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Dissertation

An empirical study of effort and effectiveness in computational building design support

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1. Introduction

1.1. Motivation

Computational building evaluation tools have the potential to provide an effective means to support informed design decision making. Computational modelling, however, comes with a cost. Thereby, the most important cost factor is not necessarily software acquisition, but the time needed for learning and using the software. The extent of required time and effort has been quoted by a number of previous studies around the world (Lam et al.1999, Mahdavi et al. 2003) as one of the main hindrances toward the pervasive use of computational building performance assessment tools by designers: currently, Modeling applications are mostly used, if at all, in the later stages of design and by specialists, rather than architects. Few studies, however, have explicitly dealt with the ascertainment and quantification of the actual effort needed to understand, master, and apply computational building evaluation tools. Thus, little factual information is available as to the cost and burden of computational building evaluation and its effectiveness in building design support. In this context, the present thesis describes a case study (Mahdavi and El-bellahy 2005) whose motivation was to estimate the time and effort needed from novice designers to computationally evaluate the performance of building designs.

1.2 Past Research

1.2.1 Foundation of energy and environmental performance assessment

The importance of the energy performance of buildings as well as the quality of the indoor thermal environment as essential design evaluation criteria is well-established (Mahdavi and Kumar 1996). Mathematical and physical foundations for the description of the thermal performance of buildings are well-understood and respective algorithmic formulations for its prediction have been developed (Clarke 2001). More recently, efforts have been undertaken to expand the environmental performance evaluation domain beyond operational energy into a more comprehensive set of indicators, thereby addressing the environmental impact of buildings over their entire life cycle (Mahdavi and Ries 1998, Etterlin et al. 1992, Fava et al. 1992). As applied to buildings, life-cycle assessment (LCA) refers to the major activities in the course of a building's life span from its construction, operation, maintenance, and final decommissioning including the raw material acquisition necessary for production of the building and its components (Ries and Mahdavi 2001, Kohler and Lützkendorf 2002, Forsberg and Malmorg 2004, ISO 1997). The LCA process is a systematic, phased approach and consists of four steps, i) goal definition and scoping; ii) inventory analysis; iii) impact assessment; iv) Interpretation (ISO 1997).

1.2.2. Tools for thermal performance and LCA

Many computational applications have been developed to support the energy and environmental performance of buildings. Examples of energy simulation applications are ESP-r (Esru 2004), Energy Plus (EnergyPlus2004), and ECOTECT (Ecotect 2004). A comprehensive list of such tools may be found in DOE 2004. Likewise, in the LCA area, a variety of environmental tools are available that are generally built on a database of environmental information and can be used to evaluate the environmental impact of products and processes. Examples of such tools are BEAT2002 (Holleris Peterson 2002), ELP (Fyrhake et al. 1998, Forsberg and Bürström 2001), Simapro (Simapro 2004), Envest (Envest 2004), Athena (Athena 2004), BEE (Berge1995), and Eco-Quantum (Kortman et al. 1998).

1.2.3. Time expenditure estimations

Few studies could be identified that explicitly deal with the quantitative assessment of the time and effort needed to prepare and conduct performance simulation studies. In a study of HVAC (heating, ventilation, air-conditioning) simulation process, Madjidi and Bauer (1995) show that the bulk of the time needed for detailed HVAC simulations is spent to collect HVAC systems data. The time required for the generation of the building model is comparatively less time-consuming. Bazjanac (2001) argues that the majority of time in the preparation of input data for energy performance simulation is spent on describing the building geometry. De Wilde (2004) reports that the energy simulation for a simple building required a full-time effort of two working days from an experienced doctoral student.

2. Approach

2.1 Overview

The time expenditure of 25 senior architecture students was documented as they evaluated the energy performance of six project submissions for a school building design competition (see section 2.4.1.). Moreover, the time needed by the author to analyze the life cycle performance of these designs was documented (see section 2.2.). Additionally, these energy and life-cycle evaluations were compared with the results of a qualitative assessment of the overall performance of the school designs by 14 senior architecture students (see section 2.5.1). Finally, the results were compared to the official verdict of the competition's actual jury (see section 2.4.2.).

2.2. ENERGY SIMULATION STUDY

The objective of this study was to estimate the time and effort needed to apply an energy simulation tool to assess and improve the energy performance of building designs. To emulate a preliminary design situation an appropriate level of resolution for the initial designs had to be identified. A total of 25 senior architecture students participated in the study, which constituted the primary content of a semester-long elective course on building performance modelling and evaluation. All students had previously attended a course on the fundamentals of thermal performance of buildings (involving a time investment of approximately 60 hours). The students were organized in terms of 10 groups (G_1 to G_10). Each group was required to analyze and report on the energy performance of a given design using an energy performance simulation tool. Moreover, a thermally improved version of the initial design was required as part of the students' final analysis report. Thereby, changes were to be suggested only to component properties; the basic geometry and massing of the buildings was to be preserved.
Six submissions to a school design competition were selected as sample designs (P_1 to P_6). As such, they represented typical instances of preliminary designs. An overview of these six designs is provided in section 3.3. The Key to the allocation of projects to groups is provided in Table 1.

Table 1. Key to the allocation of projects to groups

Group	1	2	3	4	5	6	7	8	9	10
Project	1	1	2	2	3	3	4	4	5	6

The energy performance of the designs was to be expressed primarily in terms of heating load (in kWh per project, $kWhm^{-2}$ net floor area, and $kWh\ m^{-3}$ built volume). Given the local climatic conditions at the designated building site (in upper Austria) and its pattern of use as a school, it was expected that the buildings would perform satisfactorily without cooling requirement.

Simulations were performed using Ecotect (Ecotect 2003). This tool is appropriate for energy performance assessment in the early stages of design and thus suitable for the present case study, which addresses the potential of tool usage by architects, rather than energy specialists.

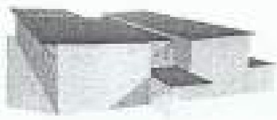
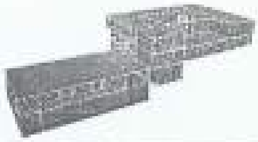
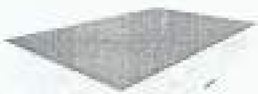
At the beginning of the study, the participating students were given an introductory tutorial for the selected energy simulation tool, requiring a time investment of approximately 10 hours. Throughout the study, the students were required to maintain a log reflecting their time expenditures for:

i) Creating a simple building geometry model in a conventional CAD environment (AutoCAD 2002);
ii) Transferring the CAD model into the energy simulation tool and preparing it for simulation – thermal properties of the main building components as well as typical occupancy and equipment schedules were provided to the participants;
iii) Performing the simulations for the initial design and possible iterations;
iv) Documentation of the results in terms of an analysis report.

The majority of the participating students already possessed proficiency in the use of the CAD tool prior to the commencement of the case study: The knowledge of such tools represents the standard part of a typical educational program in architecture (see also table 9).
Upon submission of the students' final reports, a comparative study of the time budgets of each group was performed (see section 3.1).
For benchmarking and comparison purposes, the energy performance of all six schools was also obtained independently by the author based on the same building information and using the same energy simulation tool.
To assess the backgrounds and attitudes of the participating students with regard to the value and potential of computational modelling tools, they were asked to fill a questionnaire before the start and after the completion of the case studies. The questions concerned: i) their educational background; ii) their general knowledge in the CAD (computer-aided design) area; iii) their previous experiences (if any) with building performance simulation application; iv) their previous experiences (if any)

with data exchange between CAD and performance simulation applications; vi) their opinions regarding the respective responsibilities of architects and specialist in conducting building performance simulation studies.

Table 2. Summary information on the six school design submissions,

Project	Net floor area (m²)	Volume (m³)	3D-representation
Project_1	2290	8402	
Project_2	1779	7478	
Project_3	2861	9245	
Project_4	1829	6688	
Project_5	2320	8085	
Project_6	2096	10043	

2.3 LCA Study

The objective of this study was to estimate the time and effort needed to apply a computational LCA tool to assess the ecological performance of the six previously mentioned school projects. The author applied the tool BEAT 2002 to conduct the computations. For architectural LCA of preliminary designs, this tool may be said to represent the proper level of complexity. The author had acquired the fundamentals of LCA as well as the know-how to run the tool via self-learning (time investment approximately 160 hours and 40 hours respectively). The author's effort for the LCA study of the six schools was captured in terms of time investment for: i) project data base generation; ii) modeling in BEAT 2002; and iii) documentation of the results. Specifically, out of the spectrum of indicators that can be computed using this application, nine environmental performance indicators were selected and the corresponding values were computed for the six previously mentioned school design project submissions. These indicators are listed in the following Table 3.

In order to perform the computation of the environmental indicators, for the six projects with BEAT, the following steps were followed:

i) A list of materials and components was generated for all designs;
ii) The availability of material and component descriptions in the BEAT's default database was checked;
iii) Necessary new materials were specified indicating name, dry density, and transport density;
iv) Necessary new products were specified indicating name, dry density, transport density and the description of the materials (and potentially other products) involved. At this stage, the emissions to air, liquid effluents and solid waste associated with the product are specified.
v) Necessary new building components were specified in terms name, unit, and life-time, as well as the list of their constitutive products and materials.
vi) A new building was specified in terms of name, basic building form ("I", "L", "U", "T"), expected life-time,

building type (e.g. office, school, residential), number of floors, number and size of the windows, existence of basement, operation energy demand (operational), as well as the list of all constitutive building components with their dimensions.

vii) Execution of the computation and results output.

Table 3. Computed environmental performance indicators.

Indicator	Symbol	Unit	Definition
Global warming potential	GWP	t(CO_2)	The atmosphere warming which increased as a result to the human activities which lead to accumulate CO_2, N_2O and CH_4 in the atmosphere.
Acidification potential	AP	t(SO_2)	The emissions which converted to acid and falls into a sensitive area in the earth.
Nutrient enrichment Potential	NP	t(NO_2)	The Nutrients which are important for the growth of flora and fauna. Which determine the extent to which living organisms can survive
Human toxicity	HT	t	Chemicals emitted as results of human activities can contribute to human toxicity.
Photochemical ozone formation	POCP	t	The Ozone formation in the atmosphere in the presence of sun light and Oxides of Nitrogen (NO_x)
Hazardous waste	HW	t	The quantity of Hazardous waste from rock wool and unspecified substances.
Bulk waste	BW	t	The waste from Bulk waste ending up in landfills
Ozone depletion potential	ODP	t	Ozone gas in the atmosphere, which protect the earth from the harmful ultraviolet radiation by absorbing it.
Embodied energy	EE	GJ	The quantity of energy required by all of the activities associated with a production process

2.4. Additional considerations

2.4.1 Eco-point study

To compare the computational LCA exercise presented above with a more conventional performance evaluation approach, a group of 14 students evaluated the previously mentioned six school designs using a qualitative method (Panzhauser 2000) involving the assignment of "Eco-points" to various environmentally relevant features of the buildings. The students, who were given an introductory background in building ecology (time investment approximately 40 hours), rated the ecological performance of designs by benchmarking them in terms of the following categories: i) energy performance; ii) health performance; iii) contextual performance. In a manner similar to other methods using the concept of Eco-points, points awarded to each project in these three categories were summed up to establish an overall ecological performance index for comparative project ranking purposes. Table 4 shows these three performance categories with their respective sub-categories. Rough estimations and qualitative judgments are used as the basis of Eco-point assignment. Note that the points scale allows, for some of the sub-categories, to assign negative points. Additional details about the rules and criteria for the assignment of Eco-points in this specific approach may be found in Panzhauser 2000.

Table 4. Environmental performance categories and sub-categories after Eco-point method

Environmental performance category	Environmental performance sub-category	Maximal assignable points
1. Energy	1.1. Building enclosure	10
	1.2. Heating/cooling systems	7
	1.3. Energy source	10
	∑ Eco-points(energy performance)	27
2. Context	2.1 General design /architecture factors	8
	2.2 Infrastructure	5
	2.3 Risk factors (fire, flood, avallanges, etc.)	5
	2.4 Water	5
	2.5. Biodiversity	5
	2.6. Valuable materials	5
	∑Eco-points(contextual performance)	33
3. Health	3.1. Thermal conditions (winter)	5
	3.2.Thermal conditions (summer)	5
	3.3. Ventilation	5
	3.4. Isolation (winter)	5
	3.5. Daylight	5
	3.6. Acoustics	5
	3.7. Architectural barriers	5
	3.8. Indoor air humidity and quality	5
	∑Eco-points(health performance)	40
∑ Eco-points (total)		100

2.4.2 Jury

As mentioned before, the six designs that constituted the sample for the above case studies were actual project submissions by actual architectural firms for an official school design competition. The author was provided with a summary protocol of the official jury deliberations leading to the selection of the winner project and the exclusion of others. The sequence of this exclusion process was interpreted by the author as the jury's verdict with the results of the students' computational evaluation of the energy and life-cycle performance of the designs involved, as the jury took little note of energy and environmental performance criteria in its deliberations.

3. Results

3.1. Overview

Section 3.2 includes the results of the energy performance simulation study together with associated material and observations. Section 3.3 summarizes the results of the environmental performance study using a computational LCA tool. The results of the environmental evaluatiori exercise based on an Eco-point method are given in section 3.4.1. Finally, Section 3.4.2. Provides information on the outcome of the design competition jury's deliberations.

3.2. Energy Analysis

Figure 1 illustrates the energy performance of the six original projects (in terms of annual heating load in kWh), as simulated by the 10 student groups. For comparison purposes, the figure also includes the energy performance as simulated by the author. Taking the later simulation as the "Correct" reference, table 5 lists the deviation of student's results from the reference values together with the main reasons (modeling errors) for the deviations and their frequency. These errors could be classified into four broad categories corresponding to component, geometry, zone, and material descriptions (see table 6). As a further illustration, table 7 provides instances of such errors.

Table 5. The simulated energy performance of the six design projects (annual heating load) compared to reference simulation results

Group	Project	Students $kWh.a^{-1}$	Reference $kWh.a^{-1}$	Deviation [%]
G_1	P_1	78160	91515	- 17,1
G_2	P_1	71910	91515	-15,4
G_3	P_2	67196	87548	-27,3
G_4	P_2	74478	87548	-17,5
G_5	P_3	197112	134690	31,6
G_6	P_3	116400	134690	-13.5
G_7	P_4	137325	96757	29.5
G_8	P_4	83976	96757	- 15,4
G_9	P_5	83016	72535	12,6
G_10	P_6	100945	93616	7,2

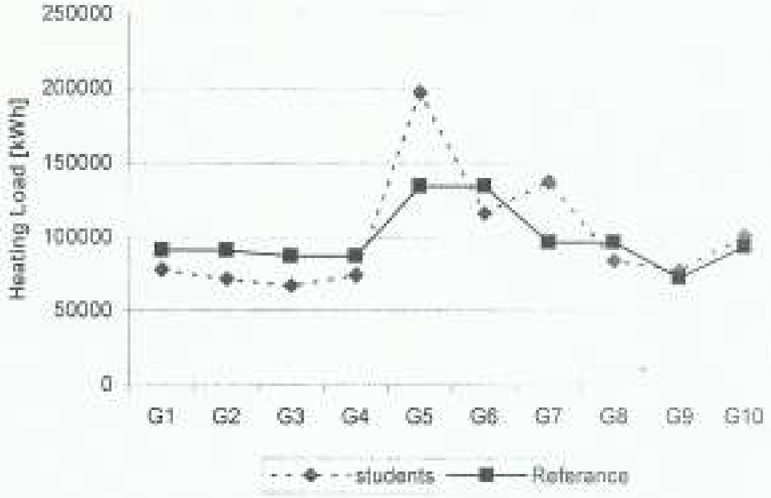


Figure 1. Simulated energy performance of the six design projects (annual heating load) compared to reference simulation results

Table 6. The relative deviation of heating loads of the six projects as simulated by 10 student groups from reference simulations together with typical simulation error types (C: component description; Z: zone settings; M: material description) and their frequency (high:+++; medium: ++; low: +; nothing: -)

Group	Project	Deviation[%]	Error C	Error G	Error Z	Error M
1	1	- 17,1	++	+	-	-
2		-15,4	+++	+	-	-
3	2	-27,3	+	+	++	-
4		-17,5	++	+	-	-
5	3	31,6	++	-	+++	-
6		-13.5	+	+	++	-
7	4	29.5	+++	-	-	+
8		- 15,4	+++	-	-	+
9	5	12,6	-	++	+	-
10	6	7,2	+	+	-	-

Table 7. Types and instances of modeling errors

Error type	Instance
C Component description	Error in the layer sequence of a multi-layered building component
G Geometry description	Erroneous room dimensions
Z Zone settings	Error in internal load assumptions (magnitude and schedule)
M Material description	Error in the value of thermal transmittance of an external wall

As mentioned earlier, the students groups were required to use simulation to come up with a thermally improved version of the initial design (via changing component properties). Figure 2. shows the simulated heating loads of the initial designs together with those of the improved version. Table 8 expresses the corresponding simulated performance improvement (heating load reduction) in percentage. Broadly speaking, two types of design changes were responsible for the energy performance improvements in the course of simulation studies. The first type involved the improvement of the thermal insulation properties of building enclosure components (beyond the standard assumptions in the design competition submissions). The second type involved changes in the dimensions of the transparent building enclosure components.

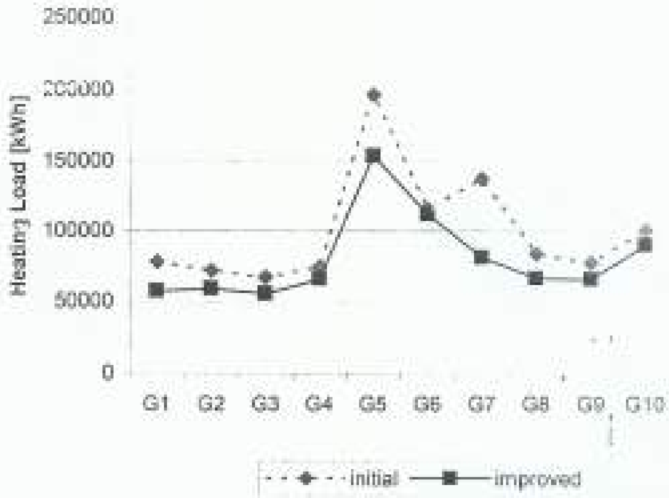


Figure 2. Simulated energy performances of the original and improved versions of the six design projects.

Table 8. Simulated heating load reduction as a result of design improvements.

Group	project	Initial simulation kWh. a^{-1}	Improved simulation kWh. a^{-1}	Percentage of reduction[%]
G_1	P_1	78160	57596	26
G_2		71910	59212	18
G_3	P_2	67196	55779	17
G_4		74478	66377	11
G_5	P_3	197112	153876	22
G_6		116400	112313	4
G_7	P_4	137325	81338	41
G_8		83976	66377	21
G_9	P_5	77224	65640	15
G_10	P_6	100495	90046	10

It was mentioned before that the participating students were required to document their time expenditures (in hours) for various modeling tasks in the course of the case study. The results of this documentation are given in table 9. They involve time spent (per group) on, i) generating a simple geometric model (2D) of the design in a CAD environment; ii) transferring the geometry model to the energy simulation tool and adding the necessary semantic information; iii) performing the simulation runs; iv) documenting the simulation results. Note that the times given in Table 9 include also the time needed for the simulation of a number of design changes (about five iterations per group averaged over all groups) involving modifications of the thermal properties of enclosure components and the size of openings in the enclosure. For comparison purposes, table 9 includes also, next to the times for each group, reference times as needed for the same modeling tasks by the author.

Table 9. Overview of the time expenditures (in hours) by the participating students groups (together with reference times of the author).

Group	Project	CAD model	Energy model	Simulation runs	Documentation of the results	Total time/ project
1	1	4.5	14.0	12.0	4.0	34.5
2	1	3.0	16.5	9.0	3.0	31.5
Ref.	1	5.0	15.8	5.0	7.8	33.5
3	2	2.0	9.0	18.5	8.0	37.5
4	2	8.0	15.0	6.0	1.5	30.5
Ref.	2	6.0	13.0	7.0	8.8	34.8
5	3	4.5	23.5	12.5	10.0	50.5
6	3	4.0	14.0	5.0	6.0	29.0
Ref.	3	7.0	10.8	4.0	5.8	27.5
7	4	4.5	16.0	5.0	4.0	29.5
8	4	4.5	16.0	12.5	7.5	40.5
Ref.	4	8.0	13.0	4.0	5.8	27.5
9	5	4.5	15.0	10.0	6.0	35.5
Ref.	5	4.0	10.0	4.0	6.8	24.8
10	6	6.0	11.0	8.0	10.0	35.0
Ref.	6	4.5	7.5	4.0	7.8	23.8
Mean(students)		**4.6**	**15.0**	**9.9**	**6.0**	**35.4**
STD(Students)		1.6	3.1	4.2	2.9	6.5
Mean(Ref.)		5.7	11.7	4.7	7.4	29.5
STD(Ref.)		1.5	2.9	1.2	1.0	4.8

As mentioned earlier, a questionnaire was filled by the participating students before and after the case studies mainly to gauge possible effects of the simulation work on their attitudes toward computational building evaluation. Selected results from this survey are summarized in Table 10.

Table 10. Selected results from students' questionnaire

Question	Answers	
	Before	After
How do you characterize your CAD knowledge?	32% very good 59% average 9% none	41% very good 54% average 5% none
Do you have experience in simulation applications?	9% yes 91% no	100% yes 0% no
Do you have experience in data exchange between CAD and simulation tools?	0% yes 100% no	27% yes 73% no
Can simulation significantly improve design quality?	82% yes 18% not sure	86% yes 14% not sure
Should architects or specialists conduct performance simulations?	77% architects 14% specialists 9% not sure	77% architects 14% specialists 9% not sure

3.3. LCA Study

The overall results of the environmental assessment of the six schools (projects P_1 to P_6) are summarized in table 2.

Table 11. Computed environmental performance indicators for six design projects

Indicator	P_1	P_2	P_3	P_4	P_5	P_6
GWP[t]	289.3	442.9	831.0	339.9	446.3	342.3
ODP[t]	41.5	3.2	7.5	130.0	67.1	4.3
AP[t]	6.4	52.5	63.6	66.4	2.2	7.6
NP[t]	7.4	2.0	14.9	1.0	1.7	7.2
HT[t.10^3]	134.8	1375.9	1594.2	1654.8	92.2	181.8
POCP[t]	0.07	0.03	0.09	0.03	0.21	0.27
HW[t]	1.2	4.5	8.2	1.1	5.4	3.7
BW[t]	15.7	41.1	16.1	11.9	19.2	21.9
EE[J.10^{12}]	18.1	7.3	3.5	3.4	5.3	17.1

In order to obtain a clearer overview of the relative environmental performance of the six projects, Figure 3 illustrates the results in terms of relative indices. For each category, the worst performing design was given the index value of 0. The performance of other schools was derived by proportionally relating their actual indicator value to the indicator value of the worst performing school in that category: Let Z_{ij} be the absolute and $Z_{r,ij}$ the relative values of the j environmental indicators of the I schools. Let Z_{wj} be the absolute indicator value for the worst performing design in category j. The relative indicator values of the other schools in that category were derived as per the following equation:

$$Z_{r,ij} = \left[1 - \frac{Z_{ij}}{z_{w,j}} \right] .100 \qquad (1)$$

Table 12. The relative indicator values of the six design projects in [%]

	P_1	P_2	P_3	P_4	P_5	P_6	Weighting points
GWP	65	47	0,0	59	46	59	15
ODP	70	98	95	0,0	52	97	10
AP	90	21	4	0,0	97	88	10
NP	50	86	0,0	93	88	52	10
HT	92	17	4	0,0	94	90	15
POCP	74	88	65	88	21	0,0	10
HW	86	46	0,0	87	35	56	10
BW	62	0,0	61	79	52	47	10
EE	48	79	0,0	90	85	51	10
Total % WP	68,5	55	25	49,4	60,2	56,7	

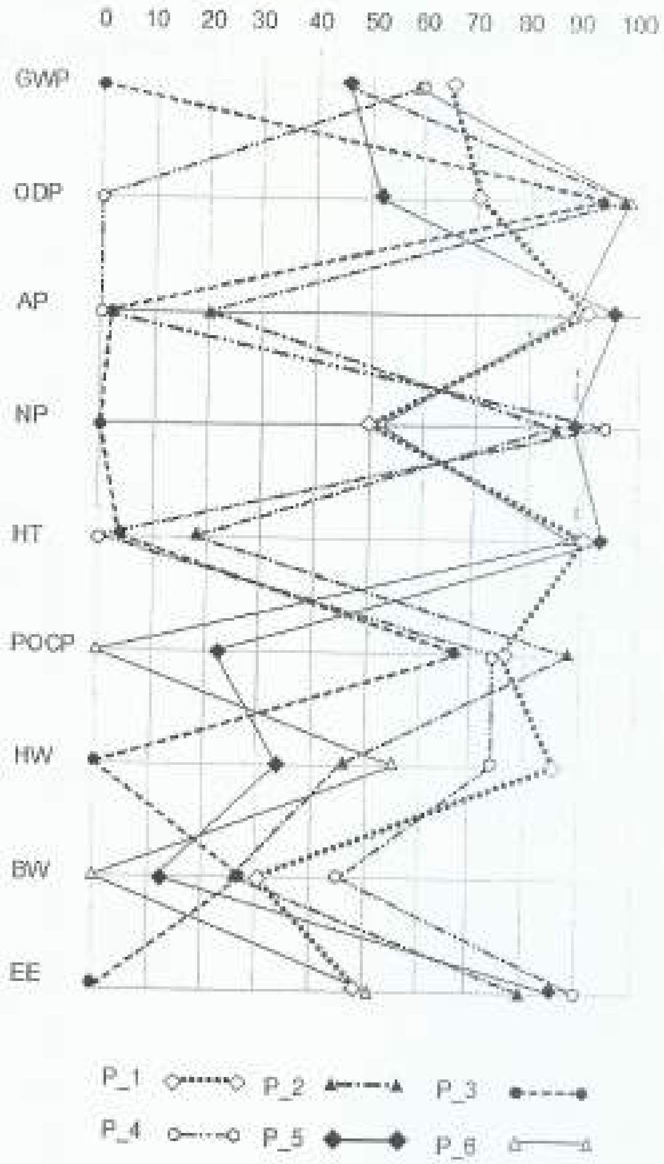


Figure 3. Calculated relative performance of six design projects (P_1 to P_6) in terms of nine environmental impact indicators

The time expenditures of the author for i) modeling the six buildings in the LCA tool and ii) documenting the results were also documented and are shown in Table 13. Note that the information in this table does not include the time needed for the generation of the project database, which amounts to approximately 24 hours for a new project with the size and complexity comparable to the design submissions considered in the present study. Once a project database is generated, the time needed for the generation of databases for similar projects (sharing a number of building materials and components) can be reduced down to about 50%.

Table 13. Time required by the author for the computational LCA of six design projects

Project	LCA Modeling (hours)	Documentation (hours)	Total time/Project (hours)
1	15	12	27
2	12	12	24
3	11	11	22
4	11	11	22
5	10	10	20
6	10	10	20
Mean	11.5	11	22.5
STD	1.9	0.9	2.7

3.4. ECO-Point study

The results of the comparative project evaluation by the 14 participating students based on the previously described Eco-point method (see section 2.4.1) are summarized in table 14.

Table 14. Students' evaluation of the environmental performance of six school design projects via assignment of Eco-points.

Performance category	Performance sub-category	P_1	P_2	P_3	P_4	P_5	P_6
1. Energy	1.1. building enclosure	8	8	7	8	9	8
	1.2.Heating/Cooling	6	5	5	5	6	5
	1.3. Energy source	9 10	9	9	9	10	10
	∑ eco-points(Energy)	23	22	21	22	25	23
2. Context	2.1 Design/Architecture	2	1	2,5	3	5	3
	2.2 Infrastructure	3	3	4	3	5	5
	2.3 Risk factors	5	5	5	5	5	5
	2.4. Water	0	0	0	0	0	0
	2.5. Biodiversity	0	0	0	0	0	0
	2.6. materials	1	2	2	2	2	0
	∑ eco-point, Context	11	11	13,5	13	17	13
3. Health	3.1winter conditions	5	5	5	5	5	5
	3.2.Summer conditions	3	4	2	3	5	3
	3.3. Ventilation	3	4	4	3	3	3
	3.4 Isolation	5	5	5	5	5	5
	3.5. Daylight	4	2	5	2	4	5
	3.6. Acoustics	4	4	4	4	4	4
	3.7. Barriers	2	4	4	4	5	3
	3.8. Air quality	5	5	5	5	5	5
	∑Eco-point, health	31	33	34	31	36	33
∑Eco-point, for the projects		65	66	68,5	66	78	69

3.5 Jury's evaluation

The jury's discussions did not result in an explicit ranking of the six design submissions, but merely provided an official winner project. However, a kind of ranking may be extracted from the protocol of jury's deliberations based on the sequence of jury's discussions. Table 15 provides a summary sequence of jury's discussions. The implied ranking together with the associated points are reproduced in Table 16. The process for the assignment of these points was as follows. 100 points were allocated to the winner project. Five points per project was subtracted based on the position of a project in the order of exclusion. An additional 10 points was subtracted from a project if the decision to exclude it was met unanimously.

Table 15. Summary of the design competition jury's discussions

Phase	Remark
1	First orientation round, general appraisal and discussion of all projects
2	Second orientation round, general discussion of the advantages
3	The request to exclude P_2 (based on "urban and architectural deficiencies") is met with unanimous approval
4	The request to exclude P_4 (based on "site planning and functional deficiencies") is met with unanimous approval
5	The request to exclude P_6 (based on "adaptability and entrance solution deficiencies") is approved based on majority vote
6	The request to exclude P_1 (based on "architectural and functional deficiencies") is met with unanimous approval
7	A detailed discussion of the remaining two projects(circling around specific design features and code compliance issues) leads to the exclusion of P_3 based on majority vote
8	P_5 is selected as the winner project

Table 16. Project ranking based on implicit considerations in the deliberations of the design competition's jury (see Table 15)

Project	P_5	P_3	P_6	P_1	P_4	P_2
Rank	1	2	3	4	5	6
Points	100	95	85	80	70	60

4. Discussion

4.1 Time matters

Consider the following scenario. A novice designer with an educational background in architecture (involving at least a semester-long course on the fundamentals of thermal performance of buildings) needs to estimate the energy performance (heating load) of a roughly 2200 m² building based on a preliminary design. The assessment should explore possible energy performance improvements (around 20% heating load reduction) via design changes (involving roughly five iterations on component properties and dimensions). Moreover, predictions should not deviate more than ± 20% from predictions made by a more experienced tool user.
For this scenario, our study implies a required time expenditure of about 30 to 40 person-hours (see table 9). Figure 4 illustrates the portions of this time spent toward generating the building model for simulation, running the simulations, and documenting the results.

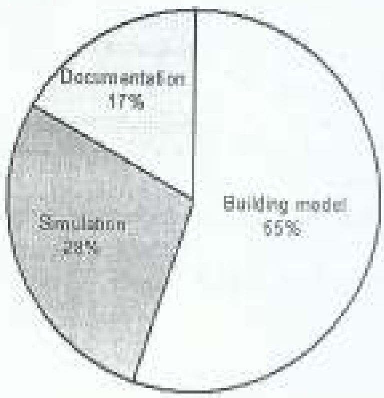


Figure 4. Time allotment for various energy simulation-related tasks

Given the overall time budget for the design of a building it is concluded that time expenditure requirement alone does not explain the paucity of energy simulation tool usage by architects in the preliminary stages of design. The required domain knowledge is an integral part of the educational curricular of most architecture schools; it may be updated via a reasonable investment in continued education, as expected from professionals in general. As to the tools and their usability, more performance simulation tools have become available recently that are suited for use in early stages of design. Such tools are not more difficult to use than typical CAD tools used by almost all architects (Mahdavi et al. 2003). Reasons for lack of use must be found somewhere else.

We must note, however, that time expenditure requirements for simulation-based thermal performance analysis can of course quickly go beyond the specifies of the above scenario. It might be the case that more design iteration would be desirable (involving also changes in building geometry). Likewise, further performance indicators (e.g. those addressing thermal comfort issues in the summer period, daylight availability) may have to be considered. One could argue that some additional simulation efforts beyond those considered in the above scenario would be still within the architects' realm of possibilities both in term of time investment and required expertise. However, in order to judge this question in a reasoned manner, a versatile time estimation instrument would be required. Such an instrument could consider various dimensions of a simulation study in terms of the factors that affect the required effort for simulation. Table 17 includes the primary dimensions of such a "simulation effort space".

Table 17. Some basic dimensions of the "simulation effort space"

Dimension	Remark
Size	The physical dimensions of the project
Complexity	The complexity of the form and assembly of the design
Resolution	Preliminary versus detailed design
Semantic iterations	Number of modifications to the building form, massing, and topology
Geometric iterations	Number of modifications to the building form, massing, and topology
Performance indicators	Types and number of performance indicators (energy, light, acoustics...)
Simulators experience	Novice versus expert tool user

This specific case study (see section 3.2 and Table 9) provides basic clues with regard to some of the dimensions of Table 15. For example, figure 5. shows the implications of a design's size (expressed in terms of net project floor area) for a) modeling time, and b) total time required for analysis. Figure 6 illustrates time requirement implications of the simulator's experience. We combined these results with additional (heuristic) assumptions regarding the remaining dimensions of the simulation effort space, to develop and test a demonstrative prototype simulation time estimation tool. Figure 5 provides a few illustrative examples of predictions using this tool. Thereby the relationship between project size and the total required simulation study time are estimated for three different scenarios as described in table 18. It was assumed that: i) all projects had low levels of resolution and complexity; ii) all performance indicators could be computed using the same performance simulation application. Low intermediate and high levels of experiences were denoted with 1, 2 and 3 respectively.

Note that figure 5 is merely meant to illustrate the potential toward estimation on the dimensions of the simulation effort based on various pieces of information on the dimensions of the simulation effort space. The tool's underlying knowledge-base is quite rudimentary at this point and needs to be substantiated in future.

Table 18. Illustrative simulation study scenarios depicted in Figure 5

Number of:	Scenario 1	Scenario 2	Scenario 3
Semantic iterations	10	5	3
Geometric iterations	4	3	2
Performance indicators	3	2	1
Level of expertise	1	2	3

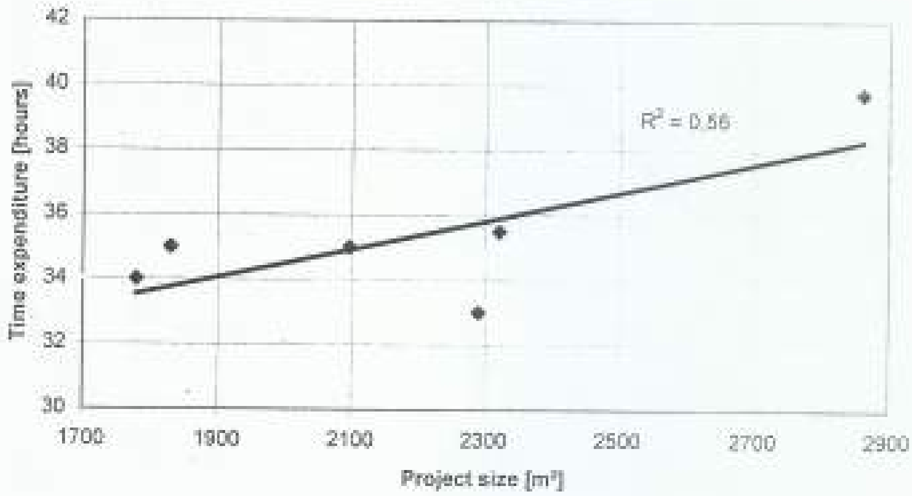


Figure 5. Simulation time investments as a function of project size

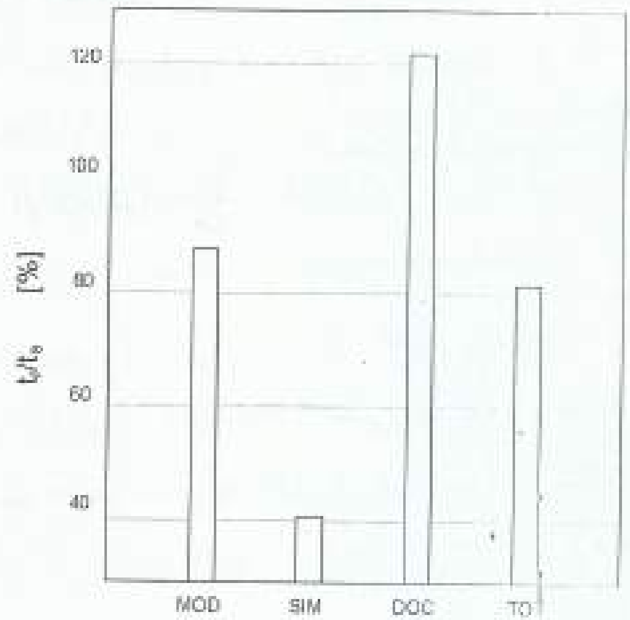


Figure 6. Simulation time investments as a function of the simulator's experience level

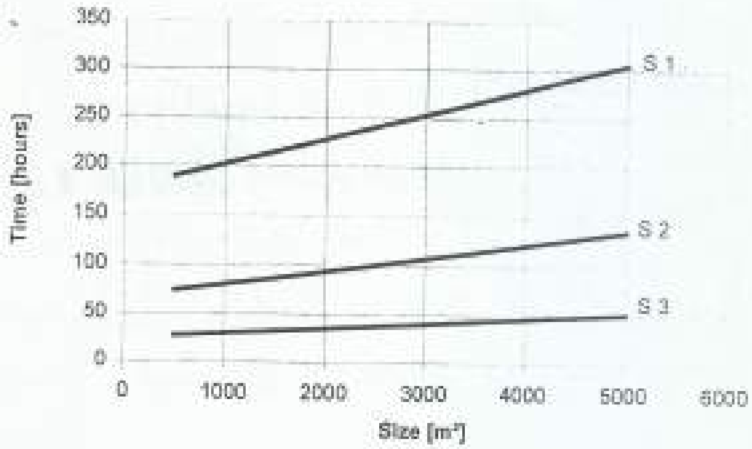


Figure 7. Illustrative examples of time requirements as a function of project size for three different simulation studies (scenarios 1 to 3 as per table 18)

The previous discussion of the required simulation effort and its estimation circled around those performance indicators, which are covered in typical architectural curricula (e.g. heating load, indoor air temperature). Yet, increasingly, energy performance is being viewed as just one of the many parameters to be factored in the evaluation of a building design.

According to this view, the environmental impact associated with building construction and operation, for example, must not only consider energy use during the operation phase but many other processes (involving embodied energy, emission of green house gases, etc.). To accommodate these additional considerations, a comprehensive environmental LCA would be necessary as exemplified in section 3.3 in view of required time and expertise. However, such a comprehensive analysis represents a different scenario from the energy simulation case. A novice designer with an educational background in architecture who intends to perform a computational LCA study would have to spend about 200 hours to acquire the required domain knowledge and to learn to use a proper tool. (This estimation is based on a self-study scenario and may be reduced if a formal LCA course and tool tutorial option is available.). To our knowledge, few architectural firms could or would be prepared to consider such level of investment, unless corresponding code compliance requirements are set in place and commensurate adjustments to the professional design fee structure have been made.

Given the scenario of a designer with knowledge of LCA and corresponding tools, the actual time required to calculate the environmental performance of preliminary building designs is, however, not excessive: our case study (see section 3.3, table 1) suggests a time requirement estimation of about 40 to 50 person-hours for the LCA of a preliminary design (competition submission) for a roughly 2200 m² building. Figure 8 illustrates the fraction of this time spent toward generating the project database, LCA modeling, and documentation.

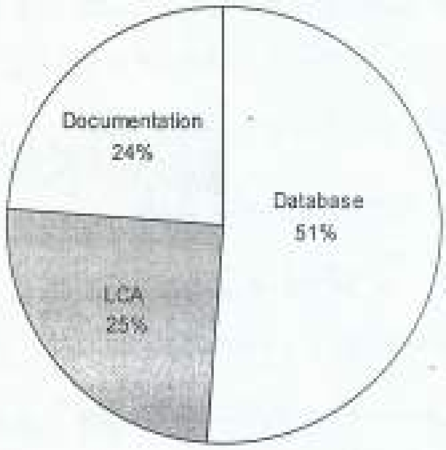


Figure 8. Time allotment for various LCA-related tasks

4.2. Considerations of effectiveness

In all those cases where clear and concise building performance guidelines and codes are available, the derivation and interpretation of corresponding performance indicator. Heating load or predicted annual energy use are examples of such indicators. We do not mean to imply that providing evidence for code compliance is the sole (or even the most important) mode of using performance simulation to support design: much more can be learned about the future performance of an actual building through simulation of its behavior in the design phase.
Nonetheless, this code compliance or benchmarking functionality of performance simulation is well-understood in principle by practitioners and is becoming more of a routine component of the building design process. Heating load, for example, may be quite a limited indicator in that it represents only one of the many indicators of a design's quality. But given a proper simulation code and procedure, it is possible in principle to derive and interpret its value in a conclusive manner. The same cannot be said of other indicators considered in this contribution. For example, LCA tools can provide a very large set of diverse environmentally relevant indicators. Not only it is rather difficult and cumbersome to assemble reliable input information for such assessments, but also it is quite a challenge to interpret their results.

In this regard, figure 3 provides a point in case. Even though the results of the analysis have been expressed here in relative terms, it is not easy to gain a clear impression as to the relative environmental performance of the six projects involved. It is of course possible to derive a weighted average of multiple indicators in terms of a single aggregate indicator of environmental performance, to demonstrate this possibility, figure 9 includes such a weighting approaches is often inconclusive and difficult to objectify, but the reasoning behind such weighting approaches is often inconclusive and difficult to objectify. To makes matters more complicated, a project ranking based on energy performance alone does not necessarily agree with a LCA-based ranking (cp. Figure 9, table 19.)

In this context, a conjecture may be appropriate. When we move from limited, concrete, and quantitative indicators to more comprehensive evaluation perspectives, we inadvertently lose on the conclusiveness of our evaluative tools and their results. For example, the Eco-Point evaluation approach (as exemplified in section 3.4) uses a mixed quantitative and qualitative approach to consider a wide spectrum of performance sub-categories. But the process is affected by subjective moments and the results are difficult to reproduce. Figure 9 includes next to energy and LCA indicators for the six design submissions, also the ranking of the projects based on Eco-Point assignments expressed in relative terms (computed using the values in Table 4 and applying a numeric adjustment process analogous to the one captured in equation 1).

Even less traceable are the deliberations of typical design competition juries and their board and open-end verbal arguments concerning the merits and drawbacks of the competing projects. Our somewhat willfully extracted numeric version of the jury's rankings is also reproduced in figure 9 to round the picture of alternative design evaluation techniques and approaches discussed in this contribution. Table 19 summarizes project rankings based on energy simulation, LCA, Eco-Point, and jury verdict. Both figure 9 and table 19 reveal considerable divergences in the outcomes of the four procedures.

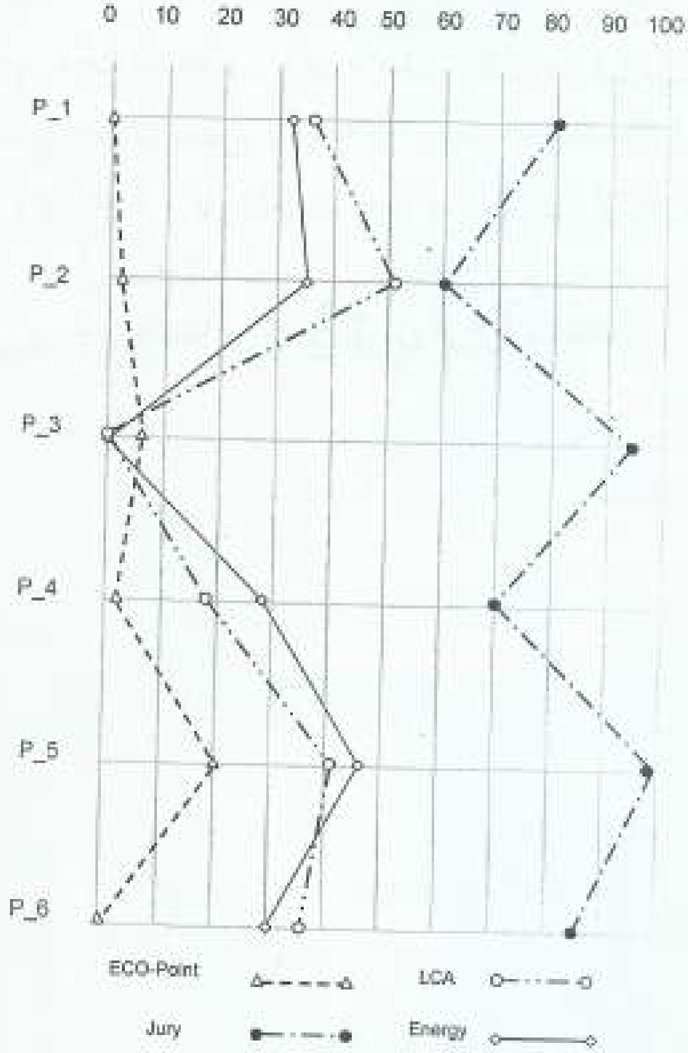


Figure 9. relative performance indicators based on energy (heating load), simulation, LCA, Eco-Point assignment and jury evaluation (0: poor, 100: good)

Table 19. summary of the six design project ranking based on heating load simulation, LCA, Eco-Point assessment, and jury evaluation

Project rank	Evaluation based on			
	Heating load	LCA	Eco-Point	Jury
1	P_5	P_2	P_5	P_5
2	P_2	P_5	P_3	P_3
3	P_1	P_6	P_2	P_6
4	P_6	P_1	P_4	P_1
5	P_4	P_4	P_1	P_4
6	P_3	P_3	P_6	P_2

We may conclude that the efforts to simultaneously maximize comprehensiveness and objective reproducibility in architectural design evaluation have not been successful. Performance simulation tools and other assessment processes provide us with various partial views and appraisals of designs. There remains a significant degree of choice on the side of an evaluator as to which of those partial views and appraisals (Including purely subjective impulses or mere first cost considerations) are made effective in the overall quality evaluation and design decision making processes. In as much as the role of purely scientific evaluation aids (those which can produce reproducible and observer-independent results) are concerned, one is almost tempted to adapt a Wittgenstein an stance: Evaluate that which can be evaluated and remain silent concerning the rest.

5. Conclusion

We may conclude that the efforts to simultaneously maximize comprehensiveness and objective reproducibility in architectural design evaluation have not been very successful. Performance simulation tools and other quantitative assessment processes provide us with various partial views and appraisals of designs. These are very useful, as they are – if properly generated – reproducible and observer-independent. But they are also partial, in that they usually have a very specific and technical scope. There remains a significant degree of choice on the side of an evaluator as to which of those partial views and appraisals, if any, are made effective in the overall design decision making and quality evaluation processes. This is not meant to devalue the role of assessment tools that aim at objectivity, but to point to the limitations of their role in the current building delivery process: the gap between the sum total of available analytical evidence about a design's attributes and an overall evaluative judgment regarding its quality can be filled in practice with all kinds of subjective impulses and bottom-line monetary considerations.

Appendix A

The Description of the design competition projects

The Case study

An architectural competition was selected as a case study. The project is primary school project in Marketgemeinde Weyer, Upper Austria.

Figure A.1. The Site of the School project in Weyer – Upper Austria

Project_1

Two longitudinal forms constitute classes and administration zone, organized by an aula in the ground floor and class zone in the upper floor.

Project data:

- Gross area 1282 m²
- Net floor area 2290 m²
- Total area = 1760 m²
- Volume 8047m³
- Facade area = 1215,78 m²
- Windows area = 337,18 m²
- Internal walls area = 401,4 m²

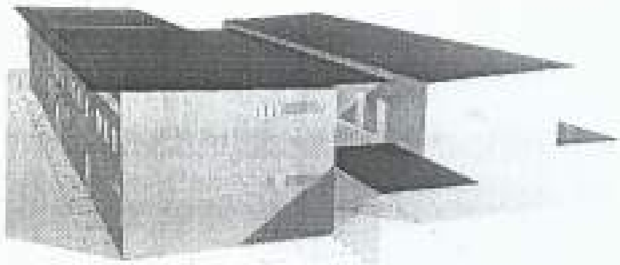


Figure A.2. View project_1

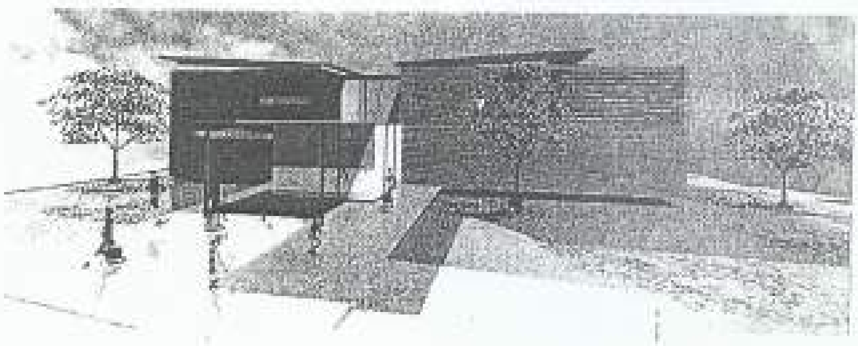


Figure A.3. North view project_1

Figure A.4. Ground floor plan project_1

Table A.1. The building components, project_1

Component	Construction
Interior walls	Chipboard, Novo pan, 621 Kg TS/m³, 1,6cm,10,8 kg/m² Insulation, rock wool, EU-rep Wood, cut up, 430 Kg TS/m³, 50.95 2,04 kg/m
Windows& Doors	Glass, sealed unit, 4 -12- 4, 20kg/m² Wood, Cut up, 430 kg TS/m³
Roof	Sealing sheet 2cm, OSB-plate 2cm, Cantilever arm/insulation rock wool 20 cm, timber beam floor, 28cm upper floor plate 5cm
Exterior walls	Battens sheet 3cm, Delta vat-OSB plate 20cm, OSB-plate 3cm, under construction sheet 5cm.
Floor	Parquet 1cm, Cement floating floor 7cm, insulation rock wool 20 cm, concrete 15cm
Ceiling	Parquet 1cm, Cement floating floor 7cm, insulation rock wool 3cm, sand 9cm, Board stable sheet 28cm, timber Plate 5cm .

Project_2

Approximately square form with approx. 35m side length accommodates the school rooms program.

Project data:

- Gross area = 1043 m²
- Net floor area = 1779m²
- total area = 1286, 55m²
- Volume = 7747 m³
- Facade area = 1076m²
- Windows area = 322,86m²
- Internal wall area = 1544,73m²

Figure A.5. View project_2

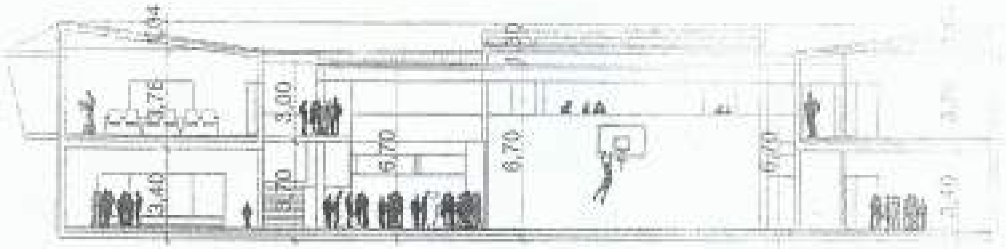


Figure A.6. Section project_2

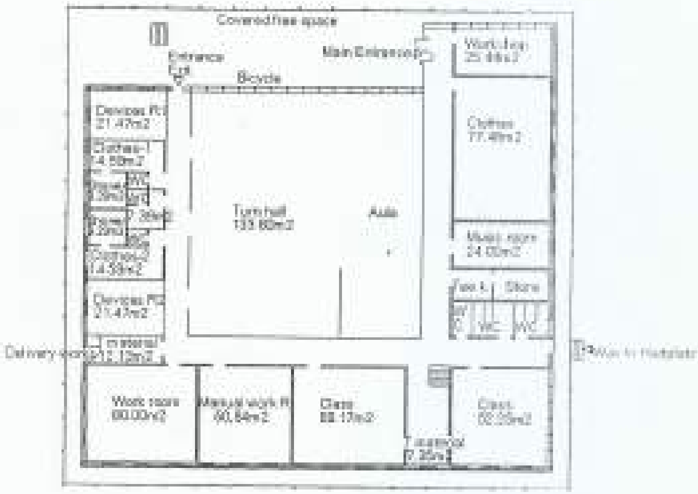


Figure A.7. Ground floor plan project_2

Table A.2. The building components, project_2

Component	Construction
Floor	Parquet 1cm, Cement floating floor 7cm, insulation rock wool 20cm, concrete 20cm
Exterior walls	3 - layers plate from prelate 2cm, Tyvek 0,2cm , insulation 15cm, wood panel 1,5cm
Ceiling	Linoleum 0,6cm, Cement floating floor 7cm, Insulation 30cm, sand 5cm, board layers wood 30cm
Roof	Tile roof 1,5cm, reek sheeting 25cm, Steam brake PE 2cm,chipboard 1,6cm, mineral compound 24cm, Gypsum board plate 2,5cm
Interior walls	Chipboard, Novo pan, 621 Kg TS/m³, 1,6cm, 10,8 kg/m²,Insulation rock wool EU-rep. Wood, cut up, 430 Kg TS/m³, 50.95 2,04 kg/m
Windows& Doors	Glass, sealed unit, 4 -12- 4, 20kg/m² Wood, Cut up, 430 kg TS/m³

Project_3

The two separate forms of the school and sport define the spatial organization.

Project data:

- Gross area = 1296m²
- Net floor area = 2861m²
- Total area = 2214m²
- Volume = 10765 m³
- Facade area =1146.23m²
- Windows area = 820,6m²
- Internal wall area = 1483,5m²

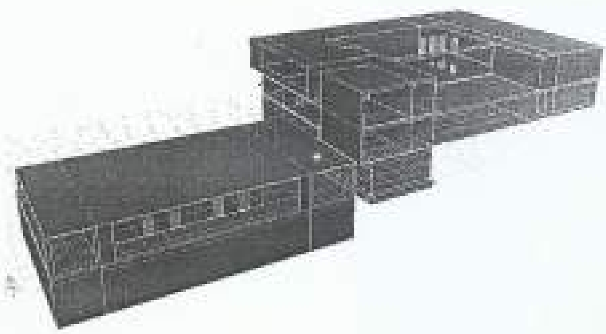


Figure A.8. View project_3

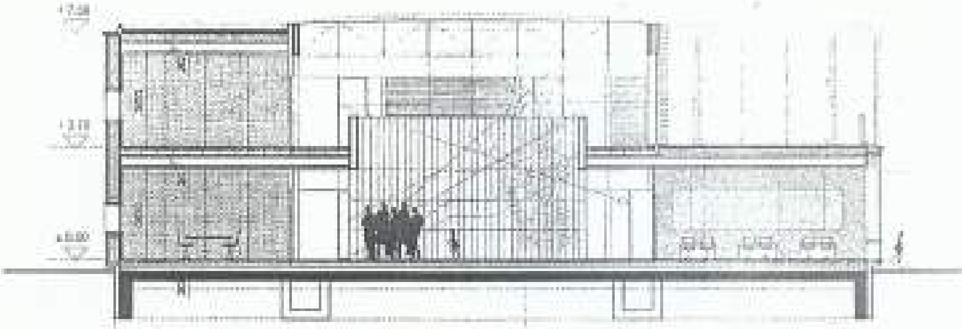


Figure A.9. Section project_3

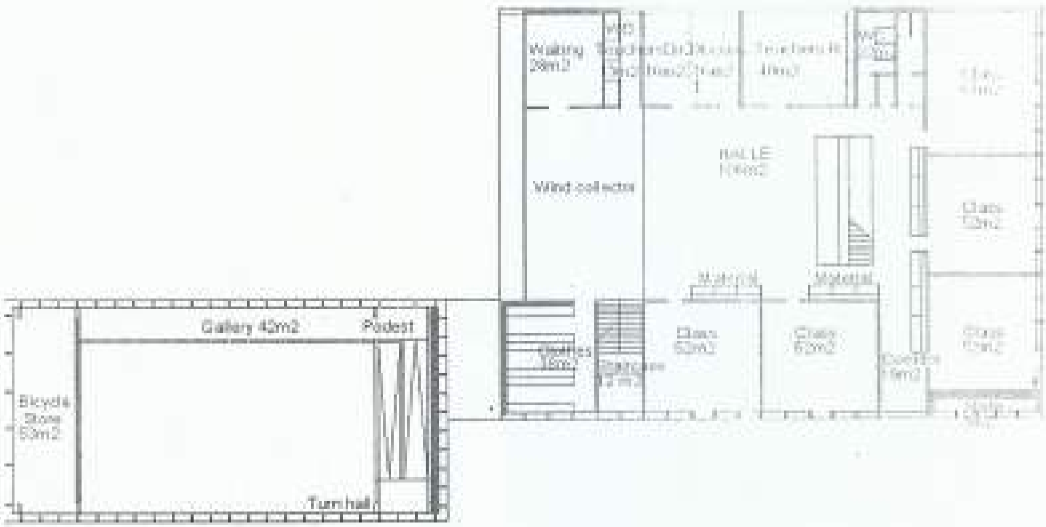


Figure A.10. Ground floor plan project_3

Table A.3. The building components, project_3

Component	Construction
Floor	Parquet 2cm,sound insulation rock wool 3cm, wood plate 2cm, distance timber stand 12cm, insulation 12cm, concrete plate 20cm
Exterior walls	2cm Wood plate, back ventilation+ wind paper 4cm, mdf - plate 2cm, timber beam panel/insulation 32cm, OSB-plate 1,5cm, Installation level 2,5cm, Loam plate 2,5cm.
Ceiling	Parquet 2cm, TDP insulation 3cm, wood plate 2cm, distance timber stand 12cm+insulation, massive wood sheets, installation level 2,5cm , Gypsum board plate 1,5 cm
Roof	Extensive green area 8cm, roof folio, OSB-plate, back ventilation wind paper 8cm, OSB-plate 1,5cm, Insulation rock wool, massive wood sheets 18cm, installation level 2,5cm, Gypsum board plate 1,5 cm
Interior walls	Chipboard, Novo pan, 621 Kg TS/m³, 1,6cm, 10,8 kg/m² Insulation, rock wool, EU-rep Wood, cut up, 430 Kg TS/m³, 50.95 2,04 kg/m
Windows& Doors	Glass, sealed unit, 4 -12 - 4, 20kg/m² Wood, Cut up, 430 kg TS/m³

Project_4

Compact U-shaped encloses a central two-level hall.

Project data:

- Gross area = 1194m²
- Net floor area = 1829m²
- Total area = 1479,25m²
- Volume = 7695 m³
- Facade area = 964,8m²
- Windows area = 305,1 m²
- Internal wall area = 354,7m²

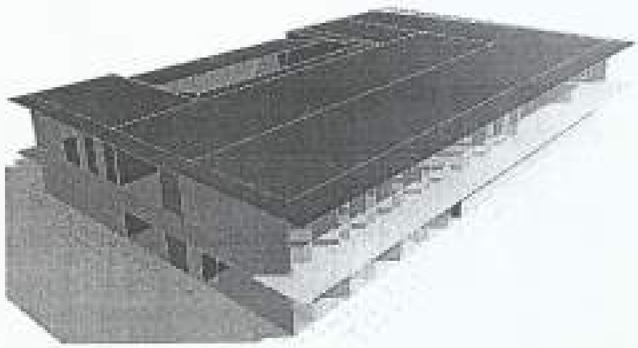


Figure A.11. View projekt_4

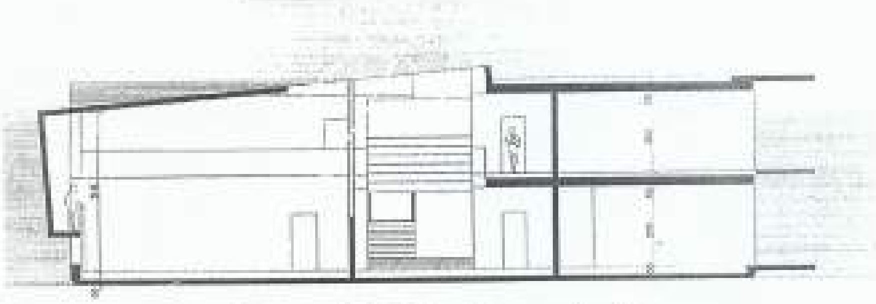


Figure A.12. Section project_4

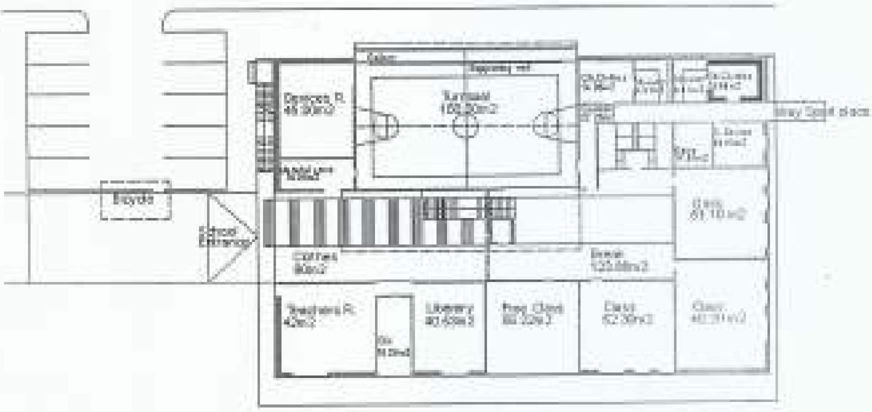


Figure A.13. Ground floor project_4

Table A.4.The building components, project_4

Component	Construction
Floor	Parquet 1cm, Cement floating floor 5cm,insulation rock wool 25cm, Sand 10cm, concrete plate 20cm.
Exterior walls	Loam plate 2,5cm, lath wood panel 5cm, OSB plate 1,8cm, stand timber beams/insulation 1,6cm, lath wood panel 5cm, wind protection PE 1,8cm, OSB plate 5cm.
Ceiling	Parquet 3cm, wooden Polster/Cork shot 6cm, Board stable floor 25cm,lath wood panel 5cm, loam plate 2,5cm
Roof	Sheet 2,4cm, timber beam/insulation 16cm, Steam brake PE 0.5cm, sheet 2,4cm, lath wood 3cm, loam plate 2,5cm.
Interior walls	Chipboard, Novo pan, 621 Kg TS/m³, 1,6cm, 10,8 kg/m²,Insulation, rock wool, EU-rep Wood, cut up, 430 Kg TS/m³, 50.95 2.04 kg/m
Windows& Doors	Glass, sealed unit, 4 -12 - 4, 20kg/m² Wood, Cut up, 430 kg TS/m³

Project_5

Multiple forms are arranged in terms of a collection of small construction units.

Project data:

- Gross area = 1287 m²
- Net floor area = 2320.m²
- Total area =1787,1 m²
- Volume = 8753 m²
- Facade area = 1264,4m²
- Windows area = 617,5m²
- Internal wall area = 1300,9m²

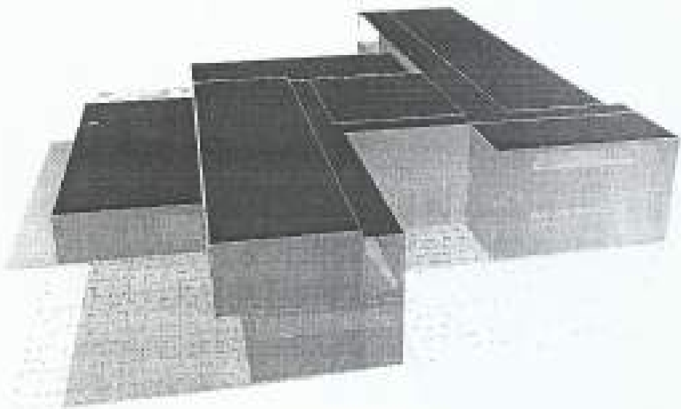


Figure A.14. View project_5

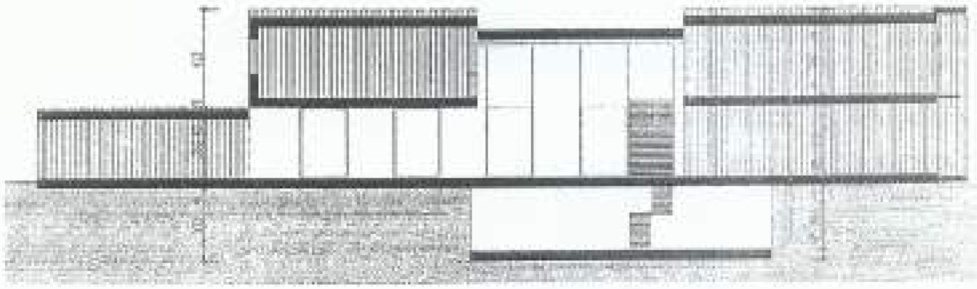


Figure A.15. Section project_5

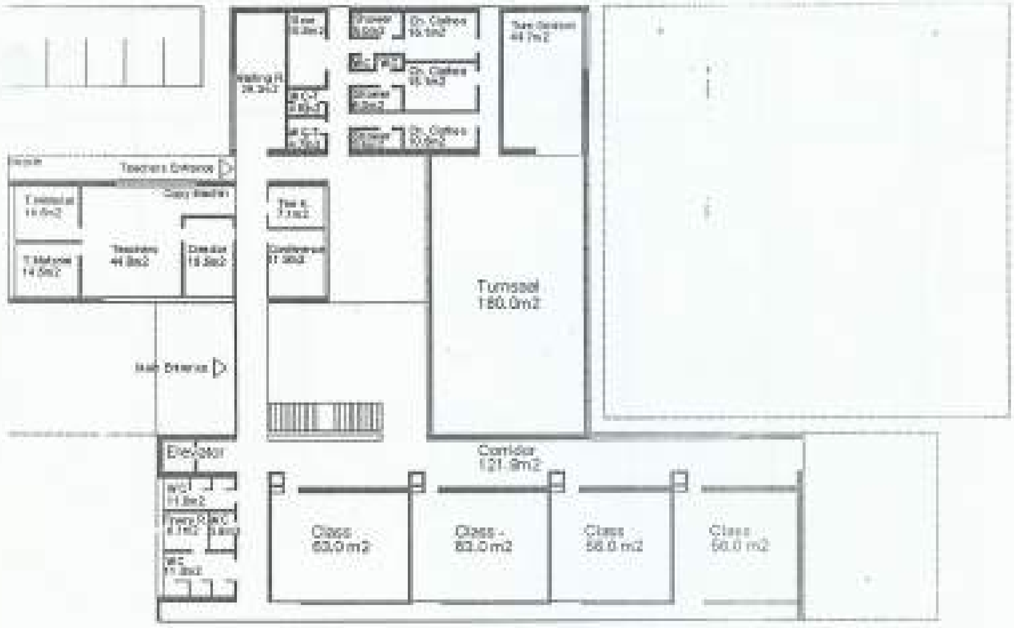


Figure A.16. Ground floor plan project_5

Table A.5.The building components, project_5

Component	Construction
Floor	Parquet 2,2cm, chip plate 2,5 cm, sound insulation rock wool 3,5cm, multi board layers 2cm, BSH-rib 20cm,floor sealing 0,5cm,concrete plate 20 cm.
Exterior walls	Gypsum board plate 2,5 cm, insulation 4cm, chipboard 1,5cm, sheet wood 3,2cm
Ceiling	Parquet 2,2cm,chipboard 2,5cm,Insulation 3,5cm, more layers plate 2,0cm, BSH rib 22cm, sound absorption 2,5cm, Gypsum board plate 1,5cm
Roof	Extensive green area 8cm, Sealing sheet 0,24cm, 3-layers plate, wood layers 40cm, 3-layers-plate 2cm, sound absorption 3cm,Gypsum board plate 1,2cm
Interior walls	Chipboard, Novo pan, 621 Kg TS/m³, 1,6cm, 10,8 kg/m² Insulation, rock wool, EU-rep Wood, cut up, 430 Kg TS/m³.
Windows& Doors	Glass, sealed unit,4 -12 - 4, 20 kg/m² Wood, Cut up, 430 kg TS/m³

Project_6

The form of the two-story building is rectangular.

Project data:

- Gross area = 1230m²
- Net floor area = 2024 m²
- Total area = 1436 m²
- Volume = 9190 m³
- Facade area = 1065,6m²
- Windows area 363.2 m²
- Internal walls area = 1247,1m²

Figure A.17. View project_6

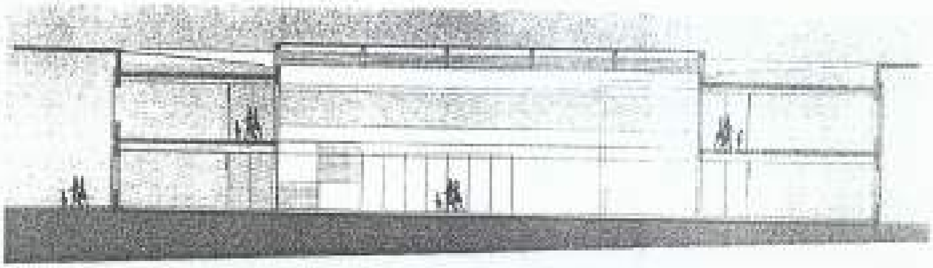


Figure A.18. Section project_6

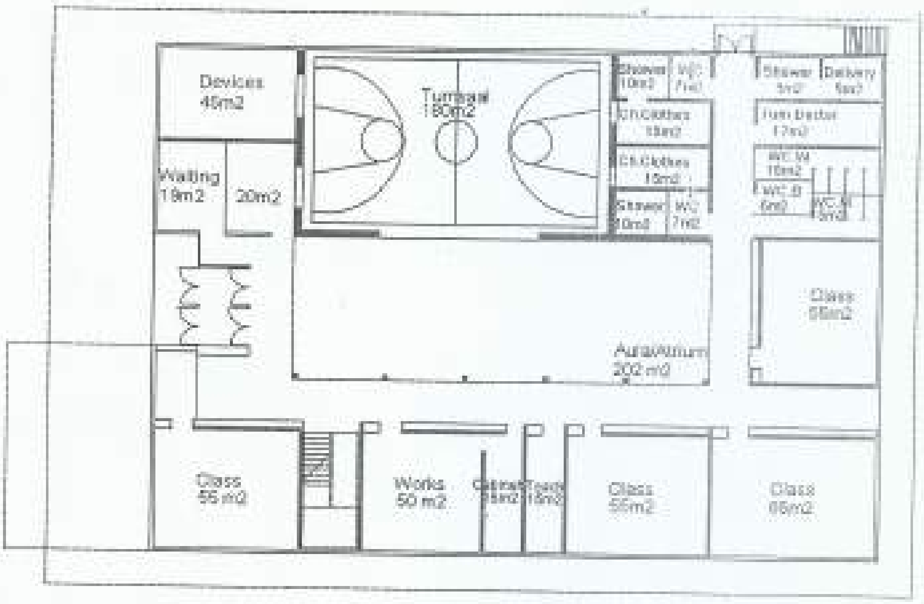


Figure A.19. Ground floor plan project_6

Table A.6.The building components, project_6

Component	Construction
Floor	Parquet 2,2cm, chipboard 2,5 cm, sound insulation rock wool 3,5cm, more board layers 2cm, BSH-rib 20cm,floor sealing 0,5cm,concrete plate 20 cm.
Exterior walls	Loam platen 4cm, under construction/insulation 7cm, OSB-plate 3cm, formatted wood 20cm, OSB-plate 3cm, lath wood panel/insulation 3cm, Gypsum board plate 2,5 cm
Ceiling	Parquet 1cm, Cement floating floor 7cm, insulation 5cm, sand 7cm, wood board 22cm.
Roof	Sheet metal 2cm, OSB-plate 2cm, cantilever chip/insulation 20cm, wood beam sheets 28cm, under construction panel 4cm
Interior walls	Chipboard, Novo pan, 621 Kg TS/m^3, 1,6cm, 10, 8 kg/m^2. Insulation, rock wool, EU-rep Wood, cut up, 430 Kg TS/m^3, 50.95 - 2,04 kg/m
Windows& Doors	Glass, sealed unit, 4 -12- 4, 20kg/m^2 Wood, Cut up, 430 kg TS/m^3

Appendix B
Additional results for the Computational studies

- Embodied Energy

Table B.1. The main contributors for the six projects embodied energy consumption.

	Unit	P_1	P_2	P_3	P_4	P_5	P_6
Electricity, hydropower	GJ	14200	5590	27539,33	2530	4020	13400
Gas,Gasol,	GJ	3560	1400	6884,83	633	1000	3350
Gas, natural gas w/precombus	GJ	0,00	0,00	0,00	0,00	0,00	0,40
Oil, Fuel oil w/ Pre combustion	GJ	8,70	34,53	33,19	37,85	4,94	12,28
Oil, gasoil w/pre combustion	GJ	265,47	235,25	309,89	218,26	277,35	296,71
Pre combustion	GJ	11,47	13,07	15,89	12,76	11,54	13,13
Total	GJ	18.065,83	7268,91	34783,13	3432,24	5318,50	17053,10

- Secondary raw materials

Table B.2.The consumption of secondary raw materials to the six projects.

	Unit	P_1	P_2	P_3	P_4	P_5	P_6
Flusspat	kg	577,20	609,10	316,80	353,35	426,15	492,76
Scrap, steel	g	-1.475	-1.556	-809,60	-903,00	-1.089	-1.259,3
Waste product, calcium Chloride	kg	-2.379	-2.278	-7.108,7	-2.997	-5.054,1	-4.206,2
Waste product, chalk filler	kg	22.078	23.297	12.117,5	13.515,6	16.300,3	18.847,9
Waste product, ferrosulfat, FeSO4	kg	384,80	406,06	211,20	235,56	284,10	328,50
Waste product, fly ash	kg	44.825	49.407	36.054	32.108,5	51.190,4	50.842,9
Waste product, industrial gypsum	kg	2.421	2.554,8	1.328,8	1.482,10	1.787,46	2.066,8
Waste product, kisaske	kg	3.864	4.077,54	2.120,77	2.365,47	2.852,80	3.298,7
Waste product, micro silicate	kg	5.730	6.559,46	6.426,2	4.646,02	8.644,50	7.958,98
Waste product, oil sludge	kg	897.87	947,48	492,79	549,65	662,90	766,51
Waste product, waste paper	kg	-609,27	12.095,66	12.058,5	14.260,1	-449.83	-520,13
Combustible, unspecified	g	-16.033	-16.919	-8.799,9	-9.815,2	-11.837	-13.69
Combustible, wood	kg	5.212	26.590,99	22.116,8	4.558,36	20.078,4	20.37
Combustible, wood (430 kg TS/m³)	m³	-12,36	-34,63	-40,024	-11,014	20.078,45	-30,12
Combustible, wood, chipboard (621 kg TS/kbm)	m³	-13,49	-51,90	-49,85	-11,92	-33,744	-41,90
Paper pulp	m³	13,66	0,00	19,30	0,00	30,70	7,86
Waste product, Concrete & mortar	t	0,00	0,00	-272,73	0,00	-112,99	0,00
Waste product, flex fiber	kg	0,00	0,00	-6.809,9	0,00	-2.821,3	0,00

- Primary raw materials/fuels

Table B.3.The main contributors to the six projects Primary raw materials/fuels.

	Unit	P_1	P_2	P_3	P_4	P_5	P_6
Bitumen	kg	31.424,40	96,59	0.00	23.304,96	64,02	29.129,79
Sand	m³	106,465	0.00	0.00	188,35	624,21	165,5
Calium chloride	g	77,90	0.00	3.33	21.35	5.294,73	31.29,2
Chalk	t	142,49	176,13	91,61	102,18	123,23	160,91
Clay	Kg	21.439,20	3.875,29	201,046	72,77	249,75	0.00
Dolomite	Kg	3.034,259	1.643,62	5.128,05	2.161,98	3.645,89	1.718,51
Gypsum, anhydrite, $CaSO4$	kg	9.640,438	15.862,38	20.443,1	1.275,98	32.26,68	2.084,35
Limestone	Kg	6.237,139	2.538,37	8.116,98	3.465,29	5.630,64	5.971,49
Ore, bauxite	Kg	10.325,58	0.00	4.417,25	2.829,88	0.00	4.147,65
Ore, Iron(50%Fe)	g	25.466,58	0.00	10.893,6	4.859,49	0.00	10.230,16
Phenol	Kg	5.946,20	2.865,01	3.955,433	482,26	7.835,98	9.241,86
Quartz sand	Kg	12.58,24	6.814,54	21.261,25	8.963,65	15.116,08	7.116,79
Salt	Kg	221,82	0.00	94,88	60,79	0.00	89,105
Sand	t	669,23	743,14	464.03	452,52	0.00	691,28
Sodium chloride	Kg	4.410,77	2.388,94	7.450,32	3.141,71	5.294,73	2.493,73
Stone	t	833,18	686,68	672,73	486,37	0.00	599,76
Straw,(90kg/m³)	m³	119,11	168,36	61,82	404,29	0.00	0.00
Water, drinking water quality	m³	17,87	0.00	0.00	0.00	0.00	50,15
Water, not drinking water quality	m³	59,16	168,36	0.00	73,25	0.00	173,69
Water, unspecified	m³	170,58	140,73	137,73	99,57	185,27	122,79
Wood (Brettschicht holz)	m³	197,05	170,32	413,71	216,08	44,05	348,52
Wood(hardwood800/m³)	m³	180,818	36,69	74,21	68,73	504,19	57,28
Wood(Sperrholz,400kg/m³)	m³	69,01	0.00	40,19	19,30	48,73	121,74
Wood, logs, 100% water content	m³	42,71	44,16	84,47	20,12	52,13	22,42
Wood,(Lattung500kg/m³)	m³	2,14	0.00	196,37	61,30	0.00	18,24
Wood, Span Platte(700kg/m³)	m³	21,82	21,74	0.00	11,55	48,73	0.00
Linoleum,80%Leinöl, 20% Naturhartz	m²	1.168,29	0.00	0.00	182,69	0.00	0.00
Perlite	t	388,15	0.00	0.00	0.00	0.00	0.00
Coal	kg	542,69	175,07	912,58	182,69	137,26	12,05
Crude oil	t	0.080	34,88	150,02	19.178,47	30.506,90	1,28
Natural gas	Nm³	6.359,19	2.771,36	12.043,53	1.506,60	5.236,56	101,95

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