%	19.1%
Total					**Additional costs for all ECM**	**11.0%**		**Total energy savings**	**79.3%**

The result of the figures in Table 18 - given by way of example - is that with additional costs for ECMs of 11% of building value, a total reduction of about 80% of energy consumption can be achieved. All it needs for this calculation is a spread-sheet and a few figures based on experience with ECMs. An application on strategic portfolio level is not foreseen.

9.3 Evaluation of energy conservation stimulus programs

Two fundamentally different stimulus programs used to boost energy conservation in buildings have been evaluated in the course of this work to ascertain if the results are applicable for prediction and budgeting of ECMs in existing buildings e.g. in the form of the CPI curve presented in Paper 4.

From the first stimulus program managed by the Stiftung Klimarappen (www.klimarappen.ch) a large database with more than 20‘000 entries (buildings receiving funding) was available. Unfortunately, basic questions like additional costs and benefits of ECMs could not be answered due to structure of the data. It was also hoped that the large database holds information about the real life expectancy of building elements, but this did not materialise either. A test run using data mining techniques being developed at ETH Zürich did not bring better results. The idea had to be abandoned despite the significant size of the database, however, one interesting result is the graph showing the stated age of the buildings receiving funds (Figure 24).

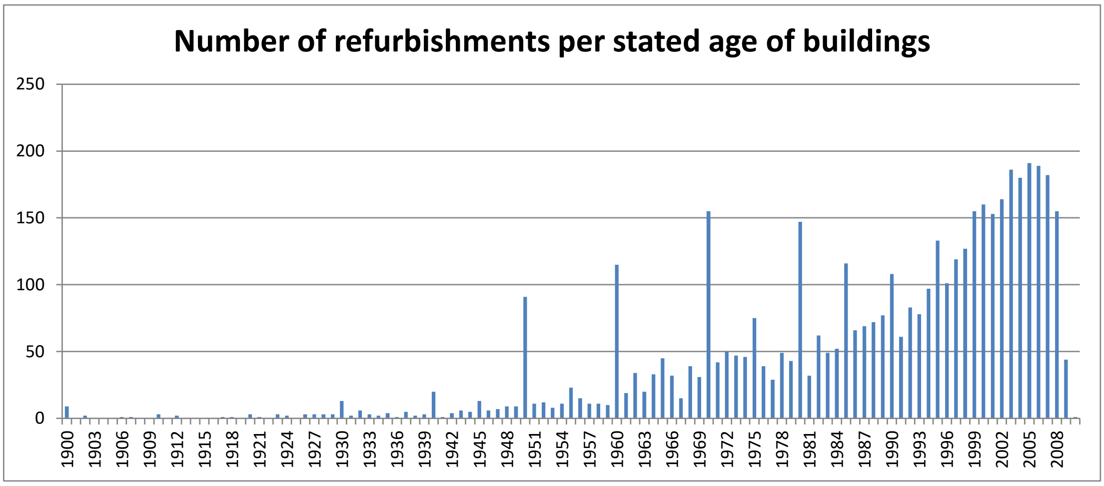


Figure 24 *Age profile of buildings receiving funds for refurbishment (source: Stiftung Klimarappen)*

Interestingly, a large share of the buildings were stated as being less than 10 years old when receiving funds. Many of the older buildings must have undergone several refurbishment cycles in their life-time, which points to the difficulty in determining the age of a building for refurbishment planning. Element based methods are able to provide a corrected average age (based on the assessed condition), which is relevant for refurbishment planning and would solve that problem. The distinctive peaks every 10 years, and less distinctive every 5 years, indicate that many owners do not exactly know the age of their buildings and therefore gave a round figure instead (earlier RMs and EMs may complicate the question of the exact age). An evaluation of the program using more detailed information is available by the Stiftung Klimarappen [45].

From another stimulus program, offering energy optimisation for public organisations (www.energo.ch), a very small database is available that contains 50 entries (Figure 25).

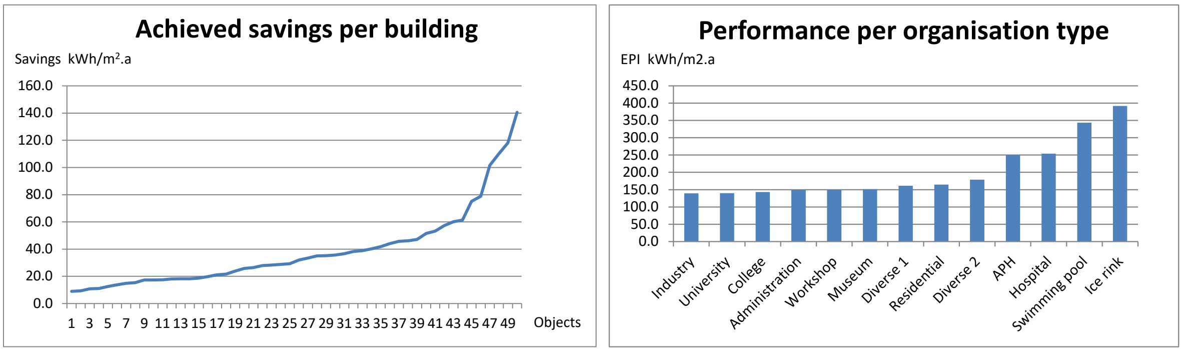


Figure 25 *Analysis of achieved savings per building and average performance per organisation type (APH = rest home; Diverse = other types not specified by the data owner) (source: energo)*

In this program, investments are paid by the achieved savings as the responsibility of the contractor while the organisations pay a moderate fee only. The achieved savings per area and year show the same convex shape as a CPI curve. Small savings have been achieved in every organisation. Large savings have been achieved in a small number of organisations. The average energy consumption of the evaluated buildings per type of organisation is not surprising. A large share is made up of commercial buildings with more or less the same energy consumption, while indoor swimming pools or hospitals generally have a larger energy consumption. There is little information about costs (mainly a service fee for developing operational measures).

9.4 Validation of service life guidelines for building construction elements using real life data

It was hoped that the large database (Stiftung Klimarappen) mentioned above would hold information about the real service life expectancy of building elements (e.g. average age of buildings when certain elements were refurbished), but this did not materialise. This would have allowed the validation of theoretical life time tables of building construction elements in guidelines with this data or to identify variables such as date of installation (materials used in this time) technology (e.g. double glazing), legislation (e.g. new clean air legislation) or listing as a heritage building, which influences these life times. As well, it may have answered the question if the characteristics of an element such as age, condition or both, need be collected to best plan refurbishment. Due to the insufficient nature and different focus of the available data in respect to this research question, it was decided to abandon this idea altogether after a thorough inspection of the data.

9.5 Multi dynamic life cycle budgeting (MD-LCB)

LCC is a powerful tool to compare the net present value (NPV) of different design alternatives. In most LCC calculations, expenses are considered to be invariable over time. However, research and experience suggest that this is not so. For example, maintenance cost has a progressive curve over the first 30 years of a building's existence (refer to Paper 3). After this time period, major refurbishments may result in lower energy consumption and better maintainability and cleanability. Major refurbishments are the second chance to influence substantially the operating costs of a building after the initial design phase, which is referred to as flexibility in Figure 26. For planning and budgeting, it is more important to know the time and absolute amount of investments and expenses than the NPV, hence the proposed name life cycle budgeting LCB. In the course of this work it was explored if such dynamic interdependences of the multiple variables used in a LCC calculation, including the influence of refurbishment and enhancement measures, can be developed into methods which can then be incorporated into the CPI curve, namely in the calculation of benefits and the respective economic gradient. This is assuming that costs and benefits in LCC calculations are variable over time and influenced by certain measures. However, little is known about these dynamic interdependences. One example is provided by Jakob et.al. [28]. They have shown that the costs of EEMs follow a learning curve and therefore change over time, which may need to be taken into account in a LCC calculation.

Unfortunately, no relevant database with all the needed information collected over several decades could be found to support and test this theory sufficiently. The development of maintenance costs over time have been evaluated in Paper 3. Benefits have been assumed to be linear in Paper 4 in the absence of reliable data. So far, variables reflecting dynamic interdependences remain a theoretical idea.

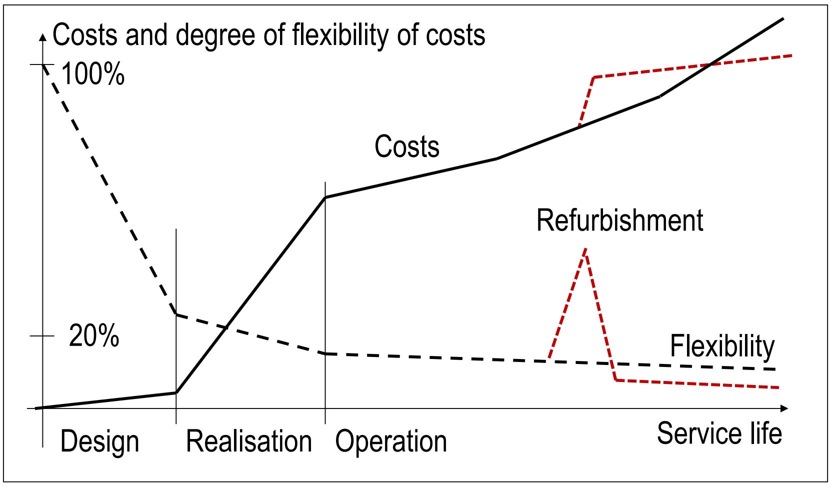


Figure 26 *Conceptual illustration of change in life cycle costs and flexibility due to ageing and/or refurbishment*

9.6 Additional costs or cost reductions resulting from ECMs

In paper 4 and section 8, it is recommended to consider additional benefits other than energy savings alone with an energy price factor. In this case, additional costs other than just up-front investment (expressed as annual capital costs) should be considered in the cost/benefit calculation. This is not generally the case in practice. In section 9.5, the idea of a method termed multi dynamic life cycle budgeting to consider exactly these additional costs (or cost reductions) during the life cycle of a building is introduced. The idea has not been further explored in the course of this work due to lack of relevant data and such additional costs are therefore not considered in the proposed factor for additional benefits.

This section outlines another approach to the estimation of the additional costs or cost reductions from ECMs. The magnitude of the additional costs resulting from ECMs can be estimated using indicators or benchmark figures, e.g. they might be 5% of the additional building value. An example of how these indicators could be used using generic ECMs on maintenance and refurbishment costs is given in Table 19.

In the example, it can be seen that one of the most expensive ECM (insulation) does not produce additional maintenance and refurbishment costs. Some ECMs may lower the maintenance and refurbishment costs (e.g. LED lighting, smaller heating system, windows with longer lasting materials), which would help to compensate for the higher costs resulting from other ECMs. In summary, maintenance and refurbishment costs may make a difference in the cost/benefit calculation for ECMs, and although they may either increase or decrease the cost/benefit ratio, it is likely that the overall effect resulting from the execution of ECMs will decrease the cost/benefit ratio in many situations.

Table 19 Example effects of different ECMs on maintenance and refurbishment costs

ECMs	**Description of effects of ECMs on maintenance and refurbishment costs**	**Example effects *)**
Additional insulation	Insulation is a passive element protected by an outer layer of the façade with a long life cycle and usually does not need additional maintenance. If ecological materials (e.g. rock wool) are used, additional costs of waste are minimal.	=
Better windows	New metal or plastic windows last longer than older wood windows and require less maintenance.	= or -
New heating system	A retrofitted building generally requires a much smaller heating system. Heat pumps require less maintenance than fossil-fired heating systems.	- -
New lighting	LED lighting costs more initially but lasts much longer and therefore needs less replacement.	-
Heating, ventilation and air conditioning	Optimised variable air volumes depending on requirements need more technique but reduce operating hours and filter replacements (overall effect on maintenance costs unknown).	= (?)
Building automation system	New building automation systems are more complex but also more reliable and provide new options in maintenance planning (overall effect on maintenance costs unknown).	(?)
Additional ventilation	A ventilation with heat exchanger is a recommended measure to save energy and improve the comfort (especially in residential buildings) but requires considerable maintenance.	+ +
Optimisation	Optimisation (reduction) of operating times (lighting, ventilation, etc.) potentially reduce maintenance costs.	-
Other measures listed in Appendix E (Table E2)	No additional costs estimated	=

*) = means no effect or equal costs; + means positive effect or reduced costs; - means negative effect or additional costs; (?) means effect uncertain

The magnitude of operating costs like administration, cleaning, safety and security can also be estimated from benchmark figures. As these costs are more related to the area of a building or user requirements, ECMs do not generally result in their increase.

Further analysis is needed to verify the preliminary thoughts expressed in this section. If it is shown that the additional costs are relevant, then they can be considered by appropriately modifying the benefit factor applied to the energy price.

9.7 Application of a controlling cycle on buildings

Quality management is an important issue in the construction industry. Every new building is a prototype and therefore contains potentially mistakes. A quality or controlling cycle could therefore be beneficial in improving the performance of buildings in the long run. Unfortunately, architects often plan, design and construct a building without the necessary follow-up by checking the fulfilment of requirements and user needs a couple of years after completion and, consequently, miss learning from the experience. It is often up to the FM department in larger organisations to collect such experience systematically and to use it in the specification and execution of the next construction project.

The concept of a controlling cycle, namely the PDCA cycle according to ISO is included in two of the four papers. Specifically the process of the CPI method has been structured following this cycle (for process diagram see Annex B). It could be envisioned to finally describe a complete controlling cycle for buildings. Existing tools for parts of this controlling cycle could be complemented and integrated in order to form one comprehensive tool, including maintenance and aspects of sustainability.[25]

9.8 Benefits of sustainability to owner/investor or society

Common definitions of the various types of benefits resulting from measures enhancing aspects of sustainability are still missing. These measures would bring investors or society, economic, social, and environmental benefits. The requirement would be to develop a model which attributes the costs of measures to the types of benefits. This is needed in order to calculate comparable indicators or benchmarks and to answer the question of whether the total benefits to the investor are sufficient to initialise measures to enhance sustainability. Another question is how the “tragedy of the commons” in this field can be avoided e.g. by internalising external costs or profits.

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[25] A new approach to this topic can be seen in the much discussed concept of building information modelling (BIM).

A respective structure and hierarchy of benefits for EEMs is proposed in Paper 4. It is shown that costs are not necessarily directly linked to specific benefits and that an individual attribution with an 1:n relation is often necessary. In section 1, synergies between RMs and measures to enhance aspects of sustainability are explained. However, linking refurbishment planning with any sustainability rating system was found to be too complex and the task was therefore confined to the aspect of energy efficiency where more data and experience was available.

9.9 The CPI as part of a sustainability reporting

More and more organisations who appreciate good governance publish a sustainability report. This activity has almost become best practice since the turn of the millennium. Reasons for this may be that this form of reporting supports an organization in analysing and managing economic, environmental and social impacts and helps to communicate them to their stakeholders [92]. The Global Reporting Initiative GRI [93] issued by the Global Sustainability Standards Board (GSSB) has become a near standard for sustainability reporting.

The CPI curve is primarily connected to the reporting of energy consumption. ECMs reduce the energy consumption and may have an influence on e.g. the CO_2 emissions. Consequently, the CPI curve could be an instrument for presenting the results of executed ECMs and the final goal regarding energy consumption of the building portfolio of the organisation.

The conclusion is that the CPI curve offers new opportunities in presenting goals and achievements in energy conservation in building portfolios as part of the overall sustainability reporting. Additional benefits would be the transparency provided by the graphic representation of costs and performance and consequently the awareness, that constant savings each year (in absolute or relative terms) are difficult to achieve over a sustained period.

9.10 Motivations and goals of building portfolio owners

Owners of building portfolios have various motivations and goals. In regards to energy conservation, a benefit structure has been developed and presented in Table 3 in paper 4. In it, benefits are classified into direct and indirect monetary measurable benefits. The motivation to harvest the direct monetary measurable benefits lies in the improvement of the financial situation and is obvious. The motivation to harvest indirect monetary measurable benefits is less obvious and often related to the interests of other stakeholders.

There are three main types of stakeholders in buildings: owners, users and public (Table 20).

Table 20 Main stakeholders in building portfolios with examples of sub-groups

Main stakeholders	**Examples of sub-groups**
Owner	Private, corporate, public
User	Employees, service providers, clients, guests, visitors
Public	Neighbours, public authority, interest groups, media

As owners often have a simultaneous role as user of a building or being part of the public, the interests and motivations may overlap. In other words, owners may have an interest in contributing to the prevention of global warming and climate change as part of their good governance or as a private person, even if it is not in the short-term financial interest of their organisation. This may result in conflicting goals, which will need to be balanced.

In paper 4, the indirect monetary measurable benefits are considered by introducing a global factor that needs to be determined by the owner. For a more detailed understanding and calculation of this factor, a better understanding and quantification of these benefits is necessary. Table 21 provides examples of aspects and of the respective interests of users and the public. To accommodate some of these interests may achieve indirect monetary benefits for the owner.

Table 21 Examples of interests of user and public

Stakeholder	**Aspects (exmples)**	**Interests (examples)**
User, Public	Optical	Less shading or limiting of views
	Accoustic	No direct noise (e.g. from air coolers)
	Sensorial	Good indoor air quality
	Olfactory	Less fumes from restauarant kitchen
	Materials	Use of sustainable materials
	Energy	Less consumption of non-renewable energies
	Gas and particle emissions	Less greenhouse gas emissions preventing climate change
	Biodiversity	Use of local plants in the surroundings
	Social	Free access to building/surroundings

The motivations and goals of portfolio owners may be influenced by the interests of users (e.g. improving satisfaction of users in order to improve productivity), the public (e.g. improving the image of the organisation bevor applying for a construction permit involving a public enquiry), or themselves in their personal role as user or public. These interests can be very individual and depending on the local situation or the specific interests of the stakeholders. An individual definition of stakeholders and their interests as well as an individual weighting and balancing of interests seems necessary.

Some recent literature about stakeholders in buildings, the integration and management of their interests, and value creation in this context can be found in [94, 95]. This work considers these interests in a global way with a factor for additional benefits in the cost/benefit calculation of ECMs. A detailed and quantified consideration is pending and more research in this field is recommended.

9.11 Miscellaneous

9.11.1 Desirability of type of measure

What is environmentally more desirable, new construction or refurbishment of buildings, is a question that is often heard. A newly constructed building is usually more energy efficient in operation than a refurbished one.

However, if embodied energy is taken into account, the decision between these two basic types of measures is not so evident anymore. The embodied energy in a newly constructed building is estimated to be 5-10 times higher than the embodied energy in a refurbishment project [46]. Refurbishment, therefore, may often be superior when looked at from an environmental perspective. Methods and tools to support this decision making process are available [38] and have been incorporated into the CPI method. An adapted version of the proposed cost and benefits structures could be applied for new construction as well because once legal compliance is achieved with new construction instead of refurbishment (anyway costs), it has to be decided if further EEMs are worth the additional costs. It can even be assumed that additional costs for e.g. supplementary insulation are nearly the same for new construction and refurbishment.

9.11.2 Other important factors in refurbishment decision making

There are other decisive factors than environmental considerations influencing the question if new construction or refurbishment of buildings is preferable. In a typical strategic portfolio decision process, one of the first steps is deciding between refurbishment and demolition then followed by new construction. Here a decisive factor is the market situation. In a demand driven market, where the price of land is high and better use of the land is possible, new construction is often preferred. In areas with low demand, only minimal RMs and EMs are executed because the market does not allow higher rents. A precondition for substantial refurbishments seems to be sufficient demand for built space and inexpensively priced land. This condition is, in many cases, fulfilled in commutable areas around city centres and thus covers a large share of all buildings. This is supported by the fact that in the Swiss market, for example, where a large share of buildings fulfils this condition, refurbishment surmounts demolition and new construction by a factor of ten [46]. For heritage listed buildings, such considerations are not necessary.

Some of these decisive factors may form part of the portfolio’s characteristics and therefore may need to be considered when drawing and using the CPI curve e.g. by treating buildings differently depending on whether they will be newly constructed rather than refurbished.

9.11.3 Data availability

The limited availability of data in the researched fields has been mentioned before as it has influenced the course of this work. At least two reasons should be mentioned here: Firstly, there is a large number of independent actors (private owners) involved in the existing stock of buildings who have no incentive or interest in collecting and providing such data after each refurbishment project. Secondly, common definitions, structures, and tools that would make the data comparable are more or less absent. The second reason is addressed by the CPI method and the proposed cost and benefit structures in Paper 4.

9.11.4 Attribution of benefits

In a newer publication called 'How to calculate and present deep retrofit value' Lovins [40], from the Rocky Mountain Institute RMI, proposes a benefits structures similar to the one proposed in Paper 4 aiming to raise awareness amongst RE investors for benefits other than just energy cost savings. Both structures have similarities and do not contradict themselves fundamentally. In Table 22 the two structures are compared and differences commented. The first column gives the RMI structure of benefits and in the second column, the matching elements of the proposed benefits structure in Paper 4, here named CPI structure, are listed.

Table 22 *Comparison of RMI and CPI benefits structures*

RMI benefits structure and numbering	Matching element in **CPI** structure and numbering	**Comments**
Main split in: A Conventional evaluation B Additional value elements	Main split in: 1. Direct monetary measurable 2. Indirect monetary measurable	Different split not relevant for comparison of elements
A1 Energy Cost Savings	1.2 Decreased expenses/costs	1.2 Is covering both A1 and B2
B1 Development Cost Reductions	2.1 Achieved legal compliance	B1 = 'Cost premium if timed with other capital improvement' (= synergies) – covered in the CPI structure by using additional costs only
B2 Operating Cost Savings	1.2 Decreased expenses/costs	See above
B3 Tenant Based Revenues	1.1 Increased income 2.3 Sensorial, behavioural benefits 2.4 Better image, PR, Branding	Similar, but CPI structure is more detailed
B4 Sales Proceeds	1.3 Optimised values, equity, assets	Similar
B (in parallel) Retrofit Risk Analysis	2.2 Reduced risks	Similar

The result of the comparison is, that most elements in one structure can be attributed to an element in the other structure. With little adaptation, the two structures could be directly compared. This is an example where the same idea has been developed in parallel by independent people, which shows the need for such structures and that the time seems ripe for the idea.

9.11.5 Differences between sectors

As mentioned in Paper 2, there are different requirements and, consequently, differences in the applied methods between industrial maintenance and maintenance and refurbishment in the RE sector. For example, in the industry sector with its individual and often complex and expensive production facilities, more precise condition assessment and monitoring is needed to prevent production failures and to optimise the considerable preventive maintenance effort. The network infrastructure sector, with its more uniform and often repeated elements, is different again. This includes the terminology used. Examples of assumed differences are presented in Table 23.

Table 23 *Examples of maintenance related differences between sectors*

Sector / Aspect	Industrial sector	Network infrastructure sector	Real estate sector
Investor	Industrial companies	Government (central agency) or government mandated organisation	Private, public or institutional owners
User	Owner-user	General public	Owner-user or tenants
Objective	Short-term productivity	Long-term service provision	Mid-term return on investment
Reference for strategic planning	Core business strategy (production may change following changes in the core business strategy)	Government network infrastructure plan (to provide network infrastructure is often a core business of governments)	Core business strategy (RE is considered as a support process which needs to adapt to this superior strategy) or private needs
Examples of strategic planning instruments	Product strategy; Short-term market prognostication (most products need constant innovation to remain on the market)	Budgets and political goals; Long-term demand prognostication (traffic has the tendency to grow constantly)	RE strategy covering mid-term user (market) requirements (changes are usually slower than for industrial products)
Examples of operational planning instruments	Maintenance management systems (see also Paper 2)	List of interventions with impact calculated using probabilistic models; Tools e.g. for bridges: PONTIS, KUBA, etc.	Different for MMs, RMs, and EMs; Refer to section 2

Table 23 exemplifies some of the differences between the three sectors. These were found in e.g. the organisation (government agency, core business or support process), the planning horizon (short-term, mid-term, long-term), and the different users. Table 23 is based on personal perception and the content is given by way of example. Other terminology is also used in each sector because there are no common standards that are universally applied.

In addition to Paper 2, a comparison between RE and network infrastructure sectors has been performed. Notable differences between network infrastructure and RE are:

- Network infrastructure is usually centrally organised vs. a large number of private owners/investors in RE: For example, many countries have a national road agency which is likely to be responsible for built assets that are more valuable than those of a number of sizeable RE portfolios combined. Size matters in that these large organisations have the resources and manpower to think about new methods on how to perform their tasks more efficiently in the long run while RE investors are often more concerned about their daily operations and short term profitability. The latter often rely on RE and FM associations or universities to perform research on new methods. Both have limited resources compared to a central road agency.
- Network infrastructure is sufficiently uniform and exists on a large enough scale to have the experience and data needed to develop and verify probabilistic models. These are applied by a few trained experts vs. more individual architectural solutions and more hands-on planning by a large number of portfolio managers/investors in RE: For example, roadways and railways look pretty much the same all around the world and have for a long period of time. Changes in technology and their impact are well documented and because management of network infrastructure is more centrally organised, information is collected and stored over longer periods and in more standardised form than in RE, where data is rarely stored more than ten years. These two factors are contributors concerning the network infrastructure sector and the fact that there are more sophisticated methods to find optimal intervention strategies both available and in use.
- Network infrastructure is politically determined (long-term public interest) vs. changing (often enough in a mid- or short-term) user or investor requirements in RE. For example, roads are here to stay and traffic is normally increasing. Buildings are sometimes deconstructed before the end of their technical service life due to changes in user requirements. This background induces a more long-term thinking in the network infrastructure sector and a need for adequate methods and tools.
- Network infrastructure methods employ assumptions such as negligible intervention time, three steps of depths of intervention, impacts to vary proportionally on the surface area of the objects vs. potential change of tenants due to interventions and variable depths of retrofit in RE: For example, a

car driver has not much choice if he wants to travel from A to B in a reasonable amount of time, which means that traffic demand is relatively inflexible and easy to prognosticate. Thus, it is relatively safe to make such assumptions in order to simplify planning methods. In RE there is much more uncertainty where occupancy and profitability is concerned. Furthermore, less is known about the random nature of some of the variables influencing the service life of building elements or of whole buildings. These may be some of the reasons why the RE sector is lagging behind in terms of planning methods to find optimal intervention strategies.

Some similarities between network infrastructure and RE, which have been observed:

- Element based methods for refurbishment do exist: In both sectors, standardised lists of elements (such as façade, windows, roof or road section, bridge, culvert) and associated material dependent deterioration curves exist. Based on these, maintenance and refurbishment planning can be performed.

- Condition states in a limited number of stages (e.g. five) with similarly shaped deterioration curves: In both sectors, similarly shaped deterioration curves that give an indication of expected deterioration speed at a given age and the respective remaining service life of an element can be observed. This, again, can be used for maintenance and refurbishment planning.

While there are some similarities, it is still expected that the different sectors will keep on developing and using different methods and tools suitable for the respective sector as can be observed today. This is partly due to the stated differences in Table 23. However, a look into the other sectors in order to make use of synergies could be beneficial for all sectors.

An interesting approach that crosses over into another sector is provided in Esders' paper 'A Methodology to Ensure the Consideration of Flexibility and Robustness in the Selection of Facility Renewal Projects' [36]. It applies probabilistic methods to the problem of the development of an army barracks. It contains an 11 step method that leads to an evaluation of the possible projects taking into consideration the ability of the manager to change their mind in the future as to what to do. The development of influencing variables is modelled and simulated using probabilistic methods. A newer contribution in this direction is Martani's paper 'A new process for evaluation of the net-benefit of flexible ground-floor ceiling in the face of use transition uncertainty' [77].

Another work that represents a number of articles dealing with optimisation of maintenance in buildings using probabilistic methods was written by Zhang [47]. He summarises as follows: "*It is a great challenge to efficiently manage and operate the facilities of a set of buildings, which are of different structural types, ages, and locations and serve for different functions required by different users, over a long-term planning horizon using limited resources to achieve multiple and often conflicting objectives. (…). Based on the state distribution, the optimal policy for the elements of each component in each year of the 10-year planning horizon can be obtained".* In his work, Zhang uses concepts which are also found in the network infrastructure sector. Building elements are hierarchically classified, measures are standardised into four types from replacement to no action, and costs and impact (benefits = performance improvement) of measures are assumed to be known. A continuous improvement process based on experience is proposed. Changing user requirements, synergies from grouping of works, and enhancements like EEMs are not considered.

A third example that crosses over into another sector is provided by Ashuri [48] and looks at energy retrofits. He summarises as follows: "*Although conventional methods such as Net Present Value (NPV) have been widely used to evaluate investments in energy retrofit in existing buildings, they cannot evaluate the flexible energy retrofit solution in which investors delay adopting an emerging energy efficiency technology until the technology becomes available at a lower price, energy prices rise to higher levels, or stricter environmental regulations are put in place making the retrofit solution a necessity. (…) The objective is to develop an investment analysis framework based on Real Options Theory to evaluate any proposed flexible energy retrofit solution".* While it is an interesting approach to look at the future development of technologies (e.g. better windows at the same price or cheaper production of renewable energy) using probabilistic methods, the assumptions taken may lead to a delay of investment. ECMs, however, cannot generally be planned in an isolated manner. Major refurbishments are performed only every 30 years or so and this delay may result in a missed opportunity.

9.12 Conclusion

In this section 9, questions related to the proposed CPI method, questions related to the work performed, and miscellaneous topics have been discussed. The necessity for further research partly resulted from some of these discussions (refer to section 10.3).

10 Summary, conclusions and further research

In this section, a summary of the work is given, conclusions are drawn, and suggestions for further research are proposed.

10.1 Summary

The main new idea brought forward in this thesis is, of course, the CPI method based on the CPI curve. The curve establishes a relation between a well-established energy performance indicator and additional costs to improve it (e.g. based on the law of increasing relative costs). The potential application of the CPI curve for strategic planning and the optimisation of EEMs is part of the respective CPI method.

A CPI curve results from plotting the cost of ECMs against the energy efficiency of the building, in this case the EPI (measured in units of energy consumption per m^2 of building energy reference area and year, abbreviated as $kWh/m^2.a$). In Paper 4, the development of the CPI curve is described, two case studies are provided, and the application of the CPI method is explained with an example on portfolio level and an example on building level in section 8.

The CPI method is an improvement on the state-of-the-art as no such method to complement maintenance and refurbishment planning, with a method to plan enhancement of energy efficiency on the strategic level, currently exists. Some of its main advantages are that it is easy to use, adaptable to individual portfolios, requires a relatively small amount of building information, compatible with existing methods for refurbishment planning, enabling the creation of scenarios, and scalable from single building elements up to a whole country. It provides an indication of what can be achieved and at what costs. It supports strategic planning as well as the optimisation between energy conservation and production of renewable energy in buildings or portfolios. Additionally, cost and benefits structures that enable systematic data collection and comparison of portfolios, are proposed.

In the following section, other results achieved on the way to the CPI method are presented.

10.1.1 Other achievements

Other results developed in the course of this work include the following points:

- Relevance of new standards in FM for the RE sector:

  Paper 1 reviews existing cost structures in this sector, examines what benefits the facility product structure in the new European standards on FM could provide, and discusses problems with existing building cost structures. The conclusion is that the new structures could be a step towards the goal that the same data can be used throughout the whole life cycle of a building as it marks a shift from the traditional building perspective to an organisational perspective and from construction phase thinking to LCC and as such supports the consideration of aspects of sustainability. The paper was probably the first one to analyse these questions in relation to the new standards. The analysis has influenced the proposed cost structures in Paper 4.

- Application of industrial maintenance methods on building maintenance:

  The idea in Paper 2 was to review industrial maintenance methods in order to evaluate their suitability for application in the building sector and group them accordingly. Few where found to be suitable to transfer. The reasons found are differences in the two sectors, for example requirements regarding performance (productivity), service life time, efforts in preventive maintenance, and individuality of production plants versus standardised building elements.

- Evaluation of the widely used method Schroeder

  The method Schroeder is probably the earliest building element based planning method published and has influenced the development of tools such as Stratus and EPIQR. These tools have found the market's acceptance. However, despite the wide-spread use and availability of data, there was no scientific evaluation found out regarding the method or any of these tools in the course of this work. Paper 3 has closed this gap and as a result, most assumptions which form part of this method have been reconfirmed.

- Maintenance signature:

  In Paper 3, the method Schroeder has been combined with the common method of (energy) signatures. In this case, a new application of the signatures was discovered for dividing maintenance and refurbishment costs by looking at their specific patterns. This never-tried-before combination was labelled maintenance signature (see also Paper 3). It draws a division between regular maintenance and intermittent (larger) refurbishment costs and thus may help to better project and plan these costs. An example has been provided.

- Reviewing, listing and comparison of planning methods:

  Existing planning and budgeting methods for industrial and RE maintenance, refurbishment, and enhancements considering aspects of sustainability have been reviewed, listed and compared. Few methods or combinations thereof were found to be suitable for the given task of strategic planning. The best result is to be expected in the combination of an existing building maintenance and refurbishment planning method with the newly developed CPI method. This combination could even be integrated in one tool. The commented lists of methods or classes of methods constitute a valuable result of this study by themselves as they provide an unique overview.

- List of sustainability rating systems (Appendix G)

  All of the sustainability rating systems mentioned in the publications and journal papers, read during and partly before this study, have been collected and compiled in a list. The list contains more than 100 entries in alphabetical order of their name or abbreviation. Where applicable, it provides information about the country of origin, organisation behind the system, and potential application. The list is certainly not comprehensive and only covers systems in English, German or French. No other voluminous list is known so it could provide a valuable basis for interested researchers.

- Proposal for cost and benefit structures

  Structures to collect and present costs and benefits in the researched fields have been proposed. These may help to start a discussion about the need for such structures and eventually lead to common definitions and new standards. It is a kind of chicken and egg problem. Without appropriate structures and definitions, no data will be collected in a systematic and comparable way and without sufficient data, no structures and indicators will be developed.

- Continuous improvement

  In Paper 4, the steps for strategic planning of refurbishment and enhancing sustainability in building portfolios follow the controlling cycle PDCA as defined in international Standard ISO 9001 Quality management systems - requirements [49]. In both Papers 1 and 2, reference is also made to this controlling cycle. The controlling cycle also integrates the phases in the CPI method and continuous improvement forms part of it. This cycle remained an integral part of the thesis as its wider application could be beneficial for the whole RE sector.

10.2 Conclusions

“The use of the proposed CPI method will help decision makers take into consideration the costs and benefits of RMs and EEMs, correctly at the strategic level, i.e. without the double counting of costs for both measures if they are executed together. Through its use, there will be an increased number of EEMs planned and executed, due to the increase in knowledge with respect to the costs and effectiveness of EEMs and, therefore, change in the actions of owners. Without this or a comparable method, decision makers need either to rely more on personal experience or more on costly and detailed analyses of buildings assigned for potential refurbishment projects and may end up with less energy efficient buildings because potential benefits are not realised” (text from Paper 4). The lack of applicable instruments and data has been described as one of the main obstacles hindering investors from tapping the full potential of economically viable energy efficiency gains [50].

When used as a prognostication tool, the CPI curve is also valuable in the early process of setting up or renewing a portfolio strategy. Later, in the definition of measures, the CPI curve supports the decision making between different packages of measures as well as finding the optimal mix between energy conservation and production of renewable energies. As well, in the monitoring phase, the CPI curve helps evaluate the achieved energy savings and thus becomes part of a continuous improvement system, giving feedback into the strategy developing process. This closed cycle of actions is summarised in the CPI method (refer to Paper 4 and the process diagram in Annex B).

The development of a CPI curve is only possible if it can be assumed that there is a relatively well defined relationship between a performance indicator and the marginal costs to improve it i.e. the current energy efficiency of buildings and the additional costs to execute refurbishment and enhancement measures to increase this energy efficiency up to a certain level. The potential use of the CPI curve for estimation is discussed in Annex F2.

10.3 Further research

At several points in this work the need for further research has arisen (refer also to the final sections in the published Papers 1-4). This includes the following three suggestions:

- Collect and evaluate more data about additional costs of energy efficiency measures and their relation to the performance of the buildings (based on the proposed or similar cost and benefits structures):
  To this end, an on-going research project should be initiated which installs the necessary framework and supports investors in collecting data about costs and benefits of refurbishment projects. Using this data, more information about the relation between different variables can be extracted e.g. using data mining techniques which aim to achieve better estimations and more precise CPI curves or to develop and test probabilistic models.

- Research the different variables influencing the CPI curve based on the aforementioned data:
  The primary question is how are variables such as age, size, construction cost, type of construction, type of usage, climate, etc. influence cost and benefits and which are the most important of these? A secondary question is whether clusters of buildings with similar characteristics can be found and how large the number of buildings in such a cluster must be to be representative and what the deviation from the average value of e.g. the estimated costs would be? Based on this research, investors can be better supported with CPI curves that are customised and tailored to fit their specific portfolio. Eventually, CPI curves may be used to model the entire building stock of a state or a country.

- Develop other ideas mentioned in this work such as element based method, maintenance signature, or incorporation of dynamic interdependences in LCC further:
  Each one of these ideas has its own potential benefits which have not been fully explored yet. The three ideas listed here were selected because they may potentially provide the largest benefits if further developed. The element based method could become an easy to use tool to estimate costs and benefits of energy efficiency measures without considerable effort. There is ample knowledge and experience of costs and benefits available on a building element level that could be integrated in one tool to model whole buildings. Alternative measures and interdependences could also be incorporated. The crux of the matter is, again, the division between refurbishment and enhancement

costs. It is a difficult task to find one or more suitable cases to validate such a method. The maintenance signature (refer to Paper 3) draws a division between regular maintenance and intermittent (larger) refurbishment costs and displays them in function of the condition and on a per m^2 base, and thus may help to better project and plan these costs. Buildings costing more than average could also be identified. The current division is often based on a fixed threshold which is easy to handle in the accounting department but is not helpful from a technical point of view or for planning as the same measure may count as a MM or a RM, depending on the size of the building. Given the use of an appropriate planning method, the required data to do more research to further develop this method is usually available. The idea of incorporating dynamic interdependences (refer to section 9.5) in LCC requires most additional research of these three. As shown in section 2, costs of ECMs may follow a learning curve over time. As another example of interdependences, it can be assumed, that refurbishment or enhancement costs reduce the following operational and possibly maintenance costs as well. Such relations have never been properly researched and described but may have a substantial influence on LCC considerations and calculations.

- Research relation between initial construction and additional enhancement costs:
  Construction costs of buildings per m^2 can vary considerably. These differences are very likely to have an effect on enhancement costs (e.g. through exclusive materials used, complex forms and structures and/or architectural design employed, high level of building technique installed, etc.). However, the assumption that they have the same effect on costs of ECMs (for example that an expensive, complicated façade is more costly to insulate) as on costs of RMs (Paper 3) remains to be validated.

- Research relation between the execution of ECMs and additional costs for operation, maintenance and refurbishment over the life cycle:
  ECMs may have an effect on these three cost categories in a magnitude which is relevant for the cost/benefit calculation. How large these effects are and if they are positive (cost reductions) or negative (additional costs) over the life cycle of a building is an open question to date which needs further analysis.

- Develop curves for other types of functional changes to buildings or portfolios:
  It would be interesting to explore other relations between desired functional changes and the costs to achieve them. This could include maintainability, cleanability, flexibility, or even work productivity.

- Combine the CPI method with advanced methods of planning e.g. for network infrastructure:
  Due to some of its differing characteristics, which are outlined in section 9.11.5 (like central organisation and large amount of similar and more standardised objects), there is more research undertaken to develop advanced statistical or probabilistic planning methods for the network infrastructure sector than for the RE sector. Examples do exist of approaches from one sector being used in another. To benefit from possible synergies, a combination of the CPI curve with such advanced methods and vice versa, should be investigated. It is also imaginable that the advanced methods are used to calculate or prognosticate such a curve while the curve itself is used to present the results transparently.

- Explore application of CPI curve in sustainability reporting:
  Sustainability reporting today is a standardised process and well established in practice. The CPI curve could be used to present goals and achievements in energy conservation in conjunction with e.g. CO_2 reductions in a building portfolio. This application of the CPI curve needs further exploration.

- Analyse motivations and goals of portfolio owners:
  Owners of building portfolios have various motivations and goals. These are often related to the interests of other stakeholders. A quantification and weighting and balancing of these interests needs further analysis.

- Find more evidence for the need to integrate benefits of short term energy optimisations and costs of long term EEMs in order to achieve optimal overall results:
  According to the CPI curve, if short term energy optimisations are executed in a first phase of measures, then the resulting benefits cannot help to pay for the execution of more expensive long term measures in a second phase. An integrated view and grouping of measures could be possible solutions.

Building maintenance and refurbishment, together with enhancement considering aspects of sustainability, is an under researched area. This work looked at a small part of this wide area, the strategic planning for building portfolios considering energy efficiency, and provides a new method for this task. The proposed CPI method provides portfolio managers with acceptable means to plan and value and thus justify necessary expenses in energy efficiency. But, more work needs to be done.

97% of buildings in the EU need to be upgraded

A decarbonised building stock by 2050 requires the big majority of buildings in the EU to be highly energy efficient, complying, at least, with an Energy Performance Certificate (EPC) label A. BPIE's analysis of available EPC data finds that less than 3% of the building stock in the EU qualifies the A-label.

From: The Buildings Performance Institute Europe (BPIE)
(http://bpie.eu/publication/97-of-buildings-in-the-eu-need-to-be-upgraded)

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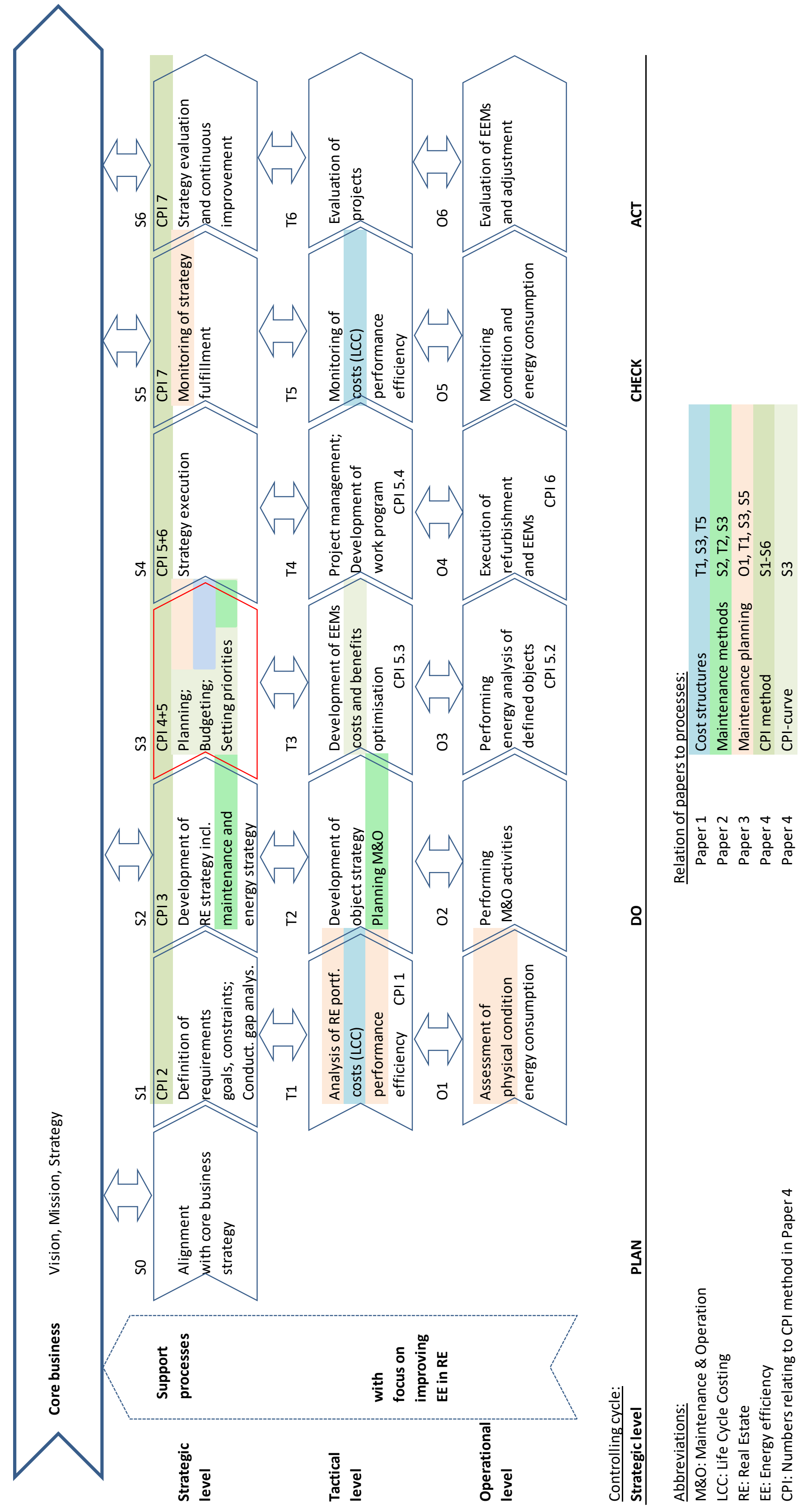
Annex A Real estate process matrix



Annex B Process Diagram of CPI Method

In Paper 4, a new method called the CPI method is proposed. The method can be described as a process which is structured following the PDCA controlling cycle (Figure B1).

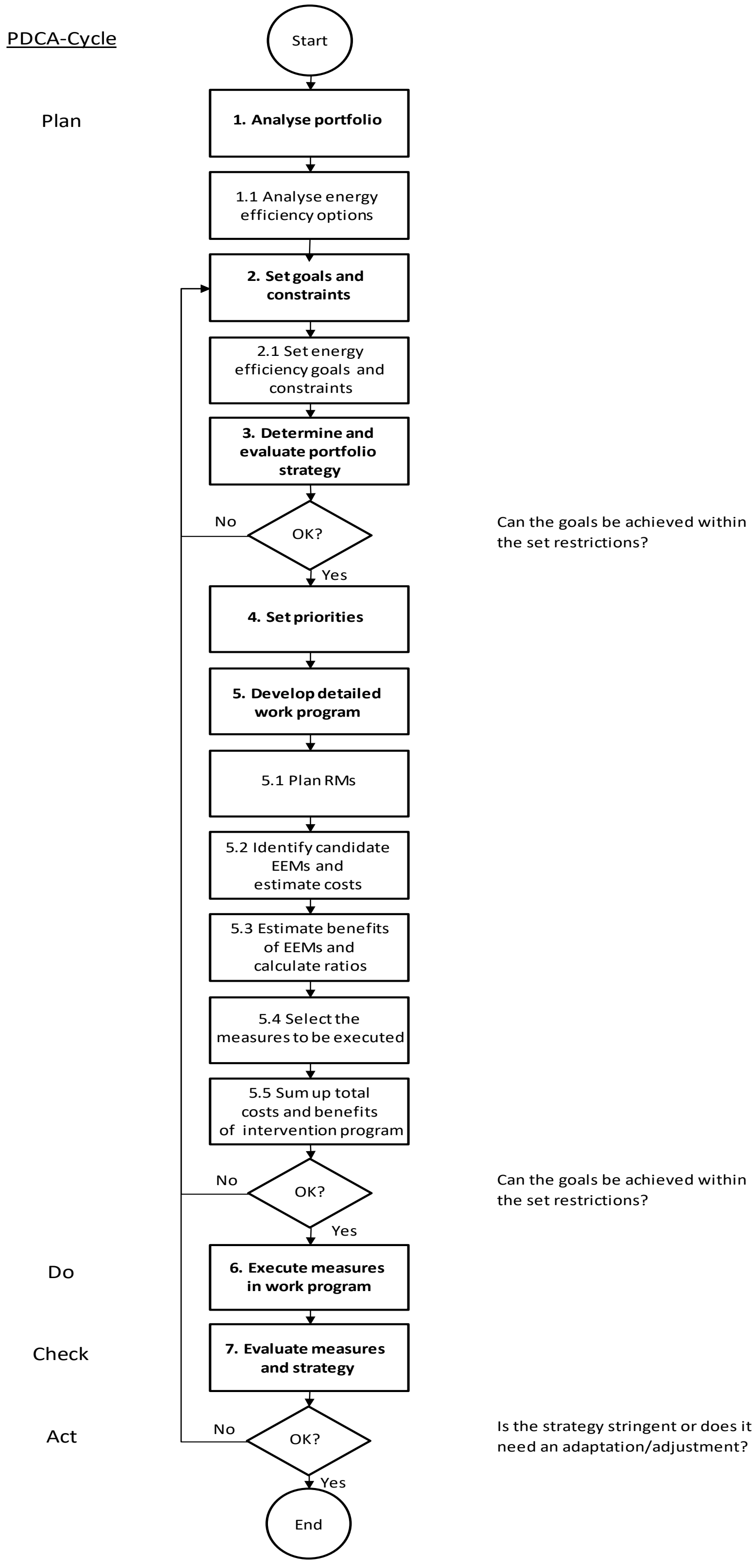


Figure B1 *Process diagram of CPI method*

Annex C Cost code structures in FM

C1 New cost code structure in FM part 1

Facility Product Map (list part 1)

From EN 15221-4

Strategic level	Tactical level	Level 1	Level 2	Level 3	Exemplary additional level (not yet standardised)	
FM	**Facility Managment strategic integration**					
	1	**Space & Infrastructure - Tactical integration (S&I)**				
A	1	1				Space (Accommodation)
A	1	1	1			Building intial performance
A	1	1	1	1		Owner / Occupier
A	1	1	2			Asset replacement and refurbishment
A	1	1	2	1		External structure and fabric
A	1	1	2	2		Internal structure and fabric
A	1	1	2	3		Technical building equipment
A	1	1	2	3	1	*BMS*
A	1	1	2	3	2	*Heating*
A	1	1	2	3	3	*Ventilation/cooling*
A	1	1	2	3	4	*Sanitation*
A	1	1	2	3	5	*Lighting*
A	1	1	2	3	6	*Lifts/escalators*
A	1	1	3			Enhancement of initial performance
B	1	1	4			Property administration
B	1	1	4	1		CAFM
B	1	1	5			Portfolio optimisation
B	1	1	5	1		Real estate development
C	1	1	6			Maintenance and Operation
C	1	1	6	1		Help desk incl. Janitor
C	1	1	6	2		Structure operation
C	1	1	6	3		Structure maintenance
C	1	1	6	4		Equipment operation
C	1	1	6	4	1	*BMS*
C	1	1	6	4	2	*Heating*
C	1	1	6	4	3	*Ventilation/cooling*
C	1	1	6	4	4	*Sanitation*
C	1	1	6	4	5	*Lighting*
C	1	1	6	4	6	*Lifts/escalators*
C	1	1	6	5		Equipment maintenance
C	1	1	6	5	1	*BMS*
C	1	1	6	5	2	*Heating*
C	1	1	6	5	3	*Ventilation/cooling*
C	1	1	6	5	4	*Sanitation*
C	1	1	6	5	5	*Lighting*
C	1	1	6	5	6	*Lifts/escalators*
C	1	1	7			Utilities
C	1	1	7	1		Energy
C	1	1	7	1	1	*Heating*
C	1	1	7	1	2	*Cooling*
C	1	1	7	1	3	*Electricity*
C	1	1	7	1	4	*Gas*
C	1	1	7	1	5	*Oil*
C	1	1	7	2		Water
C	1	1	7	2	1	*Water supply*
C	1	1	7	2	2	*Waste water*
C	1	1	7	2	3	*Ground water*
C	1	1	7	2	4	*Rain water*
C	1	1	7	3		Waste
C	1	1	7	3	1	*Burnable waste*
C	1	1	7	3	2	*Paper*
C	1	1	7	3	3	*Hazardous waste*
C	1	1	7	3	4	*Glass*
C	1	1	7	3	5	*Kitchen waste*
C	1	2				Outdoors
C	1	2	1			Land, Site, Lot
C	1	2	2			Additional space on site
C	1	2	3			Parking facilities
C	1	3				Cleaning
C	1	3	1			Routine cleaning
C	1	3	2			Special cleaning
C	1	3	2	1		Pest control

Strategic level	Tactical level	Level 1	Level 2	Level 3	Exemplary additional level (not yet standardised)	
FM	**Facility Managment strategic integration**					
	1	**Space & Infrastructure - Tactical integration (S&I)**				
D	1	4				Workplace
D	1	4	1			Occupier fitout and adaptations
D	1	4	2			Space management
D	1	4	3			Furniture
D	1	4	3	1		Plants and Flowers
D	1	4	4			Art works
D	1	9				Primary activity specific
D	1	9	1			Primary process related utilities
D	1	9	2			External workplaces
D	1	9	2	0	1	*Workplaces at home*
D	1	9	2	0	2	*Other external accommodations*
D	1	9	2	0	3	*Canteens*
D	1	9	2	0	4	*Temporary exhibition space*
D	1	9	9			Branch specific e.g. health care
D	1	9	9	H1		Maintenance of biomedical equipment
D	1	9	9	H2		Sterilization service
	2	**People & Organisation - Tactical integration (P&O)**				
D	2	1				Health, safety, security and environment
D	2	1	1			Health & Safety
D	2	1	1	1		People occupational health
D	2	1	2			Security
D	2	1	2	1		Securing people
D	2	1	2	1	1	*Access control*
D	2	1	2	1	2	*Guard and patrols*
D	2	1	2	1	3	*Body guards*
D	2	1	2	2		Assets (physical and intellectual property)
D	2	1	3			Environmental protection
D	2	2				Hospitality
D	2	2	1			Reception and contact center
D	2	2	2			Catering and Vending
D	2	2	2	0	1	*Restaurant*
D	2	2	2	0	2	*Vending*
D	2	2	2	0	3	*Extra services (Board, VIP, etc.)*
D	2	2	3			Meeting rooms and Events
D	2	2	3	0	1	*Meeting rooms*
D	2	2	3	0	2	*Events internal*
D	2	2	3	0	3	*Events external*
D	2	2	4			Workwear
D	2	2	4	1		Laundry
D	2	3				ICT (Management & Advisement)
D	2	3	1			Service Desk IT
D	2	3	2			End User Services IT
D	2	3	2	1		Client Hardware Devices IT
D	2	3	2	2		Client Software
D	2	3	2	3		On Site Support
D	2	3	2	4		Managed Client Service
D	2	3	2	5		IMAC
D	2	3	2	6		Packaging & Distribution
D	2	3	2	7		Client Hardware Special Devices
D	2	3	3			Central and Distributed Services
D	2	3	3	1		File services
D	2	3	3	2		E-mail Services
D	2	3	3	3		Print Services
D	2	3	3	4		Directory Services
D	2	3	4			Connectivity & Telecommunications
D	2	3	4	1		Connectivity Services IT
D	2	3	4	2		Connectivity Services CT
D	2	3	4	3		Client Hardware Devices CT
D	2	3	5			Training End User (ICT)

C1 New cost code structure in FM part 2

Facility Product Map (list part 2)

From EN 15221-4

Strategic level	Tactical level	Level 1	Level 2	Level 3	Exemplary additional level (not yet standardised)	
FM						**Facility Managment strategic integration**
	2					**People & Organisation - Tactical integration (P&O)**
D	2	4				Logistics
D	2	4	1			Office supplies, stationary
D	2	4	2			Document Management
D	2	4	2	1		Reprographics
D	2	4	2	1	1	*Central reprographics*
D	2	4	2	1	2	*Distributed reprographics*
D	2	4	2	1	3	*On site doc. mngt. and archiving*
D	2	4	2	1	4	*Off site doc. mngt. and archiving*
D	2	4	2	2		Post room and internal distribution
D	2	4	2	2	1	*Post room services*
D	2	4	2	2	2	*Internal distribution services*
D	2	4	2	3		Library and archives
D	2	4	3			Moves - people and furniture
D	2	4	4			Mobility
D	2	4	4	1		Fleet management
D	2	4	4	2		Travel services
D	2	4	4	2	1	*Public transport*
D	2	4	4	2	2	*Taxi*
D	2	4	4	2	3	*Air*
D	2	4	4	3		Transport services
D	2	4	4	3	1	*Staff transport on site*
D	2	4	4	3	2	*Staff transport on site*
D	2	4	4	3	3	*Goods transport on site*
D	2	4	4	3	4	*Goods transport off site*
D	2	5				Business Support (management support)
D	2	5	1			Business support finance
D	2	5	1	1		Accounting
D	2	5	1	2		Assets,property
D	2	5	1	3		Controlling, Reporting
D	2	5	2			Business support HRM
D	2	5	2	1		Salaries and pensions
D	2	5	2	2		Recruiting
D	2	5	2	3		Training and development
D	2	5	3			Legal counsel and contracts
D	2	5	3	1		Legal advice
D	2	5	3	2		Patents and copyrights
D	2	5	3	3		Insurances
D	2	5	3	4		Contracts
D	2	5	4			Marketing and communication
D	2	5	5			Procurement
D	2	5	6			Secretarial services, translations
D	2	9				Organisation specific (industry sector)
D	2	9	1			Business application providing
D	2	9	9			Branch specific e.g. health care
D	2	9	9	H1		Patient transport
D	2	9	9	H2		Bed sterilization
D	2	9	9	H3		Broadcasting services

Strategic level	Tactical level	Level 1	Level 2	Level 3	
FM					**Facility Managment strategic integration**
	9				**Central functions**
E	9	1			Sustainability
E	9	1	1		Life cycle planning / engineering
E	9	2			Quality
E	9	2	1		Standards and guidelines
E	9	3			Risk
E	9	3	1		Risk policy
E	9	4			Identity
E	9	4	1		Innovation

C2 Existing cost code structures in FM

COMPARISON OF EXISTING (COST CODE) STRUCTURES part 1

	CEEC Cost groups			DIN 18960			GEFMA/IFMA SUBMISSION CODES
A	**Construction costs**		100	**Kapitalkosten**			
A	**Design and incidental costs**		200	**Verwaltungskosten**			
C	**Costs in use**		300	**Betriebskosten**			
C	**- Maintenance**		400	**Bauunterhalt**			
C	**- Operation**						
C	**- Disposal**						
A	**- Decomissioning**						
A	**- Taxes**						
A	**Land and finance**						
A	Construction costs	A	410	Instandsetzung der Baukonstruktion	A	7	Instandsetzung
A	Design and incidental costs	A	420	Instandsetzung der technischen Anlagen	A	8	Verfolgung von Mängelansprüchen
A	- Decomissioning	A	370	Abgaben und Beiträge			
A	- Taxes	A	430	Instandsetzung der Außenanlagen			
A	Land and finance	A	440	Instandsetzung der Ausstattung			
		A	110	Fremdkapital			
		A	120	Eigenkapital			
		B	230	Verwaltungskosten, sonstiges	B	22	Kaufmännische Verwaltung und Controlling
		B	210	Personalkosten	B	3	Objektmanagement
		B	220	Sachkosten	B	24	Leerstandsmanagement
					B	5	Betriebsführung / Objekt
					B	4	Dokumentation und Berichtswesen
					B	23	Flächenmanagement
C	Costs in use	C	340	Inspektion/Wartung Baukonstruktion	C	2	Einmalige Leistungen
C	- Maintenance	C	330	Bedienung der technischen Anlagen	C	12	Gebäudeservice
C	- Operation	C	350	Inspektion/Wartung technische Anlagen	C	6	Wartung
C	- Disposal	C	310	Ver- und Entsorgung	C	9	Energiemanagement
		C	320	Reinigung und Pflege	C	16	Entsorgung
		C	380	Betriebskosten, sonstiges	C	11	Aussenanlagenpflege
					C	10	Reinigung
		D	360	Kontroll- und Sicherheitsdienste	D	13	Gebäude-/Werkschutz
					D	19	Catering
					D	18	Konferenzräume und Veranstaltungsservice
					D	14	Bereitstellung von luk-Komponenten
					D	15	IT-Dienstleistungen
					D	20	Büroservice
					D	17	Postdienste / Warenannahme / Gebäudelogistik
					D	21	Fahrdienste

Source: CEEC Source: DIN 18960 Source: German Facility Management Association GEFMA

COMPARISON OF EXISTING (COST CODE) STRUCTURES part 2

	OPIK - FM Products in hospitals			IFMA WORKPOINT ACCOUNTING		IFMA/GLOBAL FM BENCHMARKS
			DS	Direct Space		
			DSE	Direct Support and Equipment		
			C	Connectivity		
			IS	Indirect Space		
			ISE	Indirect Support and Equipment		
A	basic rent	A		Real estate tax	A	Lease cost
		A		Property and occupancy taxes	A	Leasehold improvement amortisation and
		A		Insurance for fire, liability and operating equipment	A	of fixed asset provision
		A		Construction and reconstruction of worksettings		
		A		Lease or rent expense		
					B	Facility management
C	building maintenance	C		Non specific repairs and maintenance	C	Building maintenance
C	technical maintenance	C		Electricity	C	Part of building maintenance
C	caretaker services	C		Gas and oil	C	Mechanical services
C	operation	C		Water and sewer	C	Electrical services
C	power supply	C		Trash removal	C	Small projects
C	heating supply	C		Roadways, parking and grounds	C	Electricity
C	heating supply	C		Cleaning	C	Gas
C	cooling service				C	Oil/solid fuel
C	water supply				C	Other energy
C	waste disposal				C	Potable water only
C	outside facilities				C	Non toxic effluent and drainage
C	cleaning				C	External landscaping/grounds maintenance
C	pest control				C	Cleaning and janitorial
D	security	D		Furniture, filing and lighting	D	Internal planting
D	catering	D		Security	D	Security
D	laundry services	D		Reception	D	Catering/food services
D	IT-services	D		Food services, cafeteria	D	Communications/switchboard
D	phone services	D		Voice communications	D	Reprographics
D	office supplies	D		Copy and printing services	D	Post/mail
D	repro services	D		Mail	D	Internal moves
D	mail services	D		Courier and delivery services		
D	removal services	D		Move costs		
D	fleet management					
E	maintenance of biomedical equipment				E	furniture and equipment depreciation part
E	sterilization service					
E	hygiene advice					
E	patient transport					
E	bed conditioning					
E	broadcasting services					

COMPARISON OF EXISTING (COST CODE) STRUCTURES part 3

	Danish FM cost structure			France - Apogee			QUICKSCAN
0			1	OPERATING COSTS		F	Fixed costs
			2	MAJOR WORKS		E	Energy and water
			3	COMMUNAL SERVICES		MC	Maintenance
						SC	Service cost
						C	Cleaning
						EX	External landscaping
A	Building, exterior	A	A 621	Property tax	A	F	Rent/lease
A	Building, interior	A	A 622	Local property tax	A	F	Local property taxes
A	Rebuilding and interior design	A	A61	Property insurance	A	F	Tax (by government)
		A	B21	Initial fit out or subsequent fit out	A	F	Interest
		A	B23	Other fit out costs not in B21 and B22	A	F	Depreciations
					A	F	Ground lease
					A	SC	Service charges
					A	F	Insurance
B	Management and administration				B	C	Personnel cost own department
B	Space management				B	F	Revenues by sublet
B	Cost categories for regular data collection				B	F	Parking costs
B	Planning of operational functions, including service contracting						
C	Maintenance (planned, daily, reinvestments)	C	A5	External maintenance and cleaning	C	MC	Structural maintenance
C	Operation (caretaking, control and monitoring)	C	A31	Maintenance for heating, air con and plumbing	C	MC	Maintenance mechanical installations
C	Supply	C	A32	Maintenance for electrical equipment	C	MC	Maintenance electrical installations
C	Heating	C	A33	Maintenance for elevators and service elevators	C	MC	Maintenance transport installations
C	Electricity	C	A34	Maintenace to other equipment	C	MC	Maintenance security equipment
C	Water and drainage	C	A11	Electricity, gas , oil and district heating	C	E	Electricity
C	Waste	C	A12	Water	C	E	Gas
C	Removal service	C	A 623	Refuse tax	C	E	Oil
C	Ground, incl. cleaning	C	A2	Included in internal cleaning	C	E	City heating
C	Cleaning, building	C	A5	Externa site maintenance	C	MC	Technical service
		C	A2	Internal cleaning only	C	E	Water
					C	C	Waste disposal
					C	EX	External landscaping
					C	C	Daily cleaning
D	Building and security installations	D	A42	Security	C	C	Sanitary
D	Security service, incl. guarding and gate keeping	D	A41	Reception services	C	C	Cleaning periodically
D	Reception and switchboard	D	C22	Telephone staff cost	C	C	Vermin control
D	Catering	D	C21	Telephone equipment cost			
D	Data infrastructure	D	C3	Photocopying			
D	Office support	D	D5	Internal couriers			
D	Post service	D	B22	Cost of partitions only			
		E	B22	Reconfiguration following move out			

COMPARISON OF EXISTING (COST CODE) STRUCTURES part 4

		UK Buillding Cost Information Service			BOMA CHART OF ACCOUNTS			ITOCC - IPD
	1	**DECORATION**		0			1	**Property occupation**
	2	**FABRIC**					2	**Adaptation and equipment**
	3	**SERVICES**					3	**Building operation**
	4	**CLEANING**					4	**Business support**
	5	**UTILITIES**					5	**Management**
	6	**ADMINISTRATIVE COST**					5	
	7	**OVERHEADS**						
	8	**EXTERNAL WORK**						
A	1.1	External redecoration	A	30000	Office rent	A	A1	Rent
A	2.1	Repairs to external walls	A	33000	Other space rent	A	A4	Associated facilities rent
A	2.2	Repairs to roof	A	31000	Retail rent	A	A5	Associated facilities
A	2.3	Repairs to other structural items	A	61300	Building improvements	A	E3	Project management
A	1.2	Internal decoration	A	47100	Real estate taxes	A	A2	Acquisition tax
A	2.4	Repairs to fixtures and fittings	A	61300	Building improvements	A	A3	National and local property tax
A	2.5	Repairs to internal finishes	A	34000	Additional tenant service incor	A	C1	Consolidated service charge
A	7.2	Rates	A	35000	Miscellaneous income	A	C2	Insurance
A	7.1	Property insurance	A	61400	Tenant improvements	A	B1	Fit out and improvement
B	6.6	*Property management*	B	30200	Office Insurance	B	E2	Facilities management
B	6.6	Property management	B	31200	Retail Insurance	B	E1	Real estate management
						B	C8	Reinstatement
C	3.2	Maintenance for Heating and ventilating	C	41850	General building (exterior)	C	C5	External and structural repair and
C	3.3	Maintenance to lifts and escalators	C	41800	Interior surface repair and ma	C	C3	Internal repair and maintenance
C	3.4	Maintenance for power and lighting	C	41200	Elevator maintenance	C	C4	M&E repair and maintenance
C	3.5	Maintenance for other M&E	C	41300	HVAC maintenance	C	C6	Minor improvements
C	5.1	Gas	C	41400	Electrical maintenance	C	C15	Energy
C	5.2	Electricity	C	42100	Electricity	C	C14	Water and sewerage
C	5.3	Fuel oil	C	42200	Gas	C	C11	Waste disposal
C	5.4	Solid fuel	C	42300	Fuel oil	C	C13	Grounds maintenance
C	5.5	Water rates	C	42400	Steam	C	C10	Cleaning
C	5.6	Effluent and drainage charges	C	42500	Chilled water			
C	6.5	Staff costs of rubbish disposal	C	42600	Water			
C	8	External work	C	42700	Sewer			
C	8	External work	C	40500	Trash removal			
C	4.1	Cleaning windows	C	43000	Roads and grounds expenses			
C	4.3	Internal cleaning	C	40000	Cleaning			
C	4.2	Cleaning external surfaces						
D	6.4	Security staff costs only	D	61700	Office equipment and furniture	D	B2	Furniture and equipment
D	6.3	Porterage and internal guides	D	44000	Security	D	C12	Internal plants and flowers
			D	35100	Vending machines	D	C9	Security
			D	61700	Telephone system	D	D7	Disaster recovery
			D	61700	Copiers	D	D3	Reception services
						D	D2	Catering
						D	D1	Telephones
						D	D6	Reprographics
						D	D5	Post room and internal distribution
						D	D4	Courier and external distribution
						D	C7	Internal moves
						D	D8	Transport services
			Source: BOMA, IMA Workpoint Accounting, IFMA				Source: Apogee, RICS	

COMPARISON OF EXISTING (COST CODE) STRUCTURES part 5

		CRB Nutzungskosten (CH)			JELLEMA			NEN
	N0	**Strategieentwicklung**		**F**	**Fixed Costs**		**P**	**Property occupancy costs**
	N1	**Kaufmännische Aufgaben**		**E**	**Energy costs**		**SM**	**Services and means**
	N2	**Grundabgaben**		**MC**	**Maintenance costs**		**I/C**	**Information and communication**
	N3	**Erhaltung**		**A**	**Administrative control costs**		**EF**	**External facilities**
	N4	**Betrieb**		**S**	**Specific running costs**		**F**	**Facility management**
	N5	**Mietaufwand**		**M**	**Means**			
	N6	**Kapitalzinsen**						
	N7	**Abschreibungen, Rückstellungen**						
	N8	**Dienste**						
	N9	**Übriger Aufwand**						
A	N5	Mietaufwand	A	F	Rent	A	P	Rent/sale/lease
A	N31	Instandsetzung und Erneuerung	A	F	Local property taxes	A	P	Taxes
A	N21	Steuern und Beiträge	A	F	Tax (by government)	A	P	Interest
A	N6	Kapitalzinsen	A	F	Interest	A	P	Insurance
A	N71	Abschreibungen	A	F	Depreciations	A	P	Obtain/dispose real estate
A	N51	*Miet- und Pachtzinsen*	A	F	Ground lease	A	P	Changes floorplan building
A	N22	Versicherungen	A	SC	Service charge	A	I/C	Internal infrastructure
			A	F	Insurance	A	I/C	External infrastructure
						A	EF	Supply in external accommodation
						A	P	Changes installations
B	N0, 01	Strategieentwicklung	B	S	Facility control cost			
B	N02	Steuerung	B	A	Control costs			
B	N1	Kaufmännische Aufgaben				B	F	Facility management
B	N12, 13	Objektbuchhaltung, Doku				B	P	Exploitation
B	N11	Vermietung						
C	N44	Bedienung und Instandhaltung	C	MC	Structural maintenance	C	P	Building maintenance
C	N4	Betrieb	C	MC	External maintenance	C	P	Fit out maintenance
C	N41	Ver- und Entsorgung	C	MC	Façade maintenance	C	P	Maintenance installations
C	N43	Reinigung	C	MC	Internal maintenance	C	P	Electricity
C	N431	Unterhaltsreinigung	C	MC	M&E maintenance	C	P	Gas
C	N432	Spezialreinigung	C	MC	Maintenance other installations	C	P	Oil
			C	E	Electricity	C	P	City heating
			C	E	Gas	C	P	Water
			C	E	Oil	C	SM	Waste disposal
			C	E	City heating	C	P	External landscaping
			C	E	Water	C	SM	Cleaning
			C	MC	Waste disposal	C	P	Calamities maintenance
			C	MC	External landscaping			
			C	MC	Maintenance site			
			C	MC	Cleaning			
D	N843	Parkingdienste	D	M	Fit out and furniture	D	P	fit out
D	N851	Einrichtungsmanagement	D	S	Security cost	D	P	Changes fit out
D	N42	Sicherheit	D	S	Security equipment	D	EF	External workplace and meeting rooms
D	N813	Empfangs-, Portierdienste	D	S	Reception services	D	SM	Security
D	N852	Verpflegungsdienste	D	S	Catering costs and canteen	D	SM	Reception
D	N842	Raumdienste (?)	D	M	Data communication cost	D	SM	Canteen
D	N853	Wäsche- und Textilpflegedienste	D	M	Telephone cost	D	I/C	ICT management and maintenance
D	N81	Kommunikations- und Informationsdienst	D	M	Office supplies	D	I/C	ICT hardware
D	N810	Telekommunikationsdienste	D	S	Reprographics and internal messe	D	I/C	ICT software
D	N822	Lager- und Archivmanagement				D	I/C	ICT education
D	N831	Post- und interne Speditionsdienste				D	SM	Archives
D	N832	Kurier- und externe Transportdienste				D	SM	Post room services
D	N841	Umzugsmanagement				D	P	Internal and external moves
D	N821	Bürodienstleistungen				D	F	Industrial accountancy
			E	S	Remaining costs			

Source: Jones Lang LaSalle, Delft University

COMPARISON OF EXISTING (COST CODE) STRUCTURES part 6

		Nordic Life Cylce Cost Structure LCC		ProLeMo IFMA (CH)			GEFMA 200
	1	**Capital Costs**		**Strategieprozesse**		0	**OBERSTE FM-LEITUNG**
	2	**Administration Costs**		**Steuerungsprozesse**		1	**KONZEPTIONSPHASE**
	3	**Operation Costs**		**Operative Prozesse**		2	**PLANUNGSPHASE**
	4	**Maintenance Costs**		**LOP Operative Prozesse**		3	**ERRICHTUNGSPHASE**
	5	**Developing Costs**		**LOPE Erstellung/Erhaltung**		4	**VERMARKTUNGSPHASE**
	6	**Consumption Costs**		**LOPK Kaufmännische Prozesse**		5	**BESCHAFFUNGSPHASE**
	7	**Cleaning Costs**		**LOPB Betrieb und Instandhaltung**		6	**BETRIEBS- UND NUTZUNGSPHASE**
	8	**Service Costs**				7	**UMBAU- UND SANIERUNGSPHASE**
						8	**LEERSTANDSPHASE**
						9	**VERWERTUNGSPHASE**
A	11	Project Costs	A	LOPE Erstellung/Erhaltung	A		PHASES 1-5, 9
A	43	Replacement of Exterior	A	LOPB 05 Instandsetzung	A	3.1	Bauherrenaufgaben
A	21	Taxes and Fees			A	7	UMBAU- UND SANIERUNGSPHASE
A	22	External Fees			A	6.3	Instandsetzung & Erneuerung
A	5	Developing Costs			A	1.2	Projektentwicklung
A	59	Development and upgrading outdoor					
A	44	Replacement of Interior					
A	1	Capital Costs					
A	24	Insurance					
A	51	Development and upgrading of Exterior of the building					
A	52	Development and upgrading of Internal of the building					
B	23	Administration and Management	B	LSteP 01 Mandatsübernahme/-übergabe	B	0	OBERSTE FM-LEITUNG
B	2	Administration Costs	B	LStrP 04 Umweltstrategie im FM	B	0.1	Strategisches Management
			B	LSteP 06 Qualitätssicherung	B	0.1	Oberste Leitung FM (Facility Manager) 4
			B	LSteP 03 Standards/SLA	B	6.2	Umweltschutz im FM
			B	LOPK Kaufmännische Prozesse	B	6.2	Qualitätsmanagement im FM
			B	LOPK 05 Anmietung	B	0.1	Entwicklung FM-Standards
C	4	Maintenance Costs	B	LOPE 03 Garantiemanagement	B	6.1	Objektmanagement
C	41	Periodical maintenance of Exterior of the building	B	LStrP 02 Strat. Flächenmanagement	B	6.7	Mietverwaltung
C	42	Periodical maintenance of Internal of the building	B	LOPK 12 Objektdokumentation	B	6.1	Bereitstellung von FM-Tools
C	4	Maintenance Costs	B	LOPK 01 Vermietung	B	8.1	Leerstandsverwaltung
C	31	Operation and inspection executed by own employe	B	LStrP 01 Objektstrategie	B	6.7	FM-Rechnungswesen & FM-Controlling
C	3	Operation Costs	B	LOPD 01 Operatives Flächenmanagement	B	6.8	Vertrags- und Versicherungsmanagement
C	61	Energy	B	LOPD 02 Belegungsplanung			
C	6	Consumption Costs	B	LSteP 07 Reporting	C	6.9	Handwerksdienste
C	62	Water and Drainage	B	LSteP 08 Vertragsmanagement	C	6.6	Notrufzentrale
C	63	Waste Handling			C	6.3	Objektbetrieb /Betriebsführung
C	49	Outdoor	C	LStrP 03 Instandhaltungsstrategie	C	6.3	Bedienung
C	37	Outdoor operation and inspection executed by own e	C	LOPB Betrieb und Instandhaltung	C	6.3	Inspektion & Wartung
C	79	Outdoor cleaning	C	LOPB 01 Betreiben	C	6.4	Energiemanagement
C	7	Cleaning Costs	C	LOPB 03 Inspektion, LOPB 04 Wartung	C	6.4	Versorgung
C	71	Daily/Periodic	C	LOPB 06 Versorgen	C	6.4	Entsorgung
C	72	Main cleaning	C	LOPB 07 Energiemanagement	C	6.6	Reinigung & Pflege der Außenanlagen (Sor
C	73	Special cleaning	C	LOPB 11 Entsorgung	C	6.5	Reinigung & Pflege
C	75	Façade cleaning	C	LOPB 09 Reinigung und Pflege	C	7.5	Unterhaltsreinigung
C	74	Window cleaning	C	LOPD 04 Help Desk	C	6.5	Sonderreinigung
C	32	Operation and inspection executed by external companies			C	6.5	Glas- und Fassadenreinigung
C	38	Outdoor operation and inspection executed by external companies			C	6.6	Schädlingsbekämpfung
C	45	Emergency Repair Work for Exterior					
C	46	Emergency Interior Repair			D	6.2	Ergänzung von Austattungen und Einrichtur
					D	6.6	Pflanzenpflege (außen & innen)
D	89	Furniture and Inventories	D	LOPD 14 Parkplätze	D	6.2	Arbeitssicherheit im FM
D	8	Service Costs	D	LOPB 10 Safety & Security	D	6.2	Betriebsärztlicher Dienst
D	81	Security and Safety	D	LOPD 08 Schlüsselservice	D	6.6	Schutz- & Sicherheitsdienste 6
D	82	Reception / switchboard	D	LOPD 06 Empfang	D	6.6	Revierwach- /Streifen- und Postendienste
D	86	Catering	D	LOPD 12 Catering	D	6.7	Schließverwaltung
D	84	IT-Service	D	LOPD 07 Konferenzraum	D	6.6	Objektschutz / Werkschutz
D	87	Accessories / Copying	D	LOPD 15 Wäscheservice	D	6.9	Verpflegung /Catering
D	83	Mail	D	LOPD 09 Telefonie	D	6.6	Wäschereidienste
D	85	Moving	D	LOPD 11 Druckerei/Kopieren	D	6.9	Sonstiger Support, z. B. EDV-Support
D	88	Administrative Support	D	LOPD 10 Post	D	6.1	Pflege der Dokumentationen
D	19	Remaining Costs	D	LOPD 03 Umzüge	D	6.8	Postdienste, Warenannahme und -ausgabe
			D	LOPD 13 Transport	D	6.8	Bibliotheksdienste
E	29	Various			D	6.2	Umzugsdienstleistungen
E	39	Various			D	6.9	Beförderungs- und Transportdienste
E	69	Various			D	6.9	Beförderungs- und Transportdienste
					D	6.8	Büroservices

Annex D Quantitative rating of methods (refer to section 2)

Criteria No., Class of Methods	Type of Buildings		Level of Objects		Level in Organisation		Availability, Status of Development		Usability		Data required		Total rating
	A= All	**2**	O= single Object	0	O= Operational	0	I= Theor. idea	0	**E= Easy**	**2**	**A= Usually available**	**2**	
	R= Residential	0	G= Group of Objects	1	T= Tactical	1	R= Research	0	F= Fairly Easy	1	S= Some effort needed	1	
	C= Commerc.	1	**P= Portfolio**	**2**	**S= Strategic**	**2**	S= Some Appl.	1	C= Complicate	0	L= Large effort needed	0	
	I= Industrial	1	E=Economy	1			**W=Well known**	**2**	K= Expert knowledge needed	0			
	G= Governmental	1					**U= Universal**	**2**					
1) Energy analysis / energy audit	**A**	**2**	O	0	O	0	**U**	**2**	K	0	L	0	4
2) Virtual energy audit	C, I, G	1	G	1	O, T	1	S, **W**	2	K	0	**A**	**2**	7
3) Simulation of thermal building loads	**A**	**2**	O	0	O	0	**U**	**2**	K	0	L	0	4
4) Incremental cost benefit analysis	R, A?	0	G	1	T	1	R, S	1	F	1	L	0	4
5) Top-Down building stock modelling;	A	2	E	1	**S**	**2**	S	1	K	0	S	1	7
6) Bottom-up building stock modelling	R, A?	1	E, G?	1	**S**	**2**	S	1	K	0	L	0	5
7) Archetypes modelling	R, A?	1	O, P?	1	O, T	1	R, S?	1	F	1	S	1	6
8) Definition of reference buildings/ECMs	R, A?	1	G	1	O, T	1	R, S?	1	F	1	L	0	5
9) Reference project and marginal costs	R, A?	1	G	1	T, S?	1	R, S?	1	F	1	A	2	7
10) Multi-objective optimisation	**A**	**2**	O	0	O	0	R, S?	1	K	0	L	0	3
11) Process based optimisation	R	0	O	0	**S**	**2**	R, S?	1	F	1	S	1	5
12) Specific decision making tools	(A?)	1	(O)	0	(T)	1	(R, S?)	1	(F)	1	(S)	1	5
13) Element based planning	**A**	**2**	O, **P**	2	O, T, **S**	2	**W**	2	F	1	L	0	9
14) Energy performance based	**A**	**2**	O, G, **P**	2	**S**	**2**	R	0	**E**	**2**	**A**	**2**	10
15) Risk quantification	C, I	1	O, G, **P**	2	**S**	**2**	R, S	1	F	1	L	0	7
16) Indicators, benchmarking	**A**	**2**	**all**	**2**	**S**	**2**	R, S	1	**E**	**2**	L	0	9

Table D1 *Details of quantitative rating of methods and instruments for strategic planning needs*

Note: The maximum possible rating is 12 points.

Annex E Illustration of cases

Refer to section 8

Table E1 *Figures of the assed and monitored portfolio*

Figures		Source	Assessed portfolio	Monitored portfolio (matched)	Monitored without hospitals
Number of buildings		1)	938	340	275
Number of buildings or groups of		1)	- -	73	68
Value of portfolio (reconstruction)	1'000 CHF	1)	9'458'000	5'321'684	3'030'008
Volume	m3	1)	10'362'000	5'870'852	3'927'187
Specific value per volume	CHF/m3	1)	913	906	772
Area (average height 4m) GFA	m2	2)	2'590'500	1'467'713	981'797
Energy Reference Area EBF	m2	1)	- -	1'402'952	943'366
Specific value per area GFA	CHF/m2	1)	3'651	3'626	3'086
Energy consumption thermic	kWh/a	1)	- -	158'457'635	78'139'640
Energy consumption electric	kWh/a	1)	- -	96'138'263	40'071'417
Total energy consumption	kWh/a	1)	- -	254'595'898	118'211'057
Share user related energy (20%)	kWh/a	2)	- -	50'919'180	23'642'211
Initial EPI	kWh/m2.a	1)	- -	181	125
Energy costs	CHF/a	1)	- -	26'759'161	12'241'852
Energy costs per area EBF	CHF/m2	1)	- -	19.1	13.0
Price of Energy	CHF/kWh	1)	- -	0.105	0.104
Indirect measurable benefits per kWh (1 times price of energy -> factor 2)	CHF/kWh	2)	- -	0.105	0.104
Total benefits per kWh	CHF/kWh	1), 2)	- -	0.210	0.207
Costs of photovoltaic installation	CHF/kW	2)	- -	1'800	1'800
Costs of photovoltaic energy	CHF/kWh	2)	- -	0.12	0.12
Target EPI (Minergie)	kWh/m2.a	1)	- -	55	55
Target savings	%	1)	- -	70%	56%
Target savings energy	kWh/a	1)	- -	177'433'538	66'325'905
Target benefits	CHF/a	1), 2)	- -	37'298'108	13'737'326

Source: 1) = Database Kanton Zurich; 2) = Assumption

Swiss legislation [Muk] lists a number of generic ECMs which, when implemented in optimal combination, are sufficient to reach the ambitious new legal targets for the EPI (Table F2).

Table E2 *Generic list of ECMs*

Theme	**Measure**
First step	Work out building energy passports with potential measures (Ger.: Gebäudeenergieausweis GEAK)
Insulation	Set minimal insulation standards for different building elements
Building technique	Set minimal standards for efficiency of building technique (HVAC)
Building automation	Define minimal functionality standards for building automation
Lighting	Set maximum standards for energy consumption of lighting
Inefficient heating	Replace all direct electric heating or central electric domestic hot water heating
Individual measuring	Install individual measuring and charging of heating energy in multi-family homes
Renewable energy	Install minimal share of own production of mainly renewable energy
Optimisation of operation	Execute on-going optimisation of operation (Ger.: Betriebsoptimierung)
Master plan	Initiate energy master plans for areas/plots of land and communities
Building code restriction	Apply for a relief from construction legislation so that additional insulation does not count if area or volume of a building are limited on a given area of land
Individual solutions	Use the possibility of target contracts for large consumers allowing for individual solutions (e.g. the anergic network on the Hönggerberg campus of the ETH-Zürich)
Role model	Become a role model (especially for public buildings)

Annex F Text not published in Paper 4

The following text did not make it into the final version of Paper4. It contains additional information on two topics covered in the paper.

F1 Evidence of the CPI curve being convex

The usefulness of the CPI curve depends on it being convex. There are not many practical examples of energy conservation programmes with published figures for the costs and benefits of ECMs with the required split of costs between RMs and additional ECMs available. One such example is, however, a report of the IEA [A1]. An analysis of the 27 ECMs presented shows exactly that behaviour (Figure E.1). Building values or the impact on the EPI, which are needed to construct a full CPI curve, were not available.

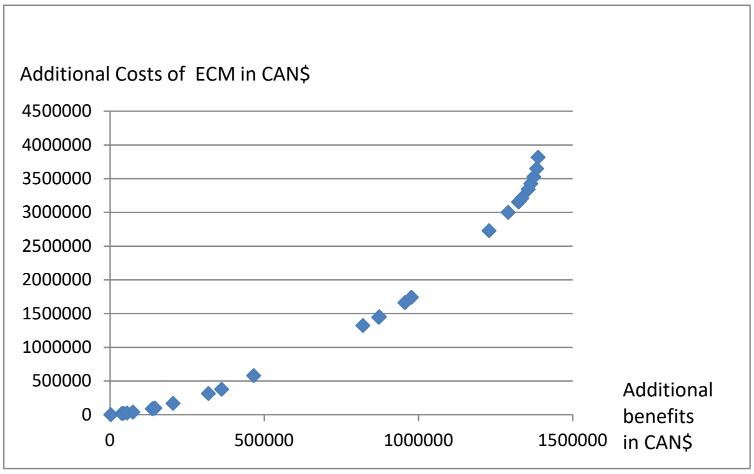


Figure E.1 *Additional costs and benefits in CAN$ from 27 ECMs in an IEA report*

A second example is a report of the world energy council (WEC) [A2] providing an analysis of 252 ECMs in 66 office buildings and factories taking part in a government energy conservation funding program in Thailand . The ECMs have been summarised in 11 categories and show the same behaviour as the first example (Figure E.2).

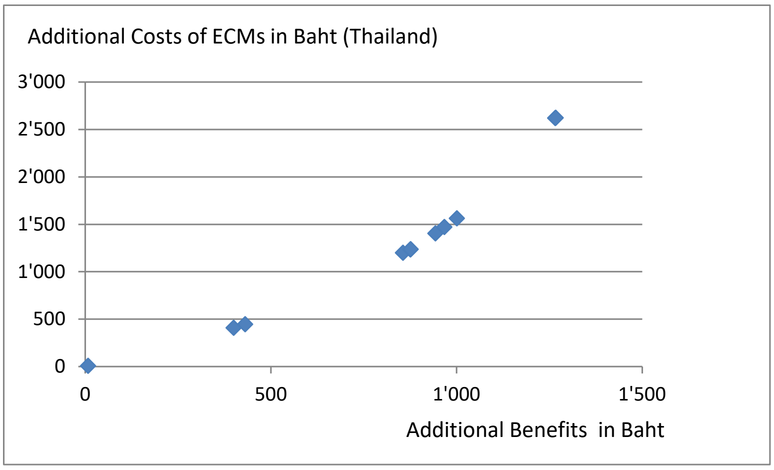


Figure E.2 *Additional costs and benefits in Thai Baht from 252 measures grouped in 11 categories in a WEC report*

Further evidence is given by a recent study of the United States Environmental Protection Agency EPA based on 35'000 buildings with ENERGY STAR scores. The conclusion was that buildings that started with low scores and thus high energy use achieved the greatest savings [A3].

Jones et.al [A4] have analysed three large-scale housing retrofit programs in Wales, UK, which delves into different depths of energy conservation. Their findings indicate that the costs of measures rise in relation to the predicted savings from around 6'000£ for 10-30% of CO_2 reduction (elemental 'shallow' retrofit) up to 70'000£ for 80% of CO_2 reductions (whole house 'deep' retrofit).

Evidence from research publications

Where scientific research is concerned, Jakob et. al. [A5] produced in 2002 marginal cost curves for a limited number of common, mainly construction related ECMs as part of a research project. These curves have the same pattern as the law of increasing relative costs. The x-axis shows the EPI in $MJ/m^2.a$ but the y-axis shows the costs per saved kWh for each measure. This means that both cost and benefits have been included in these curves incorporating all the associated uncertainties (e.g. future energy prices). In the meantime, these curves are 10 years old and the quantitative accuracy is dwindling because costs and benefits of ECMs evolve over time.

In his dissertation, Kost [A6] calculated marginal cost curves (in CHF per m^2 of building energy reference area) for the common ECMs researched in [A5], but from different starting points which were a result of assumed reference refurbishments for different residential building archetypes. The results are similarly shaped curves from different starting points. On average, he has reduced heating energy consumption by 150-200 $MJ/m^2.a$ at costs of 200-250 CHF/m^2 (<10% of building value). In practice, however, there is a larger variety of ECMs available such as improving the efficiency of building technique, lighting or appliances.

Conclusions

These six examples provide evidence that CPI curve is indeed convex. This is further corroborated by the two cases which have been presented in Paper 4. However, as has been stated before, none of these examples provide sufficient data to prove that this convex shape follows a general law.

F2 Results of presented cases in Paper 4 and conclusion for estimation

Observations case 1 in Paper 4 (180 single ECMs in five commercial airport buildings)

Using the presented CPI curve, the costs and savings in four of the five airport buildings could have been predicted fairly accurately just in one building (building 1), savings are higher (or costs lower) than the curve suggests. A possible reason for this could be found in the age of the building. It was constructed in the seventies and was closed before the first renewing cycle at the time of the energy analysis, which partly explains its large share of costs for RMs compared to the cost of additional ECMs. The general statement is valid for savings around 20%. Airport buildings are heavily used, but, the energy performance indicators do not differentiate between building related and usage related energy consumption. So, the shape of the CPI curve, if only building related energy is considered, could differ. However, this case suggests that differing variables apply depending on initial performance, amount of savings and type of building rather than just one curve including all buildings in a portfolio.

Conclusion for estimation

The available data suggests that the CPI curve of the airport example in Paper 4 could be used to estimate required costs to improve the performance by about 20% in this wide category of buildings. This is derived from the fact that, apart from building 1, estimates of costs and benefits are less than +/- 15% apart from measured values. Estimation of higher improvements may also be possible by extrapolating this curve, but this could not have been validated.

Observations case 2 in Paper 4 (300 refurbished domestic buildings)

The report mentioned in the paper gives the marginal costs in €/m^2 for residential buildings in Germany. Consequently, the %-value in the CPI curve depends on the average reinstatement value assumed (in this case a V_{GFA} of 1’500 €/m^2 is used). Due to the large number of buildings with similar characteristics that have been analysed in the report, this CPI curve may be used to produce an estimation of additional costs for ECMs, in order to achieve a certain level of energy performance in this building category. According to the report, a roughly 50% reduction in energy consumption can be achieved with additional costs of 9% of the building values.

Conclusion for estimation

The available data suggests that the presented CPI curve for German residential buildings could be used to estimate required costs to achieve a certain level of performance in this category of buildings. For example, following the CPI curve, the owner of an average single family home of 200 m^2 and worth 300’000 € with an energy performance of 90 $kWh/m^2.a$ would need to invest around 8% of its value or 24’000 € in additional ECMs to half his energy bill and improve the energy efficiency of the building accordingly. The simple pay-back time achieved would be around 15 years.

References in Annex F:

[A1] International Energy Agency (IEA), Energy Conservation in Buildings and Community Systems (ECBCS) Programme, Annex 46 - Energy Process Assessment Protocol, 2009, http://www.annex46.de/bericht.html (accessed August 2012)

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Annex G Sustainability rating systems (List of approx. 100 systems)

The following list of sustainability and related rating systems and standards has been collected and compiled over several years in the course of this work. It is a working draft only, but no other such list is known.

Table C1 *List of sustainability rating systems and related systems and standards – part 1*

Abbreviation, Title	Land, Organisation, Link	Comment
Sustainability Rating Systems and Related Systems, Calculation Programs and Terms		
AECB	GB, Association for Environment Conscious Building (AECB)	
ABS Immobilien Rating	CH, Alternative Bank	
ASTM standard: Building functionability and serviceability	USA, ASTM, www.astm.org, ISBN: 0-8031-2734-0	Building functionability and serviceability
ATHENA	CAN, Sustainable Material Institute	
BauLoop - Nachhaltigkeitsanalyse	D, Inst, f. Massivbau, TU Darmstadt, Diss. 2001 ISBN	Demontagegerechte Baukonstruktionen
BCA Green Mark	Building and Construction Agency of Singapore	Energy and water use, indoor air quality and other types of environmental impacts
BEAT 2002	DK Danish Building Research Institute in Denmark www.sbi.dk/en/publications/programs/beat-2002	
BEES 3.0	www.bfrl.nist.gov/oae/software/bees.html	
BEQUEST - Building envornmental quality evaluation for sustainability	EU + Uni Salford (GB), www.scpm.salford.ac.uk/bqextra	Städtebau, city planning
Beta Faktor	CH, refer to ESI	Objektspezifischer Risikofaktor im Kapitalisierungssatz
BNB Bewertungssystem Nachhaltiges Bauen	GER, www.nachhaltigesbauen.de	Certification
BOMA Best for retrofitted buidlings	CAN, BOMA	
BREEAM 98 for offices	UK, Building Research est. Ltd www.breeam.org, www.bre.co.uk	Umwelt Leistungs Index (EPI Env. Perform. Index), 8 Kriterien, Rating: Pass, Good, Very Good, Excellent
British land sustainability brief	UK, British land company PLC, www.britishland.com/sustainability.htm	Projektentwicklung Neubau, fünf Kriteriengruppen, 33 Untergruppen, Referenz auf BREEAM und CSH
British land sustainability brief for refurbishments	UK, British land company PLC, www.britishland.com/sustainability.htm	Projektentwicklung Sanierung, fünf Kriteriengruppen
Building Quality Assessment	NZ, VEW New Zealand	Nutzersicht, Unterlagen?
C-2000 for advance commercial build.	CAN	Demonstrationsprojekt
CAFM-Systeme, z.B. Planon	Div.	Mehrjahresplanung
Cal-Arch	USA	Benchmarking existing buildings
CASBEE (Building Environmental Efficiency)	Japan sustainable buidling consortium www.ibec.or.jp/CASBEE/ english/index.htm	Comprehensive building assessment system for buidling environmental efficiency, breiter Anwendungsbereich
CASBE	AUS	
CEEQUAL	www.ceequal.com	
CEPHEUS Cost Efficient Passive Houses as European Standards	EU	Project
CML2001	NL	
Codes for sustainable homes CSH, (Government)	UK, Department for Communities and logal Governement, Standard in England	Zertifizierung, 9 Kriterien, 1 to 6 star rating system, mandatory, Wohngebäude
CRISP - Network on construction and city related sustainability indicators	16 EU + Internat., Projekt, CSTB (F), www.crisp.cspb.fr, www.cibworld.nl	
CSCI Corporat Sustainability Commitment Index		
DGNB	GER, D. Gesell. f. nachhaltiges Bauen, www.dgnb.de	New generation of rating systems
DJSI Dow Jones Sustainability Index		
Dubai Certificate for Real Estate Sustainability	UAE	
ECO Building Optimierung (TQ Gebäudebewertung)	AU, Öst. Öko Inst. (refer to BREEM), www.iswb.at	Detaillierte Gebäudebewertung
ECO-Building	AU, www.iswb.at	Qualitätsmanagement
EcoEffect	Sweden (refer to GBC) The Royal Institute of Technology (KTH)	Alle Gebäude, all buildings
EcoHomes - BREEAM Version for dwellings	www.breeam.org/ecohomes	Wohngebäude, residential

Table G1 *List of sustainability rating systems and related systems and standards – part 2*

Abbreviation, Title	**Land, Organisation, Link**	**Comment**
EcoHomes xB - BREEAM Version for dwellings - existing buildings	www.breeam.org/ecohomes	Bestehende Wohngebäude, residential
Eco-indicator 99	CH, ETH Zürich	
Eco-Indikator	NL, www.pre.nl	
ecoinvent DB		Environmental factors
Eco-Profile (Okoprofile)	NO, refer to GBC www.ecoprofile.com	
EcoProP	VTT	
ECOQUANTUM or Eco-Quantum	NL, www.ecoquantum.nl or www.ivam.uva.nl/uk/index.htm	Planung und Bewertung, Wohnbau
Ecotech	A, www.ecotech.co.at	Berechnung: Bauphysikalisch, Energietechnsich, Ökologisch, Ökonomisch
ECOTECT	www.squ1.com	
ecotracker	CAN, Bentall LP (services, 16 Mia.)	energy, water and wastewater and monitoring GHG emissions
EDIP 2003		
Effizienzhauslabel	GER	
Energy Smart	Singapore	Energy consumption
Energy Star	USA	Energy consumption
ENVEST	UK, www.bre.co.uk, refer to BREEAM http://envest2.bre.co.uk	Planung und Bewertung
Environmental Impact Estimator 3.0	CAN, Athena www.athenasmi.ca	
Environmental Index	NL, siehe GreenCalc, Dutch Institute for Building Biology and Ecology, www.nibe.nl	
EPS 2000		
EQUER	FR, www-cenerg.ensmp.fr	
ESCALE	FR, refer to GBC	Alle Gebäude, all buildings
ESI Ecomomic sustainability indicator	CH, www.ccrs.uzh.ch	Ergänzung der DCF - und hedonischen Methoden - langfristige Optik
e-top Rating	CH, Energie 2000	Radardiagramme inkl. Soziales
GaBi - built it	GER, ISO 14040, www.gabi-software.com	Planung und Bewertung, Baustoffe
GaBi3	GER, Ökobilanzen ISO 14040, IKP Uni Stuttgart	
GBC	Refer to LEED	
GBTool 1.3	Refer to GBC, www.iisbe.org http://greenbuilding.ca/gbc98cnf	
Gebäude-Check	GER, CREIS, www.creis.net, agiplan	Betriebskosten, operating costs
Gebäudepass	GER, Gebäudepass e.V. in Zusammenarbeit mit der Bauhausuniversität	Bestandesaufnahme v.a. Energie, Wohnhäuser
Gebäudepass im Leitfaden Nachhaltiges Bauen	GER, Bundesamt (BMVBW)	
GEMIS - globales Emissionsmodel integrierter Systeme	GER, www.oeko.de/service/gemis	
Gesundes Büro	GER, www.hvbimmobilien.de	Projektleitfaden (nicht öffentlich)
Green building certification system of Taiwan EEWH		
Green Building Challenge (GBC)	Internationale Projektgruppe (OECD), neu: www.iisbe.org, www.ziegel.at/gbc-ziegelhandbuch/Default.htm	Anwendung z.B. GBC Handbuch Ziegelindustrie
Green Building Programm	USA	Wohnbau
GREENCALC	www.greencalc.com	
Green Globes	USA, Green Building Initiative GBI	web-based rating tool, ANSI procedures
Green home scheme assessment tool	NZ, BRANZ (Building Research Association of NZ)	New homes, design stage
Green Star	AUS und NZ (BREEAM), GBCA, www.gbca.org.au	
Green Star SA	GBCSA	
GreenGlobe (BREEAM CAN)	CAN	
greenproperty		
GRI Global Reporting Initiative	NL(?) www.globalreporting.org	
Hausakte	GER, Bundesamt (BMVBW)	EFH, Dokumentation, keine Bewertung
HK-BEAM	Hong Kong	56 criteria
HQE Process	FR, www.assohqe.org	Haute Qualité Environnemental

Table G1 *List of sustainability rating systems and related systems and standards – part 3*

Abbreviation, Title	Land, Organisation, Link	Comment
iiSBE - internationale initiative for a sustainable built environment	Int., refer to GBC	
Immo Check	CH, Verein Immo check, www.immo-check.ch; www.virtuellbau.ch	Grobanalyse Zustand, Wert, Potenital, Energie - Massnahmen (1'500 Fr.)
ImmoCheck	GER, Fraunhofer Inst., www.iao.fraunhofer.de	Planung Büroimmobilien
Immo-Check	GER, GTÜ	v.a. Wohnbereich, residential
ImmoPass	GER, Hypo-Bank	v.a. Wohnbereich, residential
IMPACT 2002+		LCIA methodology
IPD / IPF Sustainability property index (ISPI) UK	UK, www.ipd.com	
IPD Ecoledger	UK, www.ipd.com	Software, performance dashboard
IPD Environment Code	UK, www.ipd.com	
IPD Green Rating©	UK, www.ipd.com und Bureau Veritas, AEW Europe, AXA REIM, ING REIM	Benchmarks compatibel mit IPD env. Code, wide range of asset portfolios
ISE Corporate sustainability index	Latin America	
KBOB Empfehlungen nachhaltiges Bauen	CH, www.kbob.ch	Guidance
Key Report	GER, ATIS REAL, www.atisreal.de	Bericht zu Gewerbeimmobilien
LCAid	AU, www.projectweb.gov.com.au/ dataweb/lcaid/	
LEED Green Building Rating System	US, (refer to GBC, BREEAM) www.usgbc.org/LEED/publications.asp	Alle Gebäude
LEGEP	GER, www.legep.de	Calculation tool
LEGOE	GER, refer to LEGEP	Research project (closed), design tool
LEnSE	www.lensebuildings.com/	
LGA Gebäudepass	GER, Bayern	14 Module
LISA	AU, www.lisa.au.com	
Nachhaltigkeitsorientierte Investments	GER, Uni Karlsruhe	5 Dimensionen
Nachhaltigkeitsrating der Stadt Zürich	CH, gemäss SIA 112/1, Amstein&Walthert, Bezug auf STRATUS	Stand Instrument?
NABERS	AUS, www.nabers.com.au	Energie- und Umweltetikette für bestehende Gebäude (effektive Werte)
NAHBGreen	USA, National Association of Home Builders, www.nahbgreen.org	Wohngebäude, residential, onlinetool
Okoprofile Norwegian ecoprofile tool	NO (see under eco-profile)	Planung Renovation
OGIP	CH, www. ogip.ch www.crb.ch	Planung und Bewertung
Ökoindex 3 OI3 = OI pei + OI gwp + OI ap		
ÖÖB - Bewertungssystem für ökonomisches und ökologisches Bauen und gesundes Wohnen	GER, BMVBW, Bundesamt für Bauwesen und Raumordnung BBR, ISBN	Guidance for reporting
ProBas - Prozessorientierte Basisdaten für Umweltmanagement-Instrumente	GER, www.probas. umweltbundesamt.de/php/index.php	
PromisE	FL	
Protocollo Itaca	IT	
Rating e-top Nachhaltiges Bauen	CH, GER, www.energiekonsens.de	Planungsinstrument Erneuerung, 20-30 Kriterien
ReCiPe project	NL, http://www.pre.nl/download/ RecipePhase1Final.pd	Comb. Eco-indicator 99 u. CML2001
REN The Real Estate Norm	NL, Stichting REN Nederland	Qualitätsbewertung neuer oder bestehender Immobilien
RoSS Return on Sustainability System	GER; http://ross.htw-berlin.de/	Im Zusammenhang mit FM
SB Alliance - sustainable building	www.sballiance.org, refer to DGNB	Zusammenarbeit fördern (DGNB)
SBTool	Country specific adaptations	125 Kriterien - v.a. für Forschung
ScooBe - Sustainable constructin of built environment	NL, Int., CIB, www.cibworld.nl	
SGNI	CH, refer to DGNB, Swiss adaptation	
SimaPro	NL, www.pre.nl	
Sirados-LEGOE und WinMobil	GER	Ökobilanzierung von Siedlungen
SNARC	CH - SIA 0200	Standard
SNBCH Schweizer Standard für Nachhaltiges Bauen	CH Netzwerk Nachhaltiges Bauen, BfE (in Arbeit)	

Table G1 *List of sustainability rating systems and related systems and standards – part 4*

Abbreviation, Title	Land, Organisation, Link	Comment
SUREURO SQI Sustainable Quality Identification	sureuro.com	
Sustainable communities inititative	USA	Öffentliche Bauprojekte
TEAM for Building	GB, www.ecobalance.com/index_uk.html	
TGBRS TERI's	India, The Energy and Resource Institute	Green Building Rating System
Total Quality Building	AU	
Umweltbelastungspunkte UBP	CH	
Umwelt-Index für Bauwerke	NL	
UNAS'	CH, Implenia.ch ist daran beteiligt	Universelles nachhaltiges architektonisches Strukturmodell - Flexibilität für die Zukunft
Vitruvius	CH, Vitruv AG	Immobilienbewertung
WGBC world green building council	www.worldgbc.org/	CO2 Footprint, Zusammenarbeit fördern
crédit suisse	CH, eigene NH-Bewertung	3. Generation mit QS
PGMM	CH, Planungsfirma, eigene strategische NH-Bewertung	
	for more refer to wiki: green building	
Maintenance and Refubishment Tools		
BKI Gebäudemanager	GER: bki.de, DIN 276 (Bauteile)	Raumbuch, Kostenermittlung pro Bauteil
CIBSE Guide to ownership, operation and maintenance of building services		
DDR		
DUEGA	CH, CRB, EPIQR? Immopac, RENOVA PLUS = IP BAU? *Vom CRB nicht mehr unterstützt*	Diagnosemethode für die Unterhalts- und Erneuerungsplanung verschiedener Gebäudearten
ECBCS Retrofit Advisor		
EPIQR	CH, GER, FR: EPFL, Fraunhofer inst., refer to IP Bau	
Faktorenmethode	ISO 15686-2000	Standard
Grobdiagnose	CH, IP Bau	Schriftliche Anleitung
idi-al	GER, Bundesarbeitskreis Altbauerneuerung e.V BAKA, idi-al.ch	IH-Planung eines Gebäudes
Immopac renovaPlus	CH; www.immopac.ch, refer to IP Bau	
INVESTIMMO	FR, EPIQR add-on for prognosis, ctsb	seit Anfang 2000 nichts mehr gehört
IP Bau	CH, Impulsprogramm Bau 1999, public available	Detailanalyse baul. Zustand
Krug		
LEED-EB O&M Existing Building Operation and Maintenance	Supplemetary addition to LEED	
MEDIC	EPIQR add-on for changes over time	seit Anfang 2000 nichts mehr gehört
MER	CH, Welschland	
Methode Schröder	CH, refer to Stratus	Keine nützlichen Treffer in Google
Meyer-Meierling	CH, BKKS	1 Gebäude Sanierung anstehend
RENO-EVALUE	DK, ACES Project, Danish Building Research Institute	
Stratus	CH, Basler&Hofmann, www.stratus.ch	15 Elemente eines Baus, strategische IH-Planung Portfolio mit Budgetierung
Sustainable refurbishment Europe	www.sureuro.com	Grosses Projekt, Resultate nicht
TOBUS	EPIQR add-on for offices	seit Anfang 2000 nichts mehr gehört
XENIOS		
Energy Assessment or Management Tools		
ANNEX 31 - Energy related environmental impact of buidlings	Int., IEA, www.iea.org	Planungs- und Bewertungshilfmittel
ASHRAE bEQ Building Energy Quotient	USA	New and existing office buildings
Bau-Schlau	CH, online EnergieSchweiz	Optimierung Heizenergie
BLAST		Energy and heat balance simulation
BNB	GER	
bSol	CH, Hochschule Wallis	
Build-It	DFE-Software (Desing for Environment)	Wärmeschutznachweis
CALENER		
CBECS Commercial Building Energy Consumption Survey	USA	
CO2 Spiegel	CH, Swisstec	v.a. Haustechnik, teilweise Gebäudehülle

Table G1 *List of sustainability rating systems and related systems and standards – part 5*

Abbreviation, Title	Land, Organisation, Link	Comment
Condition assessment survey CAS	Varnier (2001)	
DOE AR energy asset rating	USA	Commercial buildings
DOE-2	USA	Energy and heat balance simulation
EARM Energy Assessment and Reporting Methodology	UK	
EARM-OAM Energy Assessment and Reporting Methodology - Office Assessment Method	UK	
Ecospeed	online	für Private
ECOTECT		Energy performance calculation
ELO energy management scheme for large buildings	DK	Large buildings >1500 m2
EM energy certification scheme for small buildings	DK	Small buildings
EnAW Check-up tool	CH, Für Grossverbraucher und KMU	Berechnet Einsparpotentiale, kostenpflichtig
Energhostat	CH, online für Kantone (energho)	Vergleich von Portfolios
Energiebedarfsnachweis	GER, gemäss EnEV	New and renovated buildings
Energiekennzahl (Wärme)	CH; SIA180/4 -> 416/1	Standard
Energiepass	GER, IWU	
Energy Advice Procedure, Energy Charter, Passive House Platform	Belgium	
energy express by epiqr	Refer to EPIQR	
Energy Smart Office Label	Singapore	Existing office buildings
Energy Star	USA; EPA,	Wohnhäuser, residential
Energybox	online Stromcheck	Haushalte, teilweise Büro und Schulen
Energyfit	CH; Swisspower und IWB (ENTECH 380/1)	Grobdiagnose und Massnahmen Gebäude
EnergyPlus		Energy and heat balance simulation
Energysystems	online	Nur Wärmeerzeugung
EPA-ED Energy Performance Assessment for Existing Dwellings	EU	
EPA-NR Energy Performance Assessment for Non-Residential Buildings	EU	
EPASS	GER, Hauser	
EPA-U Energy Performance Advice	NL	Existing non-residential buildings
EPA-W Energy Performance Advice	NL	Existing dwellings
EPC Energy Performance Coefficient	NL	New buildings
EPIQR	CH, GER	Wohnhäuser, 50 Kriterien, Sanierungskonzept mit
eQUEST	USA	Energy and heat balance simulation
ESCO (Energy Service Company)	Abkürzung, kein System	Abbreviation
Footprint	WWF	für Private
Gebäude Energieausweis	EU-Direktive "Energy Performance of Buildings" (EPBD)	
GEMIS Gesamt Emmission integrierter Systeme	AT, Umweltbundesamt, www.ubavie.gv.at	Emissionen versch. Energieerzeugunger
Gesamtenergieeffizienz	EU-Direktive "Energy Performance of Buildings" (EPBD)	Definition
Government Standard Assessment Procedures SAP	UK	Energie
HEBEAM		
HELP House energy labeling procedure	EU	Existing single-family houses
IMMOWIN	CH, KTI-Projekt, Doktorat ETH-Z	Kosten, Einsparungen, Finanzierung, Mehrertrag von Sanierungsvarianten
IPD Energy Performance Certificates EPC on all the investment properties in its UK Portfolio Analysis Service (PAS).		
IPMVP International Performance Measurement and Verification Protocol		
KWEN-S	Planer	für Planer
Lesosai	E4tech	für Planer, Energienachweis und Kondensat
Methode kumulierter Energieaufwand KEA	CH, ETH Zürich	
Minergie / -p		
National Homes Energy Rating NHER	UK	Energie
NCM National Calculation Method	EU, EPBD	Energy performance calculation
OAM Office Assessment Method		
Passivhausprojektierungspaket PHPP	GER, www.passivhaus-info.de	
SBEM Simplified Building Energy Model	NL, NEN 2916:1998	Standard
Service life prediction	LCA tools: BEAT 2000 (Denmark), Eco-Quantum (the Netherlands), Envest (Great Britain), GreenCalc (the Netherlands), Økoprofil (Norway)	

Table G1 *List of sustainability rating systems and related systems and standards – part 6*

Abbreviation, Title	Land, Organisation, Link	Comment
Stratus Energiemodul: Gebäudeausweis	CH, B&H	
TIRA	CAN	Community Energy Plan, Gebäudetypen auf Portfolio hochrechnen
TRNSYS	US	Energy and heat balance simulation
Zeroemission	WWF	CO2, für Private
Materials, Building Elements		
BauBioDatenBank	CH, gibb, www.gibbeco.org	
Bauteilkatalog	CH, CRB	
BEES		
Boustead Model		
BPG/BLP Fabric and Services Life Manuals		
Cactus and estatepro		
CSCI	Climate Savers Computing Intiative	IT Industry
Dämmstoffe auf ökologischem Prüfstand	GER, IBO 2000	
ECOBIS - ökologisches Baustoffinformationssystem	GER, BMVBW, BBR	
Ecoinvent	CH, ETH Zürich	Factors e.g. for embedded energy
ecosoft		
GaBi 4	GER, www.gabi-software.com	
GEMIS Globales Emissions-Modell integrierter Systeme	GER, Öko-Institut Darmstadt, Internationales Institut für Nachhaltigkeitsanalysen und -strategien (IINAS)	Public domain life-cycle and material flow analysis model
HAPM Component Life Manual		
IVAM database		
ixbau		
Minergie (P) ECO	CH, refer to Minergie	
MRPI/ERPI - Environmental relevant product information	NL, Baustoffindustrie, Schnittstelle zu Ecoquantum, www.mrpi.nl	Planungsinstrument
Ökomoduldatenbank "Ökobau.dat"	GER, refer to LEGEP and DGNB	Base for certification
Product Sustainability Index PSI	Ford, Automobilindustrie	CO2, Luftqualität, Materialien, Substanzen Innenraum, Sicherheit, Kapazität, Unterhaltskosten
PSA - Costs-in-use tables		
SimaPro	CML2 Baseline 2001	
SIRADOS, Elementkatalog	GER, www.sirados.de	Cost calculation
Swedish Building Research Council - The longevity of building services installations	Sweden	
TWIN	NL,Dutch Institute for Building Biology and Ecology, www.nibe.nl	
Umberto		
WINGIS (GISBAU)		
LCA	http://lca.jrc.ec.europa.eu/lcainfohub/databaseList.vm	

Table G1 *List of sustainability rating systems and related systems and standards – part 7*

Abbreviation, Title	Land, Organisation, Link	Comment
Social Aspects, Culture		
Blauer Engel	GER, Umweltbundesamt	Baustoffe
Euro-Blume	EU, Kommission der EG	Baustoffe
FSC	Forest Stewardshi Council	Holz
GI gutes Innenraumklima	s-cert	Messung (nach Fertigstellung)
IBR	GER, Inst. Für Baubiologie Rosenheim	
Nature-plus (Eco-Label)	Natureplus	Bau- und Wohnprodukte
Produkt Emissionsarm	eco-Umweltinstitut GmbH	Baustoffe, Ergänzung zu natureplus für synthetische Produkte
RUGMARK		Teppiche ohne Kinderarbeit hergestellt
ToxProof	GER, TÜV	
Economic Aspects		
Valuation methods		
DCF, hedonisch, Realwert, Ertragswert Mischformen	CH: SEKI, SVIT, SVKG, SIV	
Ertragsmethode	Mietwert, Kapitalisierungssatz, Ertragswert, DCF, Barwert	DCF: 10 Jahre Ertrag, danach Marktwert
EVS	Residualverfahren??	
Lageklassemethode	Landwert	
Methoden: IVS (SVS)	Vergleichswert (sales comparison), Ertragswert (income capitalised), Barwert, Sachwert (cost approach)	
Misch- und Differenzmethode	Misch- und Differenzmethode	
Realwertmethode	Neuwert, Minderwerte, Zeitwert, relative Landwert, Realwert	
RICS	IVS + nationale Ergänzung	
SIV:		
Statistische methoden	Vergleichswert, Kennwertmethoden, Hedonische Methoden, Renditen	
Financial Indicators		
Rendite		
EK-Rentabilität		

Table G1 *List of sustainability rating systems and related systems and standards – part 8*

Standards and near-standards	
ISO 14001	Umweltmanagementsystem, Öko-Audit-Verordnung 1836/93 der EU
ISO 14020:2000	Environmental labels and declarations -- General principles
ISO 14021:1999	Environmental labels and declarations -- Self-declared environmental claims
ISO 14025:2006	Environmental labels and declarations
ISO 14040	Internationaler Standard für Ökobilanzen («Lebensweg-Bewertungen»)
ISO 26000	Social responsability
ISO/TS 12720:2014 Sustainability in buildings and civil engineering works	Guidelines on the application of the general principles in ISO 15392
ISO 15392:2008 Sustainability in building construction	General principles
ISO 16745-1:2017 Sustainability in buildings and civil engineering works	Carbon metric of an existing building during use stage -- Part 1: Calculation, reporting and communication
ISO 16745-2:2017 Sustainability in buildings and civil engineering works	Carbon metric of an existing building during use stage -- Part 2: Verification
ISO 21929-1:2011 Sustainability in building construction	Sustainability indicators -- Part 1: Framework for the development of indicators and a core set of indicators for buildings
ISO/TS 21929-2:2015 Sustainability in building construction	Sustainability indicators -- Part 2: Framework for the development of indicators for civil engineering works
ISO 21930:2017 Sustainability in buildings and civil engineering works	Core rules for environmental product declarations of construction products and services
ISO 21931-1:2010 Sustainability in building construction	Framework for methods of assessment of the environmental performance of construction works -- Part 1: Buildings
ISO/TR 21932:2013 Sustainability in buildings and civil engineering works	A review of terminology
ISO 15392 [Under development] Sustainability in buildings and civil engineering works	General principles
ISO 20887 [Under development]	Design for Disassembly and Adaptability of Buildings
ISO 21678 [Under development] Sustainability in buildings and civil engineering works	Methodological principles for the development of benchmarks for sustainable buildings
ISO 21929-2 [Under development] Sustainability in building construction	Sustainability indicators -- Part 2: Framework for the development of indicators for civil engineering works
ISO 21931-2 [Under development] Sustainability in buildings and civil engineering works	Framework for methods of assessment of the sustainability performance of construction works -- Part 2: Civil engineering works
ISO 22057 [Under development]	Enabling use of Environmental Product Declarations (EPD) at construction works level
EN/TR 15941:2010 Sustainability of construction works	Environmental product declarations - Methodology for selection and use of generic data
EN/TR 16970:2016 Sustainability of construction works	Guidance for the implementation of EN 15804
EN/TR 17005:2016 Sustainability of construction works	Additional environmental impact categories and indicators - Background information and possibilities - Evaluation of the possibility of adding environmental impact categories and related indicators and calculation methods for the assessment of the environmental performance of buildings
EN 15643-1:2010 Sustainability of construction works	Sustainability assessment of buildings - Part 1: General framework
EN 15643-2:2011 Sustainability of construction works	Assessment of buildings - Part 2: Framework for the assessment of environmental performance
EN 15643-3:2012 Sustainability of construction works	Assessment of buildings - Part 3: Framework for the assessment of social performance
EN 15643-4:2012 Sustainability of construction works	Assessment of buildings - Part 4: Framework for the assessment of economic performance
EN 15643-5:2017 Sustainability of construction works	Sustainability assessment of buildings and civil engineering works - Part 5: Framework on specific principles and requirement for civil engineering works
EN 15804:2012+A1:2013 Sustainability of construction works	Environmental product declarations - Core rules for the product category of construction products
EN 15942:2011 Sustainability of construction works	Environmental product declarations - Communication format business-to-business
EN 15978:2011 Sustainability of construction works	Assessment of environmental performance of buildings - Calculation method
EN 16309:2014+A1:2014 Sustainability of construction wo	Assessment of social performance of buildings - Calculation methodology
EN 16627:2015 Sustainability of construction works	Assessment of economic performance of buildings - Calculation methods
SIA 112/1	Nachhaltiges Bauen Hochbau: Um-/Neubau, Erneuerung
SIA380/1 and 4, SIA 2031	Verbrauchsausweis oder Bedarfsausweis
SIA 469	Erhaltung von Bauwerken
SIA 480	Wirtschaftlichkeitsrechnung für Investitionen im Hochbau
SIA D0123	Bauteile ökolog. -> ECO- BKP
SIA D0164	Kriterien für nachhaltiges Bauen
SIA D0200	SNARC
Green guide to housing specification	UK, Building Research est. Ltd, www.bre.co.uk
ECO-BKP	CH, Merkblätter ökologisches Bauen nach Baukostenplan
KBOB/IPB	CH, Umweltmanagement von Hochbauprojekten
Leitfaden Nachhaltiges Bauen	GER, BMVBW
Ökologischer Bauteilkatalog	AU, Donau-uni Krems
Ökologischer Wohnbau Massnahmen	AU, Energieinstitut Vorarlberg, www.energieinstitut.at
Umweltleitfaden für Architekten	GER

Annex H List of Figures and Tables

Table H1 *List of Figures part 1*

Table H1 *List of Figures part 2*

Table H2 *List of Tables*

Annex I Curriculum vitae

Curriculum vitae

Markus Christen, Dipl. Ing. ETH / BWI

Born 21st of March 1960 in Winterthur/Switzerland

1985	Diploma (Dipl. Ing. ETH/BWI) in Mechanical engineering and economics, Swiss Federal Institute of Technology (ETH), Zürich
1986	Industrial consultant, Brandenberger & Ruosch AG, Zürich
1987 - 1990	Project manager Gruenberg & Partner AG, Zürich - Developing energy conservation and consultancy services - Planning and developing of complex HVAC and energy generating plants (eg. ice rink, cogeneration, heat recovery)
1989	Exam in energy management, Technikum Winterthur (now: zhaw) - Part time energy advisor for the state energy consultancy, Zürich
1991 - 1993	Senior energy consultant, Lincolne Scott, Perth, Australia - Developing the new energy consultancy unit - Analysing cost savings potential and tariff optimisation of large buildings (e.g. high rise building of the Commonwealth Bank, Perth)
1994	Second director of the unit for commercial buildings of the Integrated Energy Management Centre IEMC, Hobart, Australia - Experience with the opening of the electricity market
1995 - 1999	Head of the energy and ecology unit, Flughafen-Immobilien-Gesellschaft FIG (Real estate company of Zürich airport) - Optimisation and reducing of operating and energy costs - Energy controlling of the 5th extension phase of the airport - Negotiating new contract with electricity utilities - Measuring and cost allocation of energy - Evaluating and implementing a facility management system (CAFM)
2000 - 2001	Real estate development, Unique, Zurich airport AG - Project management of large building and software projects (e.g. Planning and construction of the new head quarter of the company)
2001 - 2003	Management course IAP (Institute of applied psychology)
2002 - 2004	Director of the Swiss Maintenance and Facility Management Society MFS - Reorganisation and developing a business plan - Projects (New strategy, CEN-standards in FM, development of federal diploma 'Eidg. Dipl. Leiter in Facility Management', new webpage, consulting of society members)
Since 2005	Investment planning, ETH-Rat Immobilien (real estate unit of the Board of the Swiss Federal Institutes of Technology), Zürich (part-time 80%) - Real estate investment planning, controlling and projects - Implementation of SAP Business Objects for various reportings

	Consultant in Facility Management, iFM, Winterthur (part-time 20%) - Consulting in submitting FM-services, developing shopping center management, evaluation of hospital maintenance management system, etc. - Teaching at the Zürcher Hochschule für angewandte Wissenschaften zhaw (facility management, benchmarking) and Fachhochschule Nordostschweiz (maintenance)
	Convenor (head) of CEN TC 348 WG3 (Taxonomy in Facility Management) - Development of new European standards in facility management
	Presentation at the Expo Real in Munich (2006) Presentation at the Euro-FM Conference in Zurich (2007) Presentations at the maintenance fair in Zurich (2008 and 2009) Presentations at the ISEC conference in Zurich (2011)
Since 2010	Part-time doctoral student first at the Chair of Sustainable Construction and then at the Chair of Infrastructure Management at the ETH Zurich writing a thesis on the strategic planning of sustainable refurbishment in building portfolios

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