BAUOPTIMIZER: MODELLING AND SIMULATION TOOL FOR ENERGY AND COST OPTIMIZATION IN BUILDING CONSTRUCTION PLAN DESIGN

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ABSTRACT
In the light of increasing energy prices and declining fossil resources, energy efficient design is an important aspect of building construction planning. Software application *BauOptimizer* supports the planner in calculating, monitoring and optimizing both energy demand and cost aspects from the very first planning phase until the final architecture improving economic and ecologic properties of the building design. Furthermore the number of required planning phases is reduced as normative limits are kept considered right from the beginning.

Costs for building hull creation and expected energy costs for the next decades are linked together as efficiency measure and all planning variants applicable for a concrete construction area are automatically evaluated, covering different material at different thicknesses, the window ratio, roof modality, and many more aspects.

Within this full construction variants coverage, the planner optimizes his architectural design and building physics aspect to approximate efficiency optimum with respect to economy and ecology.

Keywords: energy and cost efficiency, economy, ecology, construction design optimization

1. INTRODUCTION
For the architectural and conception planning of buildings several perspectives on the desired outcome exist. The architect himself wants to act out his inspiration with jutties, alignments and shifted walls whereas the building owner desires reduced construction costs and a maximum exploitation of the building development regulations with respect to net floor area. Another fundamental aspect to consider is energy efficiency of the building. Investments into increased insulation measurements are connected with increased construction costs per square meters but are intended to reduce the energy demand and all associated costs for heating and air conditioning, see Fig. 1. Furthermore the legislative body states prescriptive limits with relevance for awarding a grant.

All of these aspects must be considered in a balanced building construction plan. As there is no tool supporting for cost and energy demand calculations in the early architectural planning phase, several cost intensive design iterations are often required before all relevant criterions are met, see Fig. 2.

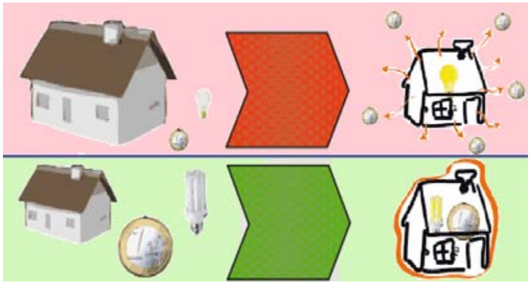


Figure 1: Focus on cheap building construction (top) leads to increased energy demand, whereas setting the focus on energy efficiency (bottom) leads to reduced energy costs at operation.

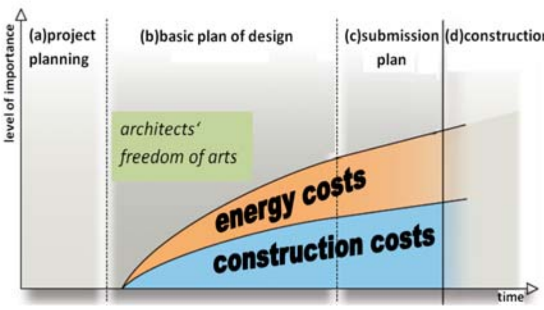


Figure 2: Delineation of the several planning phases. First the architects' design idea is a focal point whereas restrictions for construction and energy costs are considered later.

For linking and balancing the different, partially oppositional, planning criterions, a common basis for comparison must be developed. Therefore the term efficiency is intended to both cover economy and ecology and preserve a common base for comparison. Increase investments into energy demand reduction can redeem within a period of amortization. Consequently investment costs can be offset against reduction in energy demand.

The objective of project *BauOptimizer* is to develop a software tool for supporting architects and building owners in construction cost, energy demand, funding, normative limits and an efficiency evaluation, from the very beginning planning phase until the finalization of the building construction plan. Furthermore the current plan can be positioned relative to the theoretically best and worst result of economy / ecology. Thereby the stakeholders and authorities can assess the current plans distance to the global most efficient plan optimized for the particular building site and the restrictions to be considered.

2. MODELLING ARCHITECTURE, COST AND ENERGY ASPECTS

Before creating the efficiency model, all relevant parameters must be identified and their influence on costs and energy demand must be investigated on, see Fig. 3. In the following sections all parameters relevant for our efficiency model are enlisted and described in detail.

2.1. Building Site and Climate Parameters

When starting an optimization project, the planner has to specify the building site dimensions at first. Thereby the maximum constructible length, width and height as well as tolerance extents in this regard must be specified. The tolerance extent refers to local legally binding land-use plan and is relevant for e.g. jutties, loft conversions or keeping the building lines.

The climate properties comprising the country, region, sea level and orientation are inevitable for precise evaluation of solar gains and the heating demand in addition to the expected monthly average temperatures based on regional climate statistics. For calculation of the required energy demand, the difference from *20* Kelvin must be compensated by external energy supply at all times to ensure constant room air. As this tool is intended for modeling and optimizing the construction plans and choice of the building materials, the heating and ventilation system itself as well as air conditioning aspects are not being considered.

2.2. Modeling Building Geometrics and Design

The ground plan for each floor of the building can be specified by a polyline defined by arbitrarily oriented points on a regular grid of precision *0.5* meters, see Fig. 4. All defined walls are orthonormally positioned above the fundament at a floor-specific height. Copy-paste and arithmetic functions allow the user to propagate floor templates for fast entire building capture, even if there is a large number of floors to construct. That way the modeling of the building's architectonic character requires only little user interaction but provides sufficient accuracy for precise evaluations.

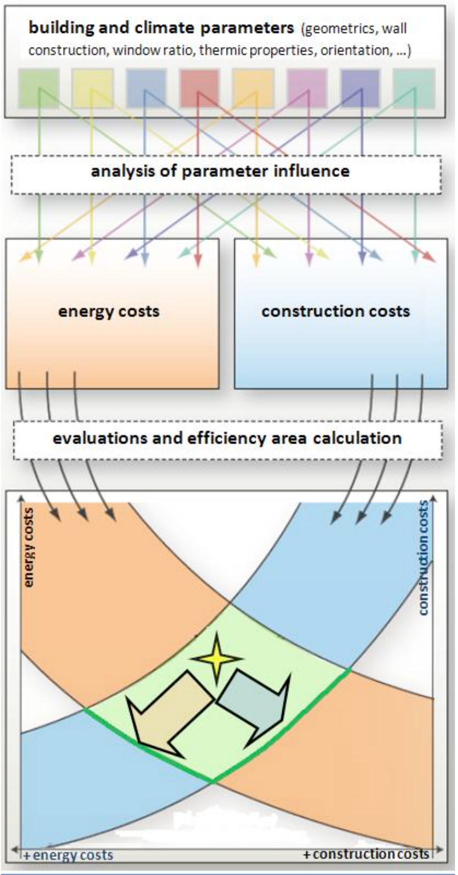


Figure 3: Higher investments into construction lead to reduced energy demand and vice versa. The parameters of the model have influence on energy costs, construction costs or both. The current planning solution (yellow star) can be optimized towards efficiency areas (arrows).

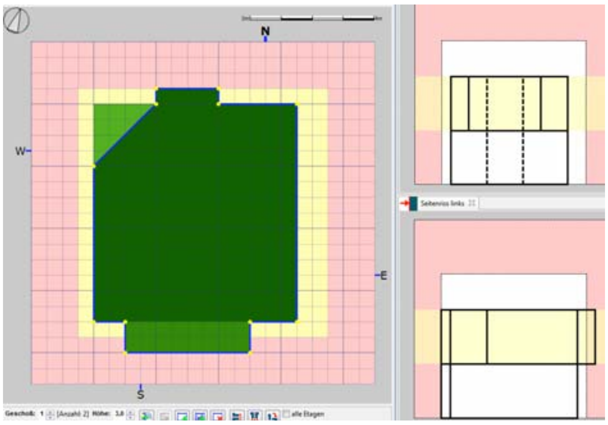


Figure 4: Floor-by-floor modeling of the building geometrics. The red area refers to the so called tolerance area. Wall jutties, offsets, ground and roof areas are displayed in shades of green. A front and a side projection provide an overview for the user.

2.3. Specifying the Wall Modalities

After creating the floor plan, for each wall the modality, i.e. properties towards the outside, with respect to specific thermal resistances, can be specified. For walls possible modalities with relevance for building physics are in extracts:

- towards surrounding air
- towards heated outbuilding
- towards unheated outbuilding
- towards soil

The modalities all show different properties relevant for heat conductance value calculation. The modality selection influences thermal resistivity from the building inside to the wall (R_{si}) as well as wall to the outside (R_{se}) and a specific temperature correction factor *F*.

Concerning the ground, roof, jutty and offset regions a modality has to be specified too. For the house top the type of the roof, like platform, gable or mono-pitch roof, has to be chosen. For the ground there is a significant difference whether there is a cellar, coil or air at raised standing buildings below the ground floor.

Another aspect to handle via modality assignation is the window ratio in percent or square meters as well as the shading strategy, like no shading, marquee, roller shutter, and so on. Depending on the wall's orientation, the window percentage strongly affects the solar gains to achieve. Consequently at the south front, larger window fronts are to be planned compared to the north front.

2.4. Selection of the wall and window construction

A catalogue of categorized and plausible wall constructions with up-to-date cost parameters is imported. For each different assignable wall modality, the planner can pick one single wall construction, see Fig. 5. That way the entire building physics aspect of the construction plan can be modeled. Up-to-now there are more than 300 of the most relevant wall, ground and roof construction sets contained in the catalogue but the coverage will be iteratively expanded.

A discrete wall or floor construction exists of several different material layers, as listed in Table 1, Table 2 and Table 3 for floor, wall and roof construction parts, where the bold-marked insulation and construction layers can be altered in thickness and material choice. These two main components, construction and insulation, can be individually altered by the planner, thus influencing thermic conductance and construction costs.

Window construction selection is specified in a quite similar way. For each different selected shading modality, a certain window type with respect to the heat conductance value can be chosen, see Fig. 6. For the window U-values, the g-value (solar energy transmittance) and the construction costs per m² are the deciding criterions used for categorization besides the window frame material (wood, plastic, aluminum,…).

Table 1: ground floor construction above soil with a total thickness of 0.634 metres, a thermal resistivity (R_{si}+R_{se}) of 0.17 and a construction-dependent total resisity R[m²K/W] of 2.673 leading to an U-value[W/m²K] of 0.374

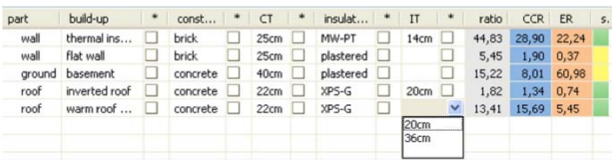
	material	d[m]	λ[W/mK]
1	**foam glass granules**	**0.160**	**0.085**
2	PAE insulation film	0.002	0.230
3	**steel reinfoced concrete plate**	**0.300**	**2.500**
4	bituminous primer	0.000	---
5	optional ground sealing	0.005	---
6	polysterene concrete	0.060	---
7	subsonic noise insulation	0.020	0.040
8	PAE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

Table 2: insulated outer wall construction with a total thickness of 0.360 meters, a thermal resistivity (R_{si}+R_{se}) of 0.17 and a construction-dependent total resisity R[m²K/W] of 3.257 leading to an U-value[W/m²K] of 0.307

	material	d[m]	λ[W/mK]
1	exterior plaster	0.015	---
2	**EPS-F (expanded polystyrene)**	**0.120**	**0.040**
3	adhesive putty	0.010	---
4	**steel reinforced concrete wall**	**0.200**	**2.300**
5	inner wall plastering	0.015	---

Table 3: insulated flat roof construction with a total thickness of 0.465 meters, a thermal resistivity (R_{si}+R_{se}) of 0.14 and a construction-dependent total resisity R[m²K/W] of 5.311 leading to an U-value[W/m²K] of 0.188

	material	d[m]	λ[W/mK]
1	PVC-film [UV-resistant]	0.004	0.020
2	**EPS-W**	**0.200**	**0.040**
3	moisture barrier film	0.000	0.250
4	concrete for leveling	0.060	0.980
5	**steel reinforced concrete**	**0.200**	**2.300**
6	plastering	0.001	1.400



part	build-up	*	const…	*	CT	*	insulat…	*	IT	*	ratio	CCR	ER	s.
wall	thermal ins…		brick		25cm		MW-PT		14cm		44,83	28,90	22,24	
wall	flat 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				13,41	15,69	5,45	

Figure 5: Modeling the building physics. The outer walls are constructed with 25cm brick stones and insulated with 14cm mineral rock wood. The construction-cost-ratio (CCR) and the energy-ratio (ER) illustrate the cost-to-energy balance with respect to the building hull proportion of each part. The color-coded state in the last column row reflects, whether normative limits are kept or not.

part	window type	*	category	*	U-value	*	ratio	CCR	ER	s	#v.
window	wood windows	☑	in free-standing building	☑	0,7W/m2K	☑	4,86	10,08	3,90		56
window	wood-aluminum w...	☐	in vacant lot	☐	0,6W/m2K	☑	8,88	26,31	4,61		7
window	wood windows	☐	in free-standing building	☐	0,9W/m2K	☐	5,53	7,77	1,70		1

Figure 6: Modeling the windows with respect to assigned shading modalities. The window quality is defined via U-value category. For each wall, ground, roof and window, construction and insulation aspects can be defined as variable or fixed via check-box selection for later variant calculation. The number of variants for each part is announced in the last column.

3. EFFICIENCY DEFINITION

3.1. Key model results and parameters

The two key results to directly compute based on the planning model are the expected energy demand in *kWh* per *m²* (square meters) and year as well as the costs for constructing the building's hull in Euro.

For calculating the annual energy demand per square meter gross floor area, the building physics calculation algorithm by Pöhn (Pöhn, et al. 2010), used for energy certificate calculations in Austria, is adapted for use with arbitrarily detailed construction plans. The calculation algorithm is conforming the Austrian policies *ÖNORM H 5055, ÖNORM B 8110-3* and implementing the initiating EU act in law 2002/91/EG (Pöhn, 2008).

3.2. Defining and Calculating the Efficiency

As common calculation basis costs in Euro are chosen. Therefore the *ΔkWh/m²/a* to achieve by increased investments in insulation for instance must be expressed as benefit in Euro. Several financial mathematics models have been presented in the past, covering amortization periods, energy cost rates, interest rates and inflation (U.S. Congress 1992; Jakob and Jochem 2004).

Our efficiency model observes an amortization period of $t=20$ years. In that period the increased investment costs charged interest are opposed to the cost savings due to reduced energy demand. The financial mathematics model covers debit and credit rates and a progressive energy cost indicator. Each model parameter can be adjusted to fit changed business conditions. Energy saving devaluation due to inflation is not considered to be relevant.

The expected construction costs per m² and the predicted energy savings in Euro per m² over the next 20 years of amortization are combined at equal weights yielding a total efficiency parameter.

As a common basis for planning variants comparison is given, automated estimation of the minimal and maximal efficiency to achieve for a certain building construction plan becomes technically feasible. Furthermore all variants of choosing different wall, ground, roof and window types can be automatically evaluated for predicting the possible changes in efficiency to achieve as distribution.

4. VARIANTS CALCULATION FOR SIMULATION AND PLAN EVALUATION

Based on the floor plans and assigned modalities defining the building geometry, we can simulate different planning variants and evaluate their predicted efficiency. Thereby for example an outer wall constructed of 20cm brick stones is to be compared to a wall constructed of 22cm brick stones or 18cm concrete. A large number of permutations designated as variants can be evaluated. The user has to decide which aspects of the building physics plan should be considered for variant calculation and which not. On a top level view the building parts can be permutated: *walls* × *grounds* × *roofs* × *windows* × *windowRatios*. For the construction group "walls", all different assigned modalities can be permutated, for example *outerWall* × *partitionWall*. The wall bordering an adjacent building can be further decomposed, e.g. according to the chosen category like fire wall or insulated wall. For each of these sub-categories variants can be arranged as *constructionMaterial* × *constructionThickness* × *insulationMaterial* × *insulationThickness* ending up in a large number of total permutations. The dimensionality of the solution space is defined by the cumulated numbers of distinctive modalities for walls (W), roofs (R), grounds (G), window shadings (WS) and window ratios (WR) used in the plan, for example $D = \overline{W} + \overline{R} + \overline{G} + \overline{WR} + \overline{WS} = 7$ defines the solution space:

$$S = \begin{pmatrix} W_{outerWall} \\ W_{flatRoof} \\ R_{shedRoof} \\ G_{groundOnSoil} \\ WS_{marquee} \\ WR_{North\_windowRatio} \\ WR_{SouthWest\_windowRatio} \end{pmatrix}$$

with $W_{outerWall}$ for example covering all permutations of *constructionMaterial* × *constructionThickness* × *insulationMaterial* × *insulationThickness* as

$$W_{outerWall} = \left\{ \begin{pmatrix} concrete \\ brickstone \\ wood \end{pmatrix} \times \begin{pmatrix} 20cm \\ 25cm \\ 30cm \\ 35cm \end{pmatrix} \times \begin{pmatrix} EPS \\ XPS \\ MWPT \end{pmatrix} \times \begin{pmatrix} 8cm \\ 10cm \\ 12cm \\ 14cm \end{pmatrix} \right\}$$

resulting in a set of 144 discrete wall constructions for walls with modality *outerWall*:

$$W_{outerWall} = \{c20EPS8, c20EPS10, \ldots w35MWPT14\}.$$

The window ratio variations can be performed for walls in one of the eight main orientation intervals. For the discrete variation of the window-ratio per orientation, the lower and upper boundaries as well as the increment can be parameterized, see Fig. 7. For application of the target window-ratio, two strategies are available:

- to assign the target window-ratio to all window-walls in the orientation interval or
- to preserve the orientation intra-group-ratio and preserve the different proportions of the walls to process. E.g. if the two equally-sized north walls with 10% and 20% window ratio and a cumulated window-ratio of 15% should be applied a total window ratio of 30%, the wall-ratios are set to 20% and 40% to keep the intra-group ratios.

window ratio	area in m²	total ratio [%]	relative ratio [%]	min	max	step width	*	#var
south-east	49,20	36,44	36,44	20	60	10	☑	6
south-west	64,80	56,84	56,84	30	55	15	☐	1
north-west	24,00	17,78	25,00	5	75	20	☑	5

Figure 7: The window-ratio of all orientation-groups can be considered for variant calculation. The relative window ratio, comprising all walls with windows at a certain orientation, is variegated in the interval [min;max] at defined step width.

If there are no fixed parameters defined as restrictions for variant calculation, a solution space with several billions of single efficiency evaluations might have to be evaluated. As the plan has to comply with legal requirements, the number can be significantly reduced. Furthermore the planner might further more restrict the problem dimension according to his or the construction owner's specifications or sequentially work on the optimization by e.g. first varying the window aspects, later on the walls and finally the roof construction. For a real world planning problem a search space of only around 10 million discrete variants will remain at the most if the optimization is performed in a sequential way, see Fig. 8.

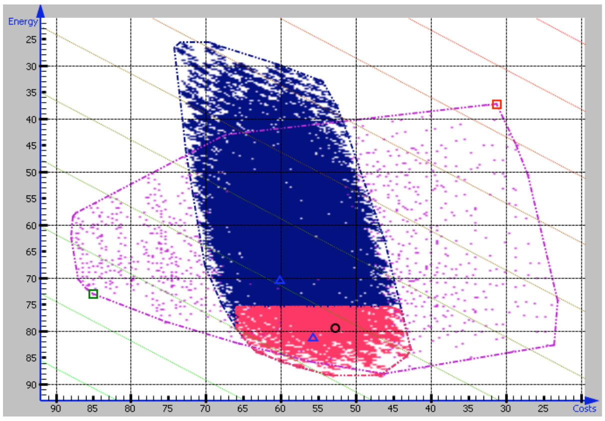


Figure 8: Results of sequentially evaluating more than 10 million variants in total. The x-axis shows the expected costs for construction the building hull as cost-efficiency percentage and the y-axis the energy costs for the next 20 years of amortization as energy-efficiency, both comparing with the defined norm building. Besides the current solution, prior planning variants and the best/worst variant are displayed.

Each construction part with all of its components can be chosen for variant calculation by the user defining the total number of solutions to evaluate, see Fig. 10. Within the variants chart the most and least efficient solution are marked with green and red quadrates respectively. The position of the current chosen construction plan is marked as black circle. The diagonal blue auxiliary lines refer to efficiency categories; the closer the results are to the origin, the higher the efficiency is. Furthermore, the variant solution space can be viewed ad arbitrary detail level by allowing continuous zoom-support.

Utilizing the variant chart, the planner can track the consequences of on-the-fly changes on the construction parts to optimize towards the optimum. Furthermore one can gain information about the parameter configurations beneath the charted efficiency results to obtain information on how to improve the plan at best, after clicking on a chart position, see Fig. 9. If performing several variant calculation runs, the planner can decide which results to present in the chart, see Fig. 10.

cost efficiency: 69,62% energy efficiency: 78,574% **total efficiency: 81,334%**

modality	variant	max efficiency	min efficiency
wall adjacent air	**brick 18cm EPS-F 20cm**	**brick 18cm EPS-F 20cm**	brick 18cm MW-PT 10cm
roof flat roof	concrete 20cm XPS-G 20cm	concrete 20cm XPS-G 36cm	concrete 25cm XPS-G 20cm
window-ratio south-east	**20%**	**20%**	60%

Figure 9: Single variant selected from the chart. For each varied parameter, the possibly best and worst are compared to the current chosen parametrization.

description	num of elements	color	show	hull curve
calculation#4	48	(7,252,41)	☐	☐
windows	1732	(183,3,206)	☑	☑
walls, ground, roof	39043	(0,0,128)	☑	☑
insulation thickness	10761	(249,40,104)	☑	☑

Figure 10: Each variant calculation run can be added a description label and a display color. Furthermore, each variant calculation run can be shown or hidden in the chart. Option *hull curve* (Preparata and Hong 1977) draws the surrounding polyline for the discrete variant results in the chart.

5. REFERENCE PLAN AS BASIS OF COMPARISON

Although construction costs and the expected energy demand can be evaluated very precisely, it is not the primary goal of BauOptimizer software to represent a cost calculation tool or a tool for energy demand approximation, precisely taking into account arbitrary architectural variations like wall ledges or jutties. Instead, comparison of different planning designs and an optimization of efficiency are achieved by efficiency definition and specification of a reference plan.

Consequently, a comparative basis for construction costs, energy demand and efficiency is required. Instead of absolute construction cost parameters in €/m² and energy demands in kWh/m²a, only relative values are presented to the planner, e.g. costs of 85.2% in the range of [0;100]% derived from the best and worst possible planning design. Energy and efficiency are only represented as quantitative comparison to the reference plan, too.

The reference plan characterizes the planning design, that best takes advantage of the given building site with respect to given preconditions and requirements, like keeping the building lines, considering restrictions like fitting into a vacant construction lot and many more. The reference plan is the simplest geometric shape to fit the construction lot without any architectonical variations but modeling the constraints, like modalities for walls to neighboring buildings, as precisely as possible.

Concerning the construction and insulation material of the ground, the walls, the roof and the windows, a preferably unrestricted wide range of construction variants is allowed.

Based on the reference plan geometrics, the best and worst plan concerning construction costs, energy demand and efficiency must be found. As the solutions for walls, roof, windows and ground are independent from each other, they can be optimized with respect to min/max construction costs, energy demand and efficiency one-by-one. Consequently, for optimization, the permutations of these groups can be additively combined as *walls* + *grounds* + *roofs* + *windows*, thus significantly reducing the dimension of the solution space that has to be searched for reference plan evaluation.

Only the window ratio cannot be seen isolated from the other part-by-part optimization. As the choice of the window ratio directly influences choice of the window type, for entire reference plan optimization, the following search space is defined as:

(walls + grounds + roofs + windows) × *windowRatios.*

With the minimum and maximum construction costs, the reference plan range of [100;0]% for comparison with other planning results is defined. The same intervals are created for energy demand and efficiency criterion. That way a relative metric for cost efficiency, energy efficiency and the cumulated total efficiency has been defined.

6. IMPLEMENTATION

BauOptimizer planning software is implemented utilizing Eclipse RCP framework for plug-in based application development (McAffer and Lemieux 2005). The charting functionality and parameter editing composites are implemented with *SWT* and *JFace* technology (Daum 2007).

Specification of the floor plans, wall construction assignment and the variant calculations can be performed in a perspective-specific configured editor. All charting and numeric results as well as 2D projections on the building geometry are implemented as viewers.

New wall construction parts, changed cost parameters or additive materials to consider can be handled via proper importers.

Concerning time-intensive variant calculation, we pursue a strategy that primarily necessitates only the recalculation of specific terms of the heating demand and cost calculations by factoring invariant sub-results, thus significantly reducing runtime. Moreover the permutations must be arranged in a sequential order to minimize the required recalculations from variant to variant.

7. RESULTS

7.1. Model Validation

We are currently validating the cost, energy and efficiency results by modeling and simulating real-world planning projects already constructed. Thereby we have to identify the aspects of the entire model that are inexact. Exemplarily the λ-values for material-specific heat conductance value calculation turned out to be modeled too restrictive. As a consequence we have introduced a concept to configure several λ-values at certain thickness intervals for each material. This allows us to add composite construction aspects to our wall construction catalogue.

Besides the abstraction precision to be evaluated and validated on real-world projects, all sub-calculations for energy demand, costs and variant optimization have already been validated separately.

7.2. Calculation of the Cost and Energy Demand Extreme Points

Theoretic considerations and evaluations showed that most of parameters are invariant towards the others. So e.g. the most expensive roof configuration will definitely be the roof for the overall most expensive building configuration as its independent to the ground and walls to choose.

Consequently only very few calculations are to be performed for calculating the best and worst plan with respect to the construction and energy costs, thus defining the 2D range within optimization can take place. This fact is taken advantage of for reference plan evaluation and range pre-calculations before each variant calculation run.

7.3. Variant Calculation Performance

Runtime tests utilizing a 32-*bit Intel Pentium 4* CPU with *2.79 GHz* processing frequency and 1*GHz RAM* an average processing speed of around 190 variant calculations per ms can be timed, see Table 4. The variant calculation task is not parallelized thus only one processor is used for processing on multi-core architectures.

Due to intensive optimization work on the heating demand and cost calculation algorithms, runtime has been reduced by a factor of 10 compared to the first implementations to reach the speed presented in Table 4. In the course of runtime optimization, method calls were replaced by inline assignments, constant terms were pre-calculated and time-consuming exponential function call, that had accounted 60% of the total runtime, was replaced by an approximation based on floating-point shift-operations and Newton's method (Deuflhard 2004, Ankerl 2007).

Table 4: Average calculation speed at different numbers of variants to calculate. Calculation throughput increases with the number of variants to calculate due to communication overhead and constant initializations.

number of variants	calculation time [ms]	calculations per ms
252	31	7.875
2,016	32	65.032
24,192	219	110.466
96,768	860	112.521
290,304	1,875	154.829
2,032,128	11,797	172.258
12,192,768	65,031	187.491
156,473,856	810,136	193.145

7.4. Findings concerning Material Choice

Besides planning project-specific optimization of the building construction material, several findings concerning general material choice guidelines and rules of action can be derived. One aspect even very surprising for the architects and building physicians is that a common brick stone wall generally outperforms a wall made of concrete by far and that thermal insignificant parts of the building, e.g. a partition wall to a heated adjacent building, have a deciding potential for cost reduction.

Analysis of the hull curves resulting from variant calculations show, that planning results of a certain energetic quality can be achieved at different material choices, thus leading to a broad cost spectrum for construction, see Fig. 11 and Fig. 12.

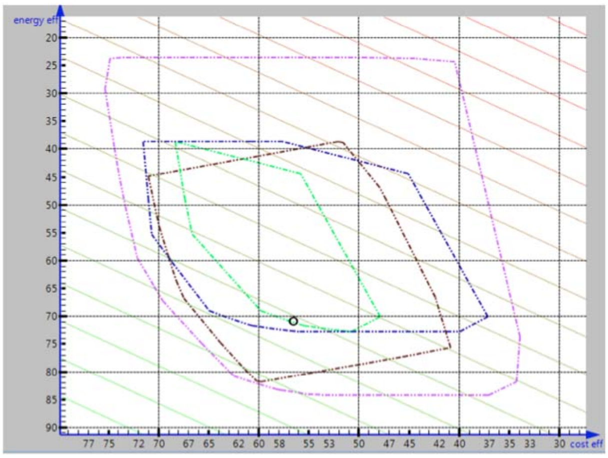


Figure 11: Results of varying construction and insulation material and thickness. The broadly based hull curves illustrate, that results in the same energy efficiency class can be achieved by solutions at a wide spectrum of cost efficiency.

The theoretical inverse correlation of cost and energy efficiency cannot be observed in variant calculation. Increased construction costs do not automatically lead to a reduced energy demand and higher energy efficiency can also be achieved by cheaper material respectively. For window choice, the g-value quality is another deciding factor besides costs and U-value as energy criterion.

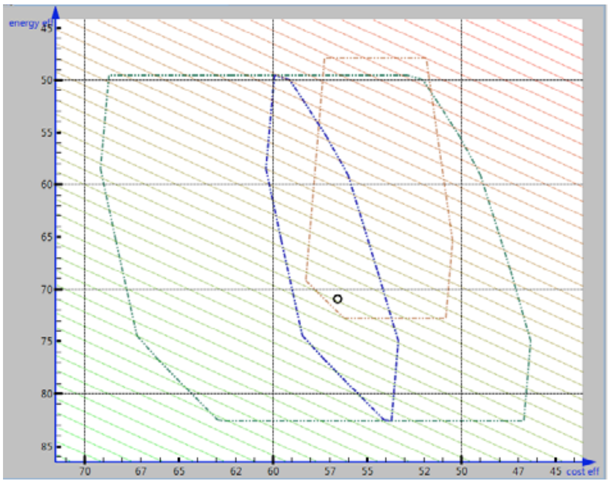


Figure 12: Results of varying window type and quality. The horizontally oriented borders of the hull curves indicate, that the same energy efficiency intervals can be achieved at window constructions at very different costs.

7.5. Trend-Chart for Energy-Cost Correlation Analysis of the Variant Optimization Space

The findings discussed in the prior section raise the demand for detailed analysis of the variant optimization space. Each single variant solution is sorted according to cumulated efficiency value and charted with respect to energy and cost efficiency. The distribution of the solutions in the variant optimization is modeled as color-coded intensities, see Fig. 13 and Frig. 15.

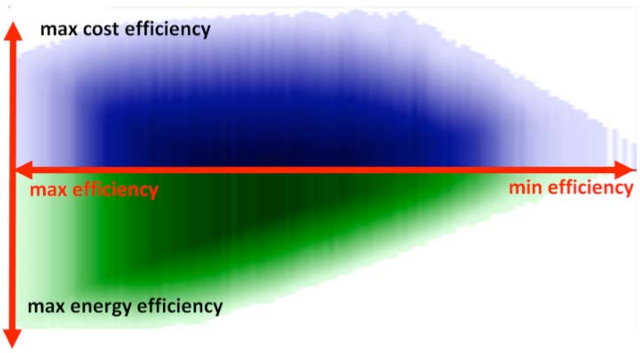


Figure 13: Trend-chart for variation of insulation material and thickness. The y+ axis plots cost efficiency, whereas the y- axis plots the energy efficiency for each single variant solution cumulated efficiency x axis position. Comparing costs and energy at high intensity values in the midst of the efficiency spectrum illustrates, that there is a linear correlation between energy and cumulated efficiency optimization, whereas the cost aspect shows slightly indifferent tendency. The maximum cumulated efficiency at the very left shows higher energy efficiency compared to the costs. At the very right solutions can be found, that show both, low cost and low energy efficiency.

If analysis of single efficiency intervals must be performed, normalization allows filtering-out the distribution-based intensity variation to facilitate analysis of the energy-to-cost efficiency ratio at different intervals, see Fig. 14 and Fig. 16.

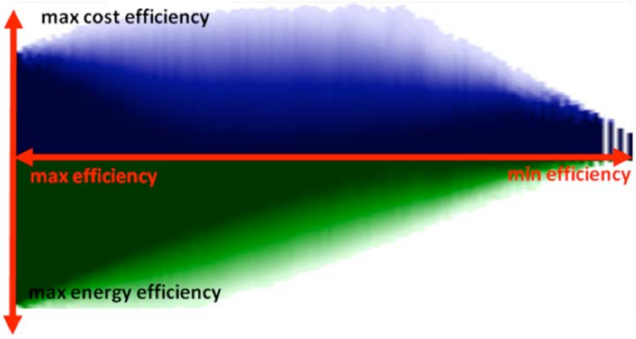


Figure 14: Trend-chart on same variant results data as plotted in Fig. 13. To equalize the distribution-based variation, normalization has been performed to independently handle the color-coding intensities of each cumulated efficiency slot. The sample above shows high variability of the cost efficiency in the midst results and less variability for the energy efficiency. Maximizing energy efficiency leads to the best results whereas solutions with high cost efficiencies are slightly ranked at back.

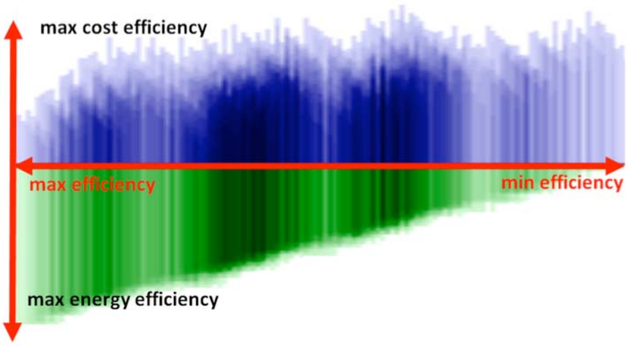


Figure 15: Trend-chart for variation of window frame material and window glass insulation quality. A strong linear correlation between energy efficiency and the solution quality can be observed. The expensive window solutions are at the first ranks, whereas the cheaper windows can be found at the lower end of the efficiency range.

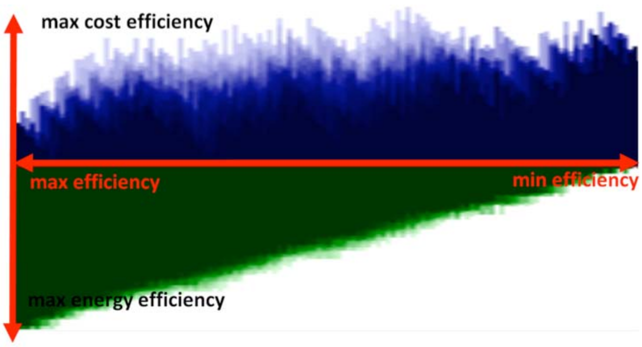


Figure 16: Trend-chart on same variant results data as plotted in Fig. 15 with normalized intensities.

7.6. Evaluation based on Real-World Reference Planning Projects

Evaluation and validation of the described modeling and analysis software must be performed based on real-world reference planning and construction projects carried out in the past. There are several aspects to validate:

- is the 0.5m grid accurate enough for modeling the building geometrics?
- does the construction material catalogue have a sufficient extensiveness for modeling arbitrary construction strategies and concepts?
- is the geometrics-dependent energy demand calculation valid?
- is the cost-approximation valid?

By now two major planning projects have undergone detailed analysis. As building-hull dependent energy demand and building-hull dependent cost fraction are no common parameters to survey in architecture and construction engineering, they have been approximated for the two projects to evaluate. Accurate cost parameters for constructing the building-hull will be collected for future projects from now.

7.6.1. Reference Planning Project I

Construction area dimension *22.5m* × *35m* × *10.5m*, orientation *4°* north was covered with a 5 floor building and total net dwelling area of *3,041.25m²* at a sphericity of *33.98%*, see Fig. 17. The chosen plan shows a total efficiency of *32.71%* (cost efficiency 53.44% with 233.94€/m² and energy efficiency 20.96% with 23.55 kWh/m²a) compared to the reference building. The possibly best, optimized building design would show a total efficiency of *64.461%* (cost efficiency 41.26% and energy efficiency 81.94%), see Fig. 18.

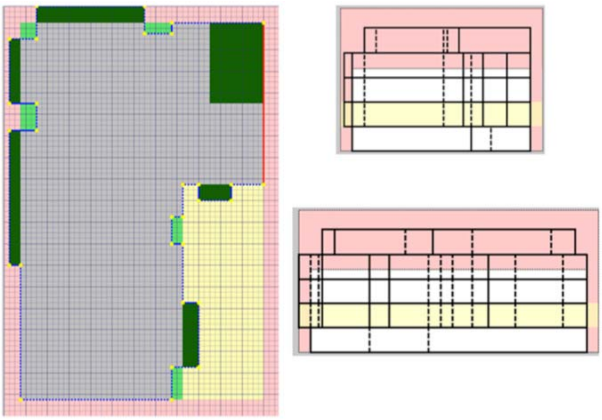


Figure 17: Horizontal, front and side projection of the reference planning project I construction design.

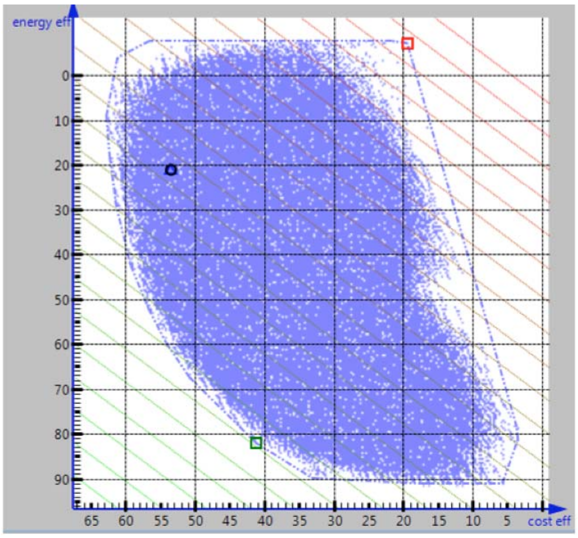


Figure 18: The chosen planning solution at [53.44;20.96] could approach the achievable optimum at [41.26;81.94] by increasing insulation and window quality and decreasing the window ratio at north walls. The increased construction costs are over-compensated by the energy savings.

7.6.2. Reference Planning Project II

Construction area dimension *15.5m × 15m × 16m*, orientation *40°* north was covered with a 7 floor building and total net dwelling area of *1,370.12m²* at a sphericity of *38.64%*, see Fig. 19. The chosen plan shows a total efficiency of *18.34%* (cost efficiency 41.42% with 248.09€/m² and energy efficiency 10.60% with 21.25 kWh/m²a) compared to the reference building. The possibly best, optimized building design would show a total efficiency of *70.291%* (cost efficiency 45.20% and energy efficiency 90.37%), see Fig. 20.

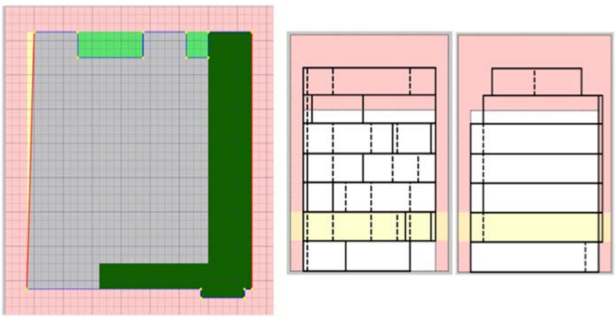


Figure 19: Horizontal, front and side projection of the reference planning project II construction design.

7.6.3. Conclusions from the Reference Planning Projects

The 0.5m grid offers sufficient precision and the construction material catalogue contained the required wall, ground and roof construction concepts for precisely modeling the reference planning project designs.

Energy demand calculation and hull-specific construction costs have been compared to results of conventional energy demand calculation and the hull cost approximation. The marginal deviance results from floor-plan-specific energy demand calculation in our application, whereas common software of building physics cannot handle the exact geometry and can only give a rougher approximation.

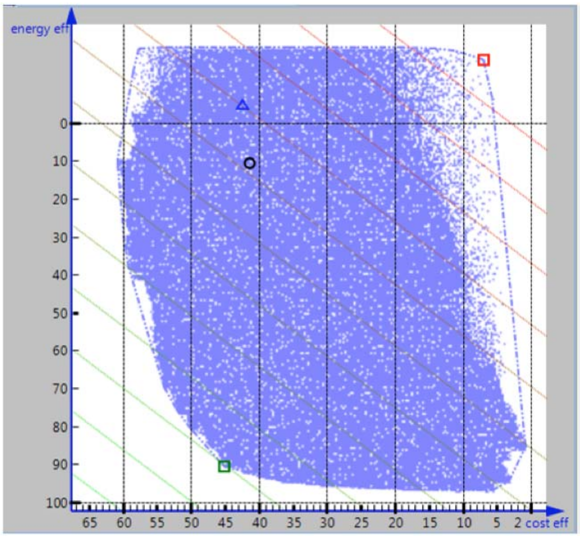


Figure 20: The chosen planning solution at [41.42;10.60] could approach the achievable optimum at [45.20;90.37] by increasing insulation and window quality and decreasing the window ratio at north walls. The increased construction costs are over-compensated by the energy savings.

8. DISCUSSION

We have developed and presented a planning tool already appropriate for precise modeling of the different construction planning aspects and ready to perform automated optimization with respect to cost and energy efficiency.

For the first time changes on the building geometry, like adding or removing a jutty can be evaluated towards cost and energy demand consequences on-the-fly.

Furthermore the legislative body can check the permission plan not only for keeping the normative limits but also for exhausting the construction-site specific potential in future. Consequently future financial promotion for building projects might not only depend on the normative limits of the single construction parts but also on the distance from the optimal achievable limit with respect to efficiency.

For construction companies usage of the planning software is expected to take advantage of cost reduction potentials when competing with rival applicants in the course of award procedures.

A future field of application is planning thermal rehabilitation activities. Thereby the simulation could predict how many years it will take to redeem the investment costs and which measurements have the highest payoff. Not every investment instigated in the light of energy saving and CO_2 reduction for ecology might effectively be worth a consideration. Up to now thermal rehabilitation activities are not planned according to highest efficiency but highest energy savings to achieve and best-practice manuals (Gabriel and Ladener 2009) instead considering the required investment cost.

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REFERENCES

Ankerl, M., 2007. *Optimized pow() approximation for java and c/c++*, available from http://martin.ankerl.com/2007/10/04/optimized-pow-approximation-for-java-and-c-c/

Daum, B., 2007. *Rich-Client-Entwicklung mit Eclipse 3.3*. 3rd ed. dpunkt Verlag

Deuflhard, P., 2004. Newton Methods for Nonlinear Problems – Affine Invariance and Adaptive Algorithms. Berlin: *Springer Series in Computational Mathematics*, vol. 35.

Gabriel, I. and Ladener, H. (eds.) 2009. *Vom Altbau zum Niedrigenergie- und Passivhaus*. 8th ed., Ökobuch Verlag.

Jakob, M. and Jochem, E. 2004. *Kosten und Nutzen-Wärmeschutz bei Wohnbauten*. Bern: Centre for Energy Policy and Economics, Swiss Federal Institutes of Technology, available from http://www.cepe.ch/download/staff/martin/WaermeschutzWohnbautenKosten_Nutzen.pdf [08.04.2010]

McAffer, J. and Lemieux, J.-M., 2005. *Eclipse Rich Client Platform: Designing, Coding and Packaging Java Applications*. Amsterdam: Addison-Wesley Longman

Pöhn, C., 2008. *Die EU-Gebäuderichtlinie*. Magistratsabteilung MA39, available from http://www.bauxund.at/fileadmin/user_upload/media/service/nachhaltigKrankenhaus08/Poehn_vortrag_KAV080618.pdf [08.04.2010]

Pöhn, C., Pech, A., Bednar, T. and Streicher, W., 2010. *Bauphysik Erweiterung 1: Energiesparung und Wärmeschutz. Energieausweis – Gesamtenergieeffizient*. 2nd ed. Wien: Springer.

Preparata, F.P and Hong, S.J., 1977. Convex Hulls of Finite Sets of Points in Two and Three Dimensions, *Commun. ACM*, 20(2), 87-93.

U.S. Congress, 1992. *Building Energy Efficiency, Office of Technology Assessment*. Washington: U.S. Government Printing, available from http://www.fas.org/ota/reports/9204.pdf [08.04.2010]

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