Towards a Normalized Reference System in Building Construction Planning for Automated Quantitative Assessment and Optimization of Energy and Cost Efficiency

Gerald Zwettler[1], Paul Track[2,4], Florian Waschaurek[3,4], Richard Woschitz[2,4],
Elmar Hagmann[3,4], and Stefan Hinterholzer[1]

[1] School of Informatics, Communication and Media, Upper Austria University
of Applied Sciences, Softwarepark 11, 4232 Hagenberg, Austria
{gerald.zwettler,stefan.hinterholzer}@fh-hagenberg.at
[2] RWT PLUS ZT GmbH, Karlsplatz 2/6-7, 1010 Wien, Austria
{p.track,r.woschitz}@rwt.at
[3] Dipl. Ing. Wilhelm Sedlak GmbH,
Quellenstraße 163, 1100 Wien, Austria
{waschaurek,hagmann}@sedlak.co.at
[4] ARGE Innovation Bautechnik und Bauprozessoptimierung OG,
Quellenstraße 163, 1100 Wien, Austria

Abstract. The conceivable future shortage in fossil resources and savings in building construction engineering for competitiveness on the market are the ecological and economic stimulus for well-considered and optimized architecture and material choice to maximize the trade-off between cost and energy optimization. *BauOptimizer* construction planning application allows monitoring and optimization of both, energy and cost efficiency from the very first planning iteration to the final design. Simulated building construction costs and the energy cost forecast for the next decades are linked together to establish a quantitative assessment of construction plan efficiency and further allowing to automatically evaluate all possible planning variants by altering the construction types of the walls, the windows and all other modalities. Based on the solution space of planning variants and legal norms, a construction site specific scale for assessing the quality of a single construction plan compared to the theoretically most efficient design to achieve can be performed.

Keywords: modeling and simulation, energy and cost efficiency, multi-criteria optimization, computer-based design.

1 Introduction

The architectural and construction planning of a building has to balance between different aspects and diverse satisfaction of needs of the involved stakeholders. The architect wants to express his inspiration and all of his ideas, like jutties or shifted walls, as artistic spirit of the construction plan design without having

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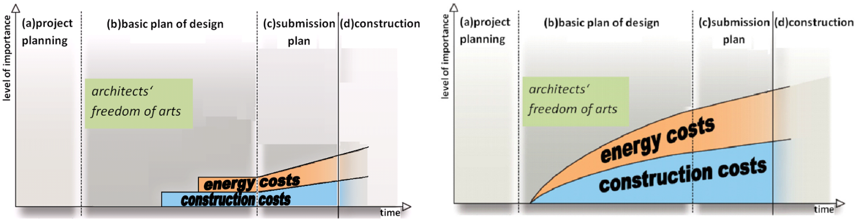
to think about construction costs, expected energy demand and plain, efficient building shapes all the time. In contrast, the building owner wants a maximized net floor area to be achieved by optimally exploiting the available space of the building construction lot. An indispensable key aspect of today's architecture to consider is energy efficiency[1,2]. Although higher investments in insulation material typically go along with significantly increased construction costs of the building hull, amortization and repayment is typically expected to be achieved within the next couple of years, as the expected savings in heating demand related energy costs sum up very fast over the years. Furthermore, norms and restrictions of the legislative body must be considered from the very first planning phase to get the final design approved or be awarded a grant for ecologic architecture. For achieving a balanced building construction design, all of these aspects must be considered from a very early planning stage. The traditional process of architectural planning, illustrated in Fig. 1(a), emphasizes the artistic freedom at the early stages. The importance and relevance of the key aspects, construction and energy costs, and related legislative restrictions grows in the later planning phases. Not considering the entire model from the very beginning increases the risk of cost and time consuming re-design to finally meet all requirements and restrictions.



(a) Traditional Planning Process (b) Improved Planning Process

Fig. 1. Illustration of the iterative building construction planning process. The relevance of energy and construction cost considerations typically doesn't grow before the later phases, thus increasing the risk of requirements for re-design and additional planning phases if certain requirements cannot be fulfilled (a). Utilizing automated simulation and modeling, the energy and cost aspects can be considered from the very first planning steps (b).

Utilizing BauOptimizer software, the risk for requiring a re-design can be significantly reduced, as the entire model with all aspects can be evaluated from the very first planning actions until the final construction, see Fig. 1(b). The multi-criterion optimization of the design requires a balanced linkage of the different, partially oppositional aspects of building construction to serve as common basis of quantitative comparison. Linking together construction costs and expected energy costs over a certain period of time allows the establishment of an efficiency term, which facilitates balancing the two key goals of building construction planning. Increased investments into energy saving strategies can redeem within a period of amortization. Consequently investment costs can be offset against a reduction in energy demand. It has to be explicitly stated that the cost factors of the insulation layers are of high importance today. The importance and correct material choice will gain in future, as the insulation materials, like EPS, are produced by fossil resources, thus also depending on the energy cost index. It is not reasonable only to maximize the energy efficiency and not consider the costs[3].

The developed software application BauOptimizer[4] supports architects and building owners in balancing the aspects energy demand, construction costs, necessitating only a low number of planning iterations and keeping normative limits during the entire planning cycle. Based on a normalized reference system, single planning variants can be quantitatively compared, thus allowing automated optimization of cost and energy efficiency.

2 Modeling the Building Construction Environment

Accurate modeling of the building construction environment is a pre-requisite for reliable simulation and optimization results. The relevant model parameters will be enlisted in the following sections.

2.1 Building Site

The building site dimensions are defined by the maximum constructible length, width and height and a tolerance extent for all of these directions with respect to local legally binding land-use plan and keeping the building lines, e.g. in case of jutties.

The climate properties of the building site are of high importance for accurately calculating the specific energy demand based on the solar gains and the annual temperature distribution in the target region. As climate properties, the average monthly temperatures with respect to the particular sea level and the orientation based solar gains are required as model parameters. For calculation of the required energy demand, the delta to *20 Kelvin* in the daily average must be compensated by heating energy to ensure constant minimum room temperature.

2.2 Building Geometrics

The building geometrics are modeled by specifying a single floor plan for each level at a specific floor height. Each floor plan is specified as a set of arbitrarily oriented polylines, all defined on a *0.5m* grid, see Fig. 2. The walls specified via polyline sections are orthonormally positioned towards the fundament. The intersections of a floor compared to the lower and upper level define jutties, offsets and intermediate ceiling in case of congruent shapes respectively.

That way a sufficient approximation of the true building geometrics can be achieved with minimal requirements for user interaction. Based on the building geometrics model, heating energy demand can be calculated more precisely compared to the rougher approximations of the building shape used for energy certificates in Austria and Germany.

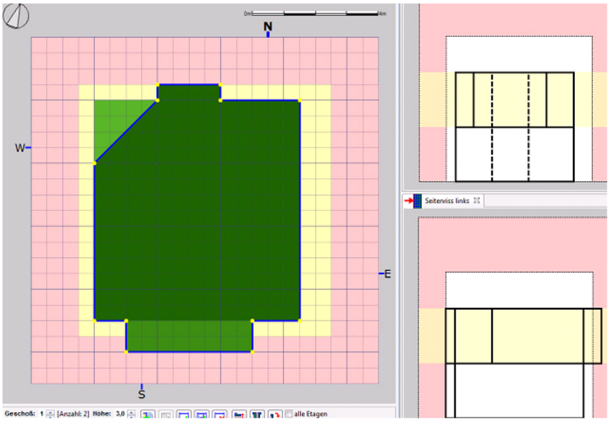


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Fig. 2. The building geometry is specified by modeling the ground plan of each floor. The different types of intersection regions with the neighboring levels are color-coded. The main projective views (front, back, side) allow the planner to inspect the designed fronts of the building.

2.3 Building Construction Material

In each building model, construction material must be assigned to main construction parts, the *walls*, the *floor* and the *roof* sections. These main construction parts are subdivided according to their modality, i.e. the building physics relevant outside condition, like air, soil or heated adjoining building, all with different thermal resistivity to account for in the model, see Tab. 1. The four categories *air*, *adjoined building heated/unheated* and *soil* are applicative for the three main construction parts.

For windows there are additional modality types according to the shading strategy, see Tab. 2. The shading factor is of high relevance at it can significantly reduce the solar gains to achieve. The window ratio and modality can be specified as optional property of each wall.

Overall there are at most 18 different modality categories to specify for a single planning project. For each modality category a certain construction assembling, like e.g. a brick stone wall of 25cm with 12cm EPS-F insulation, has to be chosen as parameter of the building model. Each construction consists of a primary structure layer (*steel, brick stones, concrete,*) and an insulation layer (*EPS, mineral wool,*) that can be varied with respect to their thickness. Furthermore for a certain construction assembling, additional layers that are kept constant may be present, see exemplarily Tab. 3 for a fundament.

For the roof sections, different shapes like mono-pitch or platform roof are to be chosen as modality sub-category. The architect or planner can choose the construction assembling for each modality based on a catalogue with building physics properties and cost parameters that are kept up-to-date. Overall the catalogue of presently available construction types has more than 200 elements and is extended according to the current developments on the building construction sector.

Table 1. Subset of modalities to be applied to the main construction parts and their individual resistivity terms R_{si} and R_{se} from the building inside to the construction part and from the construction part to the outside environment respectively. The modality-dependent correction factor F is a weight for handling modalities with lower thermal relevance.

part	modality	R_{si}	R_{se}	F
wall	towards air	0.13	0.04	1.00
wall	adjoined heated	0.00	0.00	0.00
wall	adjoined unheated	0.13	0.13	0.70
ground	adjoined unheated	0.17	0.17	0.60
ground	towards soil	0.17	0.00	0.70
roof	towards air	0.10	0.04	1.00
roof	adjoined unheated	0.10	0.10	0.90
roof	under soil	0.17	0.00	0.70

Table 2. The window modalities are discriminated according to the particular shading strategy

part	modality	$shading\ factor$
window	inside jalousie	0.88
window	outside jalousie	0.24
window	marquee	0.36
window	roller shutter	0.19
window	full shading	0.00
window	without shading	0.99

Table 3. Ground floor construction above soil with a total construction thickness of *0.634m*, a cumulated thermal resistivity of *0.17* ($R_{si} + R_{se}$) and a construction-dependent total resistivity of *2.673* ($R[m^2K/W]$) leading to an U-value of *0.374* W/m^2K. For this construction concept, the variable primary structure is layer 3 and the variable insulation is layer 1. The other components are kept fixed during optimization.

layer	material	$d[m]$	$\lambda[W/mK]$
1	foam glass granules	0.160	0.085
2	PAE insulation film	0.002	0.230
3	steel reinforced concrete plate	0.300	2.500
4	bituminous primer	0.000	—
5	optional ground sealing	0.005	—
6	polysterence concrete	0.060	—
7	subsonic noise insulation	0.020	0.040
8	PAE insulation film	0.002	0.230
9	screed	0.070	—
10	lining	0.015	—

3 Efficiency of a Planning Project

The efficiency metric to define is based on the two input parameters, construction costs of the building's hull in $€/m^2$ and the energy demand in kWh/m^2a.

Calculation of the building's annual heating demand per gross floor area square meter is performed by utilizing the calculation algorithm by Pöhn[5], used for energy certificate calculation in Austria. Pöhns calculation algorithm is conforming the Austrian policies *ÖNORM H 5055*, *ÖNORM B 8110-3*[6] and is implementing the initiating EU act in law *2002/91/EG*[7] similar to German energy certificate[8]. The original calculation procedure is improved to accurately account for the buildings geometry instead of a rough block-shaped hull approximation. This improvement leads to a significantly higher accuracy concerning specific heating demand, a prerequisite for any automated efficiency optimization tasks to perform.

3.1 Definition and Calculation of Efficiency Metrics

As the construction costs are to be described as square meter prices of the building hull anyway and the expected energy demand results in annual energy costs, using the cumulated costs per m^2 as calculation base is the consequential choice for defining efficiency metrics. Therefore the heating energy demand expressed as kWh/m^2a must be expressed as monetary demand for the service life time of the building. Several financial mathematics models have been presented in the past, covering amortization periods, energy cost rates and their expected change, interest rates and inflation[9].

Our developed amortization model observes a period of *t=20 years*. In that period the increased investment costs charged interest are opposed to the cost savings in day-to-day operations due to reduced energy demand. The developed model covers debit and credit rates and a progressive energy cost indicator. Each model parameter can be adjusted to current business conditions. The chosen amortization period of 20 years accounts for about half of the expected durableness of the construction. Amortization must be achieved before any need for renovation actions arises.

For our efficiency metric, the building's hull approximated construction costs per m^2 and the predicted energy demand in € per m^2 over the next 20 years of amortization are cumulated at equal weights yielding a significant and comparable efficiency parameter.

The defined common basis of planning variants comparison facilitates automated evaluation of the solution space for detecting the minimal and maximal efficiency values to achieve with a certain building construction plan.

3.2 Automated Construction Parts Variants Evaluation for Optimization

The building geometry defined by specified floor plans and the construction assemblings assigned to the required modalities facilitate automated simulation of different planning variants and the evaluation of their efficiency results. Thereby the constructions are altered with respect to the primary structure and insulation layer material type and the particular thicknesses. For example a wall constructed of 20cm concrete can be compared to a wall built of 22cm with the goal to evaluate, if the increased costs for the thicker wall are justifiable with reduced energy demand or not. Normally higher investments in the wall construction go along with reduced energy demand, as presented in results section, but only evaluation of the efficiency allows for each modality a statement, if thicker or thinner primary structures or insulation should be preferred for achieving a more efficient building design. The fitness landscape[10] of each construction part optimization is good-natured as no local optima exist and the global optimum can be found via simple optimization method of steepest descent[11].

Based on the different construction parameterizations applicable for each building modality, a large number of permutations to evaluate arise. It is up to the planning user to decide, which aspects of the building physics can be considered for variant calculation and which not. A rational planner must check the statics in the course of a structural analysis of his plan. Building without a single window at all might not meet the customer's expectations. From a top level view, the following building parts can be permutated: $walls \times basements \times roofs \times windows \times windowRatios$. For the construction groups walls, basements and roofs the four different modalities (*air, adjoined building heated/unheated*) can be permutated at most. For the category windows the six different shading strategies, enlisted in the prior chapter, can be differentiated. Finally for the orientation-dependent window ratio, the eight main orientations (*N, NE, E, SE, S, SW, W, NW*) must be distinguished. The solution space can have at most 26 different modalities to handle, each to treat as single dimension. As a common building at least has a basement, walls, a roof and some windows at least at one single front, the minimum number of modalities to handle is five. A particular solution space covering seven different modalities is exemplarily illustrated in Eq. 1 for two walls (W), one roof (R), one type of basement (B), one window shading strategy (WS) and two orientations for the window ratio (WR):

$$M = \begin{pmatrix} W_{air} \\ W_{adjoinedHeated} \\ R_{air} \\ B_{soil} \\ WS_{marquee} \\ WR_{north\_windowRatio} \\ WR_{southWest\_windowRatio} \end{pmatrix}. \qquad (1)$$

For each single modality in the group *walls*, like *wall towards air*, all applicable construction assemblings can be permutated with respect to primary structure and insulation material and thickness as $constructionMaterial \times construction Thickness \times insulationMaterial \times insulationThickness$ resulting in a set of *144* discrete wall constructions for modality *wall towards air*, see Eq. 2. One discrete wall construction assembling for example would be *20cm concrete* as primary structure with *12cm EPS* insulation.

$$W_{air} = \left(\begin{pmatrix} concrete \\ brickstone \\ wood \end{pmatrix} \times \begin{pmatrix} 20cm \\ 25cm \\ 30cm \\ 35cm \end{pmatrix} \times \begin{pmatrix} EPS \\ XPS \\ MWPT \end{pmatrix} \times \begin{pmatrix} 8cm \\ 10cm \\ 12cm \\ 14cm \end{pmatrix} \right) . \quad (2)$$

The window ratio variation can be performed for each of the eight main orientations by specifying a lower and upper window ratio border together with an increment, thus leading to a dynamic number of permutations with respect to the window ratio. When applying the different window ratios, the strategy is to preserve the intra-group ratio and the different window-to-wall proportions of the walls with the target orientation E.g. if two north walls showing the same area with *10%* and *20%* window ratio each and a cumulated window ratio of *15%* must be altered for a total window ratio of *30%* during simulation, the particular wall ratios are set to *20%* and *40%* to best keep the intra-group window ratios.

Without any restrictive parameters for simulation, a solution space with several billion variants far too large for full enumeration will arise. But as the plan must comply with legal requirements and the construction owner's specifications are to be fulfilled, the solution space can be significantly reduced. Furthermore, sequential optimization of the available modalities, e.g. first varying the walls towards air, then the basement above soil and finally the roof construction scales down the solution space to a fraction. For a real world planning project, evaluation of more than *10 million* variants at once in course of simulation will never be required.

3.3 Identify Potential for Construction Part Optimization

The two key numbers *construction cost ratio* (CCR) and *energy ratio* (ER) are introduced in BauOptimizer project for identifying the optimization potential of a single construction modality of a plan with respect to its relative *surface ratio* (SR). The parameter *CCR* refers to the construction cost ratio of a single construction modality with respect to the entire construction costs. The *ER* ratio of a single modality is calculated taking into consideration U-values, climate properties and solar gains as well as ventilation volume aspects to subdivide the buildings heating demand to all of its components, see Tab. 4. A particular construction part assigned to a certain modality is expected to show a *CCR* and *ER* ratio similar to its *SR*. If the *CCR* is higher than the *SR*, then the currently chosen construction assembling is more expansive than the average and consequently shows a potential for optimization. Construction parts with a *CCR* above the expected ratio should also be reviewed for improvement potential.

Table 4. Enlistment of the construction assemblings chosen for the building modalities. The basement modality in the third line misses a proper insulation layer and contributes to the building energy demand with 60.98%, although the basement area is only 15.22% of the whole building hull, thus indicating a significantly disproportional factor. Window constructions will in general show higher costs compared to common wall constructions.

part	build-up	primary constr.	insulation	SR	CCR	ER
wall	insulated outer	brick 25cm	MW-PT 14cm	44.83	28.90	22.24
wall	partition wall	brick 25cm	plastered	5.45	1.90	0.37
ground	basement	concrete 40cm	plastered	15.22	8.01	60.98
roof	inverted roof	concrete 22cm	XPS-G 20cm	1.82	1.34	0.74
roof	warm roof	concrete 22cm	XPS-G 20cm	13.41	15.69	5.45
window	wood	full shading	$1.4W/m^2K$	4.86	10.08	3.90
window	wood-aluminum	roller blend	$1.3W/m^2K$	8.88	26.31	4.61
window	wood	marquee	$1.2W/m^2K$	5.53	7.77	1.71

3.4 Optimization of the Building Geometry

Optimization of the building geometry is supported by BauOptimizer software but has to be manually performed by the planner. Each change on the floor plan in on-the-fly evaluated to give a feedback for the influence on the efficiency measures. Sphericity[12], i.e. the surface to volume ratio compared to a sphere is a good indicator for efficiency of the building geometry. The more net floor area can be constructed with the same area of building hull, the more efficient the plan will be classified compared to other architectural variants.

Due to on-the-fly evaluation, the influence of each small floor plan adaption, like removing or adding a jutty, for the cumulated plan efficiency can be presented to the user.

4 Planning Project Specific Normalized Reference System

Although utilizing BauOptimizer software construction costs and expected energy demand can be calculated very precisely, it is not the primary goal to serve as simple calculation tool. Instead of that, the quantitative comparison of planning variants gets feasible via efficiency definition and a planning project specific normalized reference system that comprises the entire variants solution space.

Instead of evaluating the planning solutions with respect to numeric construction costs in $€/m^2$ and energy demand in kWh/m^2a, all quantitative parameters are evaluated with respect to a reference system as percentage values. Each planning solution's quality is described by three percentage values in the core range [0;100]%, one for the construction costs, one for the energy demand and finally one for the entire efficiency. A cost efficiency of *85.2%* for example would indicate that the construction costs are already close to the theoretical optimum to achieve.

The geometric preferences of the reference plan are defined based on the building site's properties and the construction owner's preconditions like house passages, floor height intervals, the target number of floors, keeping the building lines or restrictions due to fitting the building into a vacant construction lot. Consequently, the reference plan geometry is the simplest shape to fit and fill-out the construction lot and fulfilling all conditions and restrictions but abstracting from any architectural inspiration.

For the reference plan the construction assemblings get only restricted by normative and legal restrictions, thus a huge solution space remains applicative for the planning project to evaluate.

The reference plan is to be defined based on the planning variants that show the highest and lowest efficiency value for construction costs, energy and total efficiency. These six parameters are required for building up the reference plan as basis of efficiency comparison. As the solutions of single modalities of the walls, the basement, the roof and the windows are independent from each other, e.g. the thermal quality or price of the flat roof construction is invariant from choosing wood or aluminum windows for the north front, the solution space can be significantly reduced. For detection of the search space extreme positions, the permutations of the wall, basement, roof and window modalities can be additively combined as $walls + basements + roofs + windows$ splitting the entire optimization problem into smaller sub-problems that can be independently processed and solved.

In contrast to the independent modalities, the window ratio cannot be handled independently from the window type to choose, the window U-value and g-value, the window orientation and the window-containing wall properties. The search space must be defined as $basements + roofs + (walls + windows) \times windowRatios$. The resulting minimum and maximum efficiency values are used for defining the normalized value range between [0;100]% of construction costs, the energy demand and the total efficiency as quantitative efficiency metrics.

5 Implementation

The BauOptimizer planning software features comprehensive modeling, analysis and reporting features for building construction plan efficiency optimization. The software application is implemented utilizing the Eclipse RCP framework for plug-in based application and software product development[13,14]. Interactive charting functionalities and the parameter editing composites are implemented with the *swing widget toolkit* (SWT)[15] and *JFace*.

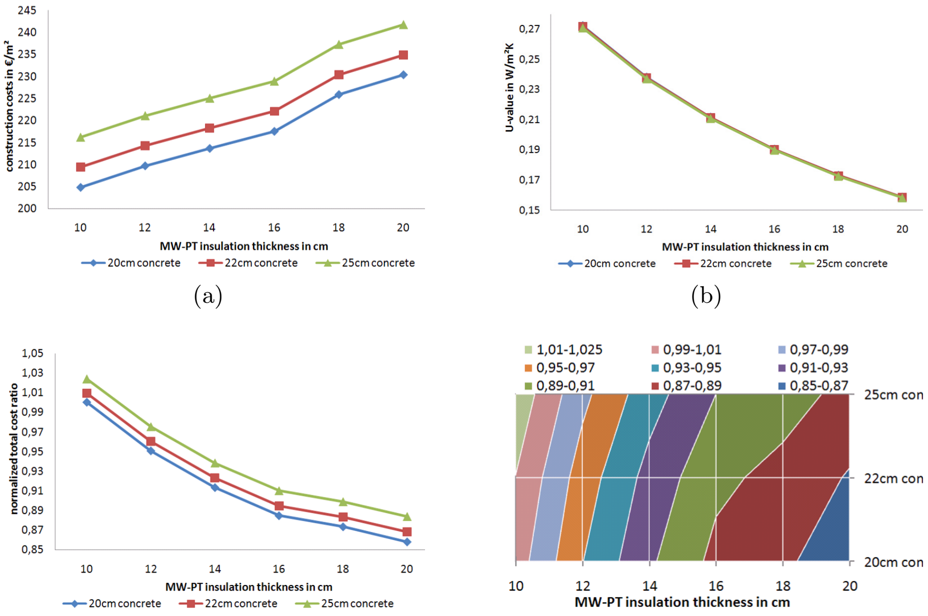
The huge solution space to evaluate has raised the need for optimization of the implementation. By applying the common Java optimization strategies[16] , factorization of invariant calculation time, abandonment and reduction of object-oriented overhead in procedural energy demand calculation as well as utilizing an approximation for exponential function instead of using java default *Math.**-library functionally[17,18], the required processing times could be significantly reduced.

Additional information concerning implementation details and BauOptimizer application features can be found in[4].

6 Results

6.1 Correlation of Construction Costs and Energy Demand

BauOptimizer software allows the planner to evaluate the trade-off between higher construction costs due to increased wall thickness and the reduction in energy demand and vice versa respectively. For each construction assembling the particular configuration can be calculated that minimizes or maximizes the efficiency values of the construction costs, the energy demand and the total efficiency. If the thermal quality of the primary structure is low, minimization of the thickness will lead to increased efficiency values, see Fig. 3.

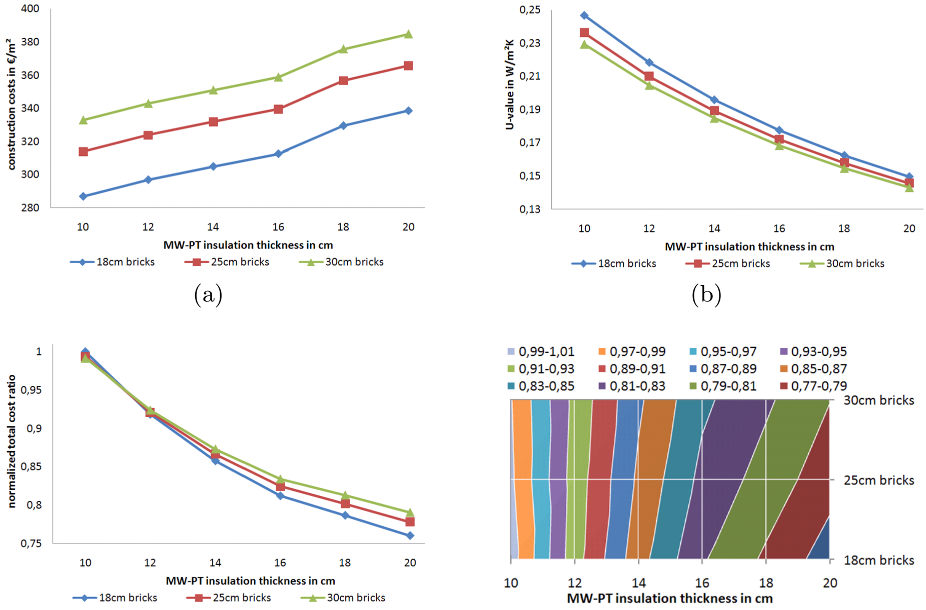


(a) (b)

(c) (d)

Fig. 3. Influence of varying a basement above air construction with primary structure of concrete ($\lambda = 2.500$) at thicknesses 20cm, 22cm and 25cm with an MW-PT insulation layer ($\lambda = 0.038$) at thicknesses in interval [10;20]cm with a 2cm increment. The wall construction assembling has 3cm subsonic noise insulation with a thermal conductivity $\lambda = 0.038$. Changing thickness of the primary structure and the insulation layer have approximately the same influence on the construction costs in $€/m^2$ (a). The MW-PT costs show a disproportionally high gain from 16cm to 18cm due to changed construction procedure to apply. For the influence on the U-value, changes in the primary structure thickness in contrast to the insulation layer are almost irrelevant for the thermal quality of the wall (b). Thus, the normalized total cost ratios optimum is reached by maximizing the MW-PT insulation thickness (20cm) at a minimized primary structure thickness (20cm), see (c) and (d).

A primary structure with thermal relevance used for outside building walls, like a brick stone wall at a specific thermal conductivity $\lambda = 0.39$ has significant impact on the U-value, see Fig. 4(b). Consequently, for thin insulation layers, the thicker brick stone constructions lead to higher efficiency, see Fig. 4(c).



(a) (b)

(c) (d)

Fig. 4. Influence of varying an outside wall construction with primary structure of brick stones ($\lambda = 0.39$) at thicknesses 18cm, 25cm and 30cm with an MW-PT insulation layer ($\lambda = 0.038$) at thicknesses in interval [10;20]cm with a 2cm increment. Up to an insulation level of 12cm, the thicker primary structure walls are preferred.

Comparing construction part assemblings with different primary structures and different insulation material, the regularly indirect correlation of costs cannot be observed. The significantly lower construction costs for a brick stone wall compared to a concrete wall will always lead to an outperformance with respect to efficiency, although brick stone walls will require higher thicknesses due to statics in general, see plot of the solution space in Fig. 5 and Fig. 6. The multivariant scatterplot allows zooming into the solution space to select and inspect single result's parameterization. That way modality-by-modality or optimization of several different modalities at once becomes feasible. Multi-variant scatterplot allows display of results from several variant optimization runs at once, allowing analysis of the modalities with highest potential for optimization.

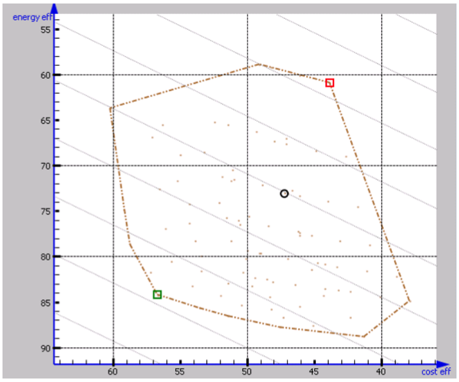


Fig. 5. Scatterplot showing results of varying the outer wall construction assembling with 92 different parameterizations to evaluate. Brick stone walls (18, 25, 30, 38)cm and concrete walls with (18, 20, 25, 30)cm are permutated as primary structure, whereas the insulation is chosen as MW-PT in the range [10;20]cm with 2cm increment or EPS-F in the range [10;20]cm with 2cm increment. The currently chosen solution is marked with a black sphere; the solutions showing highest and lowest efficiency are marked with a green and red square respectively. A hull curve[19] surrounding the single solution positions is shown for shape characterization. The broadly based hull curve illustrates, that results in the same energy efficiency class can be achieved by wall construction assemblings at a wide spectrum of costs.

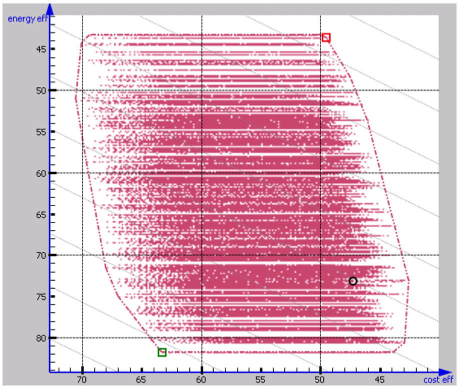


Fig. 6. Scatterplot showing results of varying the window types and quality with 175.616 single window parameterizations to evaluate. Similar to the wall configuration solution space plotted in Fig. 5, the same thermal quality can be achieved at very different prices. Besides the U-value, the window's g-value is of high importance. Cheaper windows allowing more solar gains in combination with a proper shading strategy show a high potential for optimization.

The findings discussed before raise the demand for a detailed analysis of the variant optimization space. For that reason a trend chart is introduced for plotting the energy-to-cost ratio of solutions at different total efficiency. Each single variant solution is sorted according to cumulated efficiency value and charted with respect to normalized energy and cost efficiency. The distributions of the variants are modeled as color-coded intensities, see Fig. 7 and Fig. 8.

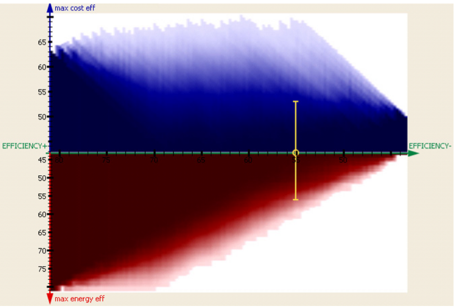


Fig. 7. Trend-chart for entire variation of the basement, wall and roof assemblings. The $y+$ axis plots the cost efficiency, whereas the $y-$ axis plots the energy efficiency at the x axis position of each solution with respect to the sorted total efficiency range. The results showing highest efficiency can be achieved by an energy efficiency of around 85% and a cost efficiency of around 63%, thus focusing on energy minimization. The broad spectrum of cost efficiency intensities in the mid section illustrates that comparable thermal quality can be achieved at very different cost levels. Analysis of the energy efficiency shows high linear correlation compared to total efficiency values. The parameterization of the current solution is displayed at 55% total efficiency.

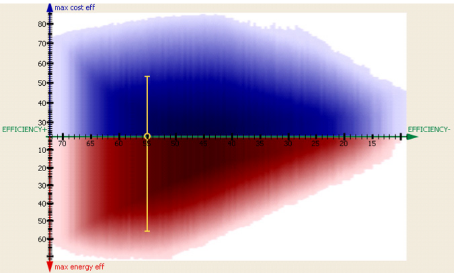


Fig. 8. Trend-chart for variation of the window properties. The results show a slight focus on the cost factor for achieving results with high total efficiency. The cost and energy efficiency trend curves indicate that for windows the correlation between costs and energy efficiency is lower.

6.2 Model and Variant Calculation Validation

The cost, energy and efficiency calculation is currently being evaluated based on real-world planning projects already constructed. Validation with real-world project facilitates identification of model parameters that need additional refinement. That way the need for adding construction assemblings with more than one insulation layer could be identified. Modeling of the floor plans based on a 0.5m grid grants a sufficient level of precision.

Besides evaluation of the building construction model itself, all calculation algorithms have been validated separately via comprehensive test suites and thus the calculation algorithms correctness can be trusted in.

Validation of the building hull costs is hard to achieve as the real-world project's construction costs have been calculated separately for the surface hull related costs. Approximating the surface hull costs from the real-world reference project's total costs matches the results achieved by evaluation of our model.

Concerning the variant calculation, theoretical considerations and performed test runs have shown that most modalities and parameters can be calculated and optimized independently from each other as discussed in the sections before. Nevertheless it is inevitable that the calculation of several million variants can be performed within a short period of time. Runtime tests utilizing a *32-bit Intel Pentium 4 CPU* with *2.79 GHz* processing frequency measured an average processing speed of *190 variants per ms* after intensive optimization work. That means only *14,500* processing cycles can be used under theoretically best circumstances for each entire variant calculation which is already a very low amount of processing capability with respect to the complex algorithm to execute for cost and energy efficiency calculation. Runtime test performed on the target processor showed that a double-precision multiplication requires *73.3 cycles* and a division *106.7 cycles* respectively. As cost and energy efficiency calculation require many floating point multiplications and division and further very time consuming array indexing and evaluation of exponential functions, the achieved runtime is already at a sufficiently optimized state. As the ratio of the communication overhead decreases at a larger number of variants to calculate, the number of calculations to process per ms increases with the growing solution space, see Tab. 5.

6.3 Evaluation Based on Real-World Reference Planning Projects

The following two testing projects show modeling, evaluation and optimization based on the input design of planning projects that have already been designed and constructed in real.

Reference Planning Project I. For a construction area dimension $22.5m \times 35m \times 10.5m$ at an orientation of 4° *north*, a building design with *3,041.25*m^2 net floor area on 5 floors with a surface sphericity of *33.98%* was designed, see Fig. 9. The implemented and constructed plan shows a total efficiency of only *32.71%* (cost efficiency: 53.44%; energy efficiency: 20.96%). Automated

Table 5. The average calculation throughput increases with the number of calculations to perform due to communication overhead and constant pre-calculation ratio

#calculations	time in ms	calc. per ms
252	31	7.88
2,016	32	65.03
24,192	219	110.47
96,768	860	112.52
290,304	1,875	154.83
2,032,128	11,797	172.26
12,192,768	65,031	187.49
156,473,856	810,136	193.15

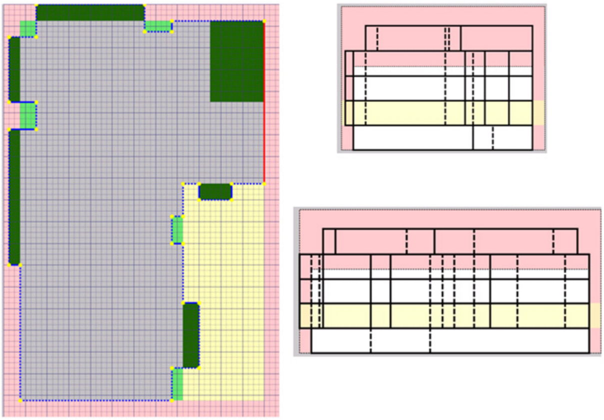


Fig. 9. Front and side projection of the reference project construction design at the right views. The horizontal projection illustrates the floor plan of the first level and the intersection regions compared to the neighboring floors. Due to presence of architectural elements, the total efficiency of 32.71% is far below the optimum of this specific building site.

optimization results in a maximum efficiency value of *64.46%* (cost efficiency: 41.26%; energy efficiency: 81.94%) for the possibly best planning variant, see Fig. 10. With building construction costs increased by *12.35%* a reduction in energy demand by *54.77%* could have been achieved.

Reference Planning Project II. For a construction area dimension $15.5m \times 15m \times 16m$ at an orientation of 40° *north*, a building design with *1,370.12*m^2 net floor area on 7 floors with a surface sphericity of *38.64%* was designed, see Fig. 11. The implemented and constructed plan shows a total efficiency of only *18.34%* (cost efficiency: 41.42%; energy efficiency: 10.60%). Automated optimization results in a maximum efficiency value of *70.29%* (cost efficiency: 45.20%; energy efficiency: 90.37%) for the possibly best planning variant, see Fig. 12. The optimized planning variant shows that both, cost efficiency and energy efficiency could have been improved.

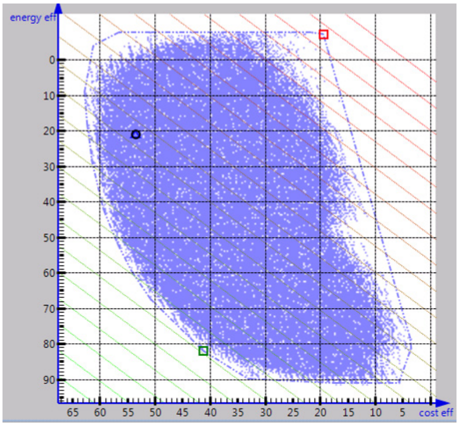


Fig. 10. The chosen planning solution at *(53.44,20.96)* could approach the theoretically achievable optimum at (*41.26,81.94*) by increasing insulation and window quality whereas decreasing the window ratio at the north front. The increased construction costs per m^2 are over-compensated by the resulting savings in energy demand.

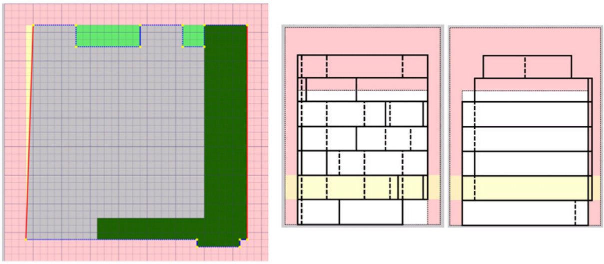


Fig. 11. Front, side and horizontal projection of the floor plan design chosen for reference project II

7 Discussion

A tool for modeling, simulation and optimization of building construction plans is presented with BauOptimizer software. For the first time changes on the building geometry can be evaluated with respect to their influences on the net floor area, the costs, the energy demand and quantitative total efficiency. Furthermore all important aspects and goals of construction plan design can be modeled and evaluated from the very first delineation of the building's shape to the final construction plan.

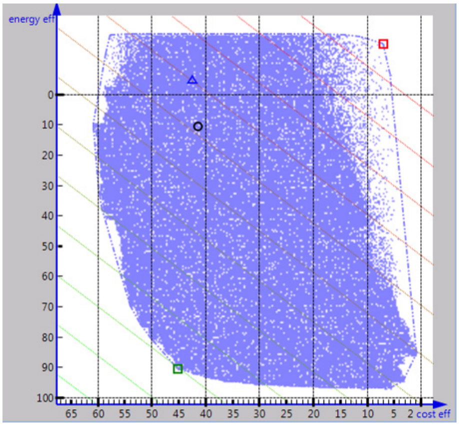


Fig. 12. The chosen planning solution at *(41.42,10.60)* could approach the theoretically achievable optimum at *(45.20,90.37)* by increasing insulation and window quality whereas decreasing the window ratio at the north front. The increased construction costs per m^2 are over-compensated by the resulting savings in energy demand.

For the legislative body the potentiality arises, to check permission plans not only based on keeping all normative limits but in addition to check how much of the building construction site's achievable efficiency is reached. Future financial promotion for building projects will not only depend on the normative and legal restrictions, but also based on how efficient a plan is with respect to the theoretically achievable optimum.

For construction companies *BauOptimizer software* allows detailed analysis for choosing the best construction part assemblings. As the content of the building construction catalogue is kept up-to-date, novel construction techniques or changing prices lead to a steady updating of the efficiency definition and the best practice concepts for building e.g. an outside wall. For a construction company, BauOptimizer software allows reduction of costs, a significant benefit when calculating in the course of a mandate awarding procedure.

A future field of application for BauOptimizer software is also the field of thermal rehabilitation of buildings. The automated simulation can predict for the user, how many years it will take to redeem the investment costs. Furthermore it could be evaluated which measurements and materials contribute for the highest payoff. Up to now thermal rehabilitation activities are not planned according to the highest efficiency to achieve, but the maximization of the energy savings and best-practice manuals[20,21] instead of focusing on the required investment costs too.

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