NTNU – Trondheim
Norwegian University of
Science and Technology

Department of Civil and Environmental Engineering
Building and Construction Engineering-Group
Building and Material Technology-Team

Mohamed Hamdy, Phd, M.Sc., Eng.,
Associate professor – my LinkedIn

Mobile : (+47) 92 05 28 76
Email : Mohamed.Hamdy@ntnu.no
Visiting address: Høgskoleringen 7A, Room 2-236

Department of Civil and Environmental Engineering

<u>Research groups:</u>

- **Building and Construction engineering**
- Geotechnical engineering
- Road, transport and geomatics Engineering
- Marine civil engineering

<u>Research/Education profiles:</u>

- **Building and material technology**
- Construction technology and production management
- Project mangement
- Facility and property management

Visions and Missions

We aim at achieving sustainable/energy-positive built environments <u>optimized for comfort, health, and/or productivity throughout the whole building life.</u>

Our research and teaching focuses on:

- Building performance simulation,
- Simulation-based optimization,
- Integrated building design,
- Cost-optimality, Life cycle cost analysis (LCC),
- Life cycle assessment (LCA),
- Benchmarking,
- Performance Gap- Simulation vs Reality
- Impact of climate change on building performance,
- Building flexibility,
- Advanced facades,
- Building information modelling,
- Etc.,

<u>Software:</u>

IDA-ICE 4.7,
EnergyPlus,
DesignBuilder,
MODELICA,
SAM: System Advisor Model
HOMAR
SimaPro
Etc.,

Visions and Missions

We adopt a holistic optimization approaches;

investigating all available and innovative technologies

(e.g., advanced facades, renewables, construction, management techniques, BIM, etc.,)

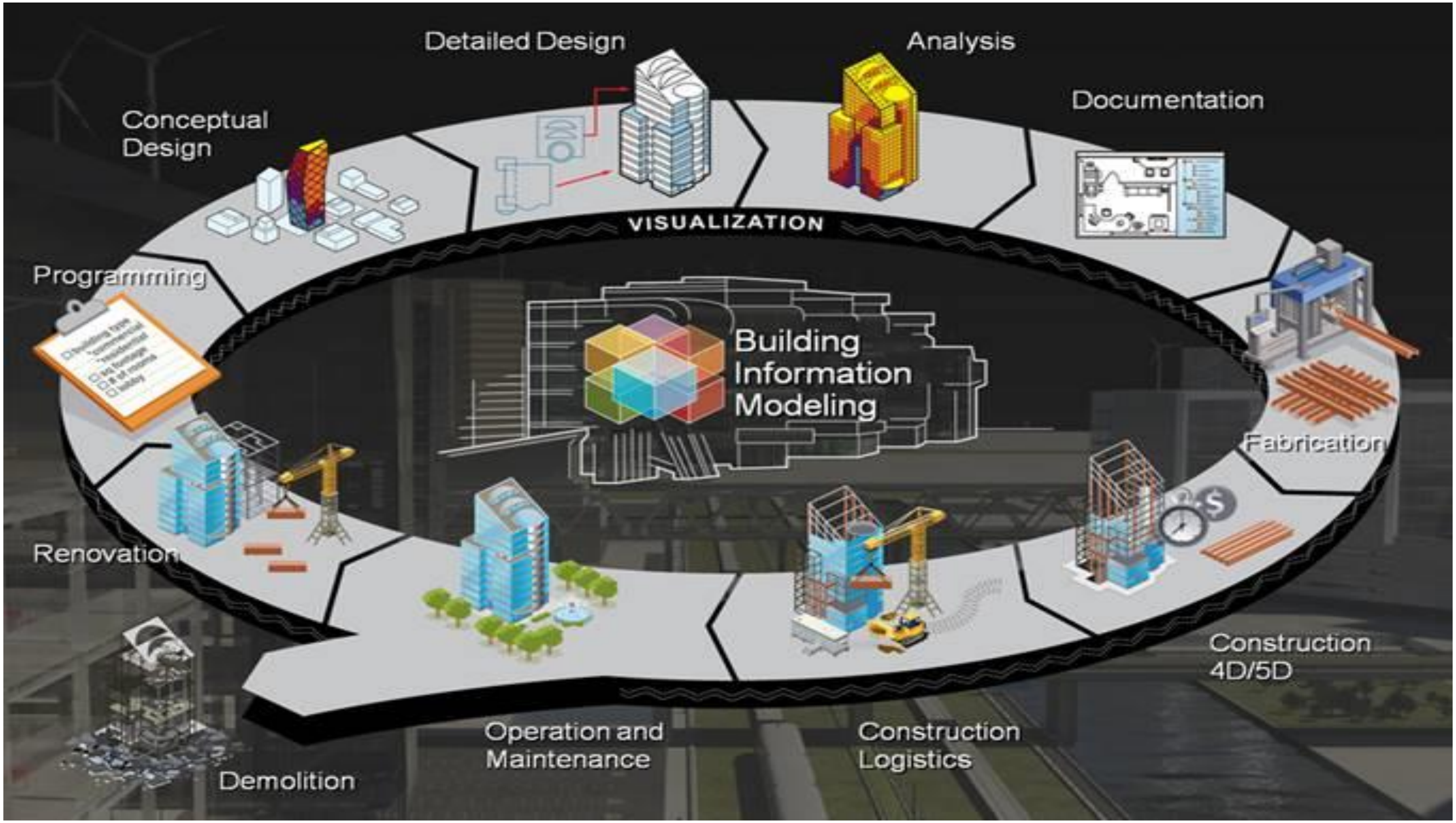
for meeting predefined stakeholders' criteria

(i.e., national/international targets, energy-efficiency, cost-effectiveness, and well-being).

Stakeholder

- architects,
- engineers,
- contractors and
- facility managers.

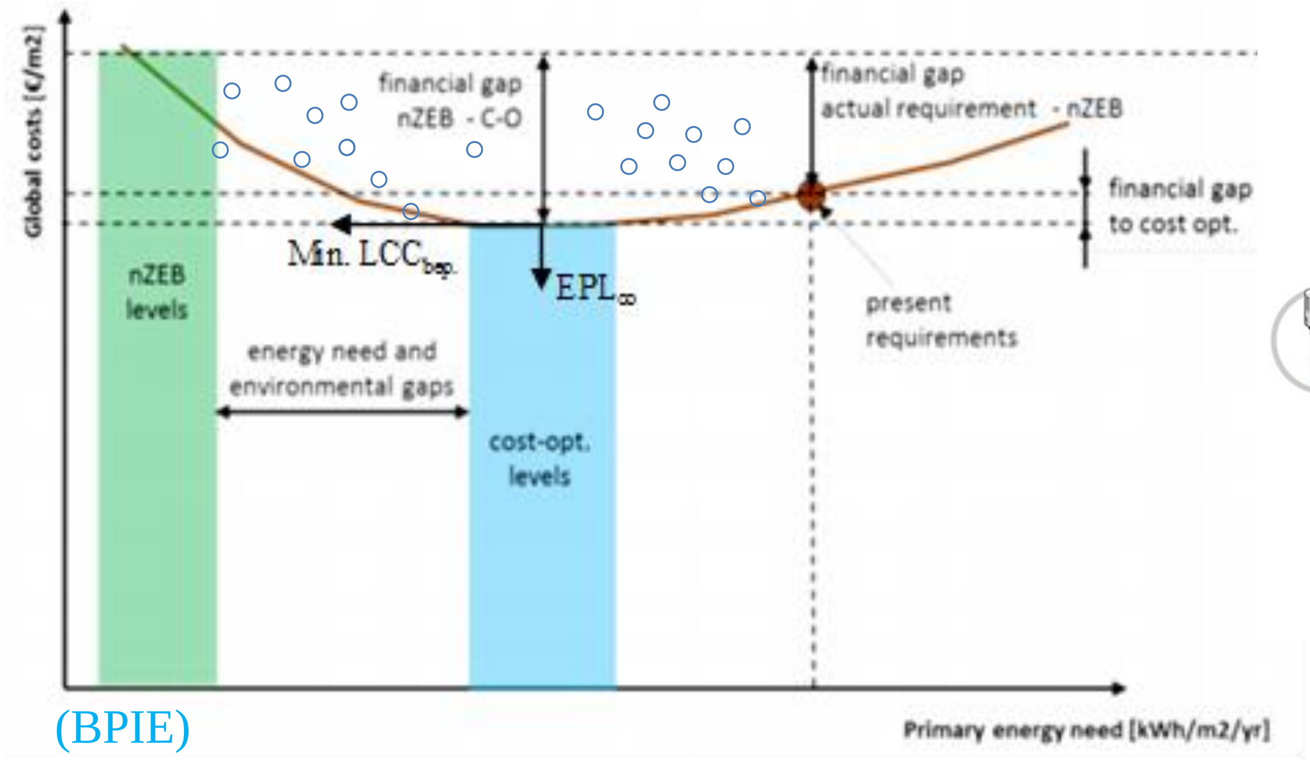
Optimizing the Building Life Cycle



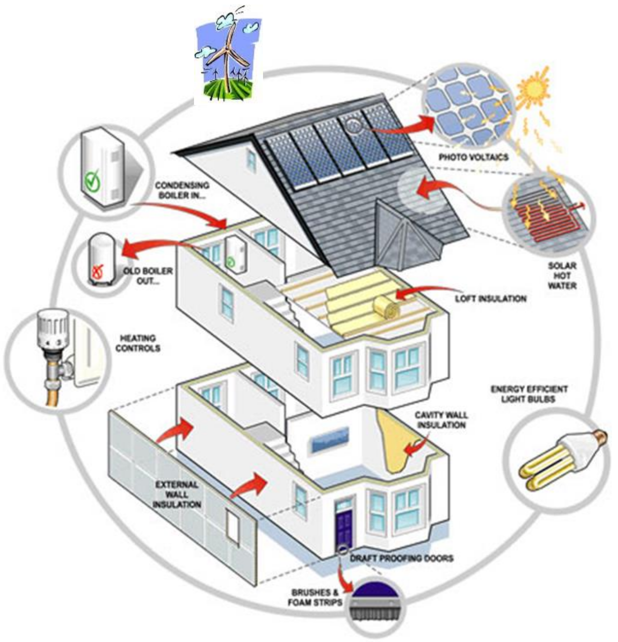
BIM-based BPS

Focus on cost-optimality framefowk

According to the European Energy Performance of Buildings Directive (EPBD 2010/31/EU), all EU-Member states are obliged to continuously *(at least every 5 years*) apply analysis on cost-optimal levels of minimum energy performance requirements towards nearly/Net Zero Energy Buildings (nZEBs).

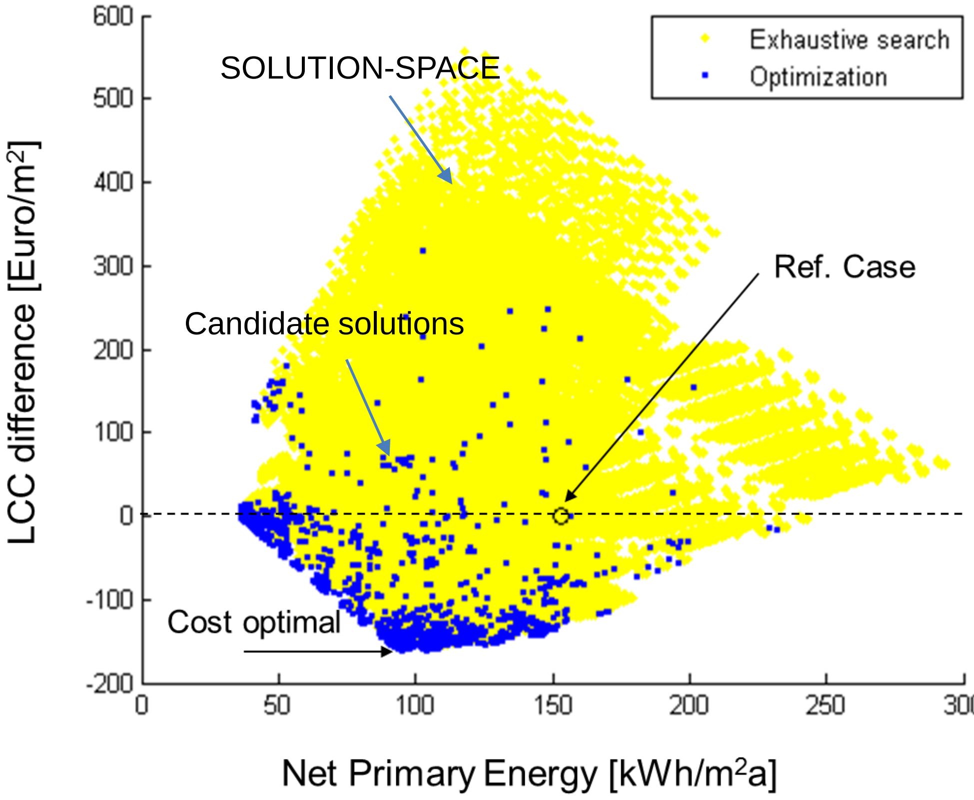


(BPIE)

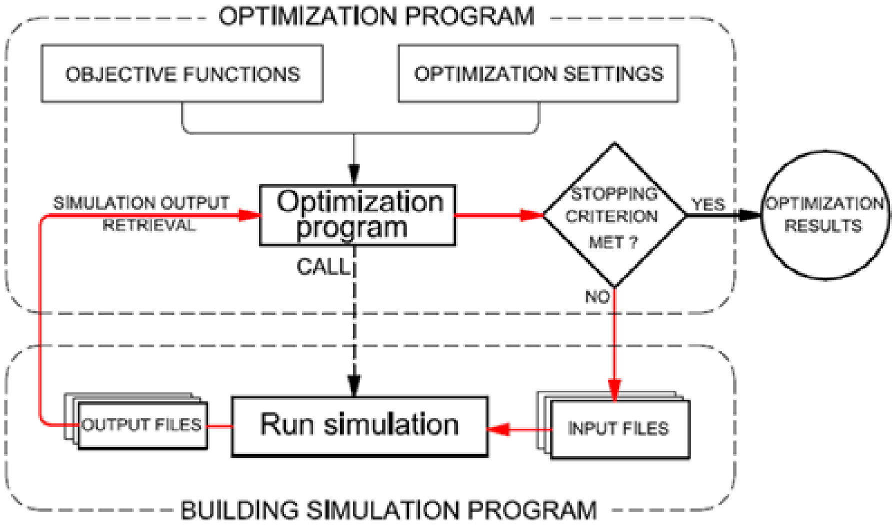


Design variables

Simulation-Based Optimization (Traditional)



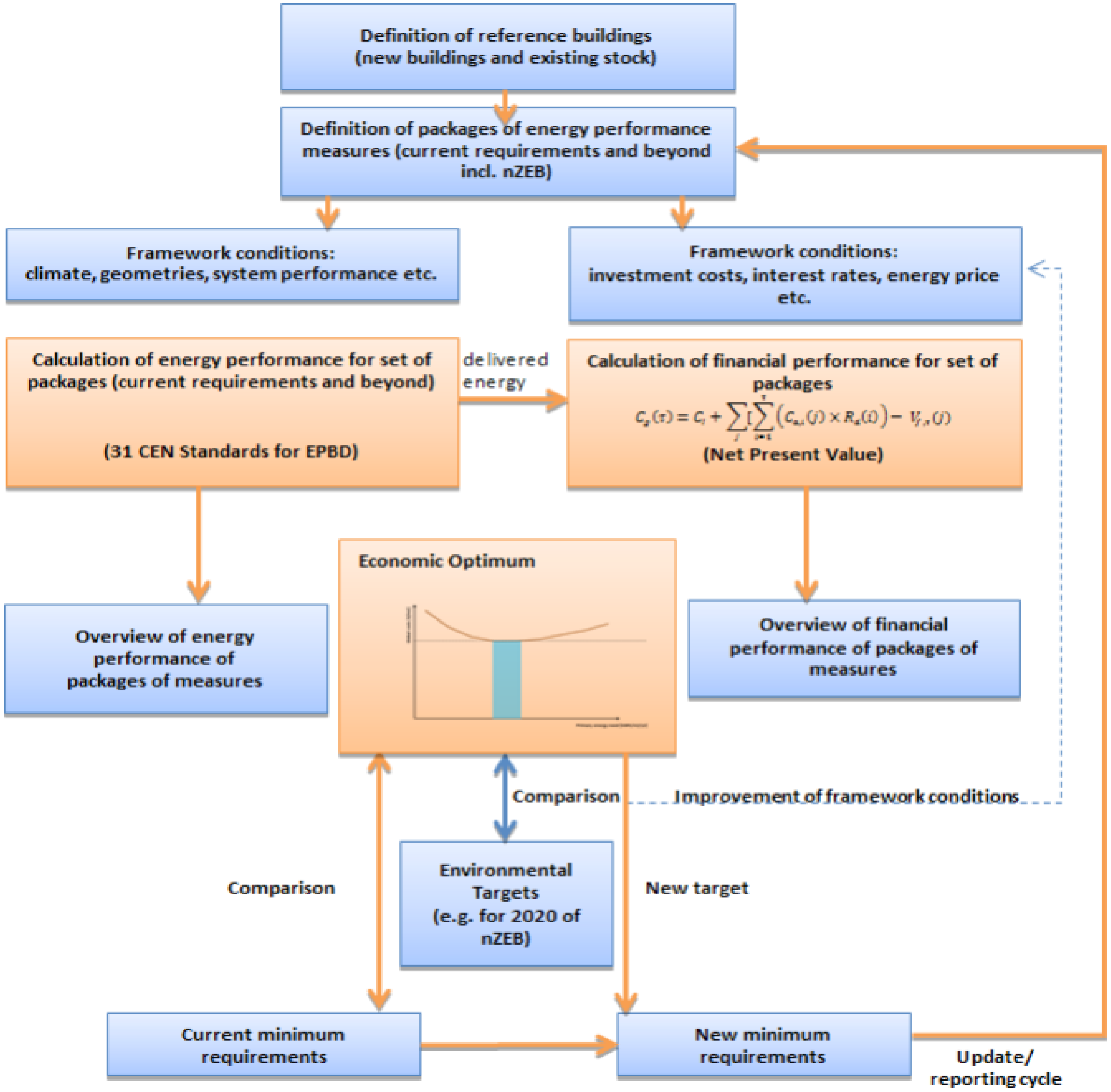
100,000 points
3000 points



The usual structure of simulation-based optimization in building performance studies (Nguyen, Reiter, and Rigo 2014) .

Source: Hamdy M., Hasan A. (2013). A Holistic Simulation-Based Optimization Approach for Dimentioning Cost Optimal and nearly-Zero-Energy Buildings. 1st IBPSA-Egypt Conference, Building Simulation Cairo 2013. 23rd- 24th June 2013.

Challenges



Definition of reference buildings
(new buildings and existing stock)

Definition of packages of energy performance measures (current requirements and beyond incl. nZEB)

Framework conditions:
climate, geometries, system performance etc.

Framework conditions:
investment costs, interest rates, energy price etc.

Calculation of energy performance for set of packages (current requirements and beyond)

(31 CEN Standards for EPBD)

delivered energy

Calculation of financial performance for set of packages

$$C_g(\tau) = C_I + \sum_j [\sum_{i=1}^{\tau} (C_{a,i}(j) \times R_d(i)) - V_{f,\tau}(j)]$$

(Net Present Value)

Overview of energy performance of packages of measures

Economic Optimum

Overview of financial performance of packages of measures

Comparison

Improvement of framework conditions

Comparison

Environmental Targets
(e.g. for 2020 of nZEB)

New target

Current minimum requirements

New minimum requirements

Update/
reporting cycle

Challenges in the Design and Modelling of Green Buildings

Although it is common knowledge that the impact of design decisions is greatest in earlier design stages, detailed BPS software is rarely used to support early decision for optimal green buildings. This is mainly because:

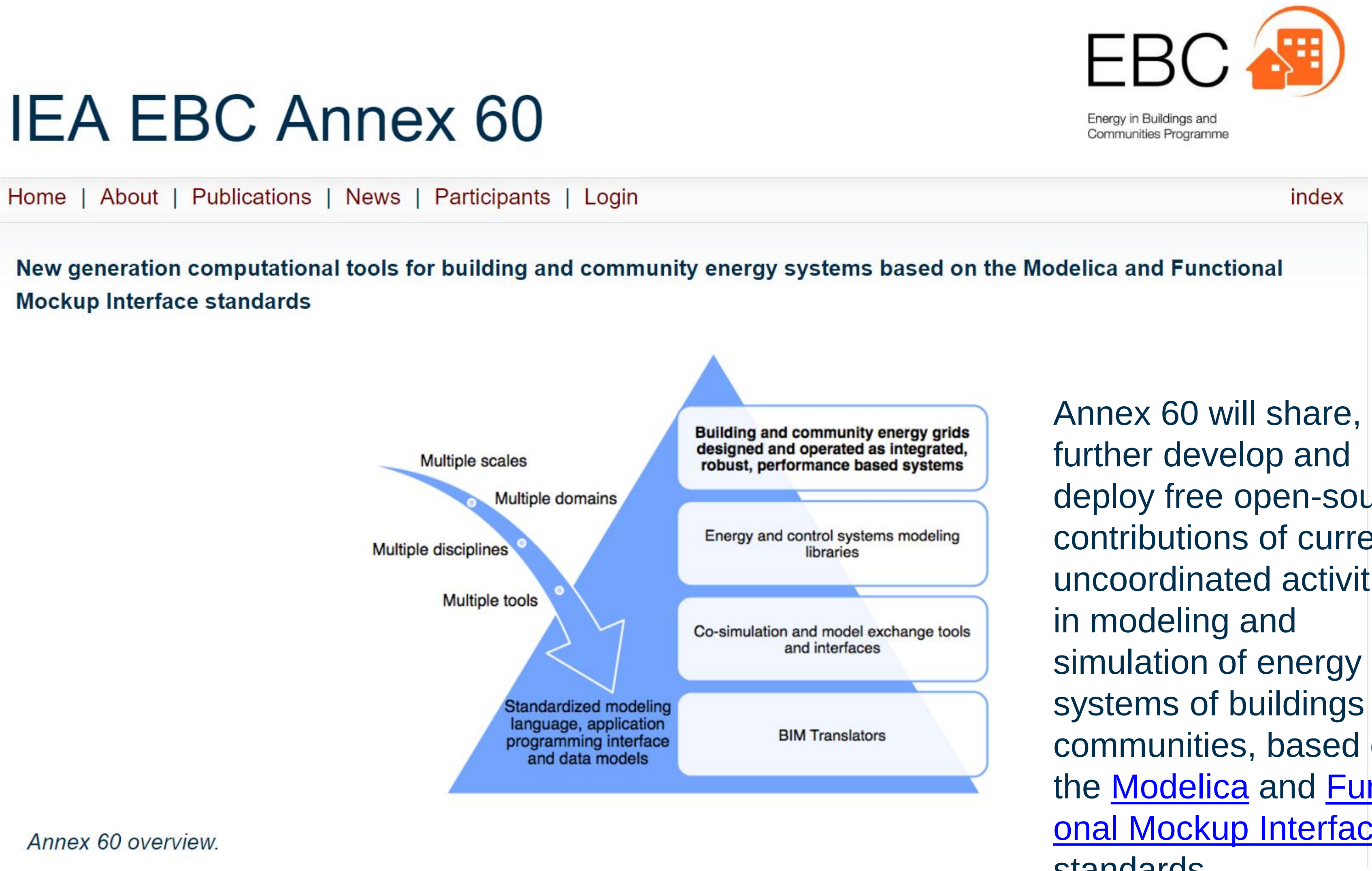
- the lack of knowledge regarding how to select appropriate BPS tool,
- the lack of experience to correctly use the available BPS tool,
- the limitations of the existing BPS tools to model and integrate,
- the lack of time to conduct detailed enough simulation work,
- the lack of experience to analysis the simulation results,
- the limitations of the existing BPS tools to communicate with different stakeholder.

Handbook of Energy Systems in Green Buildings| Editorial Workflow

Challenges in the Design and Modelling NZEN

- Wong [10] states that ‘’the research in sustainable design and construction tends to be very fragmented. It is essential that a more holistic approach should be developed to better understand the relationship between urban, building, building systems, and material´´.

IEA EBC Annex 60



IEA EBC Annex 60

Energy in Buildings and Communities Programme

Home | About | Publications | News | Participants | Login

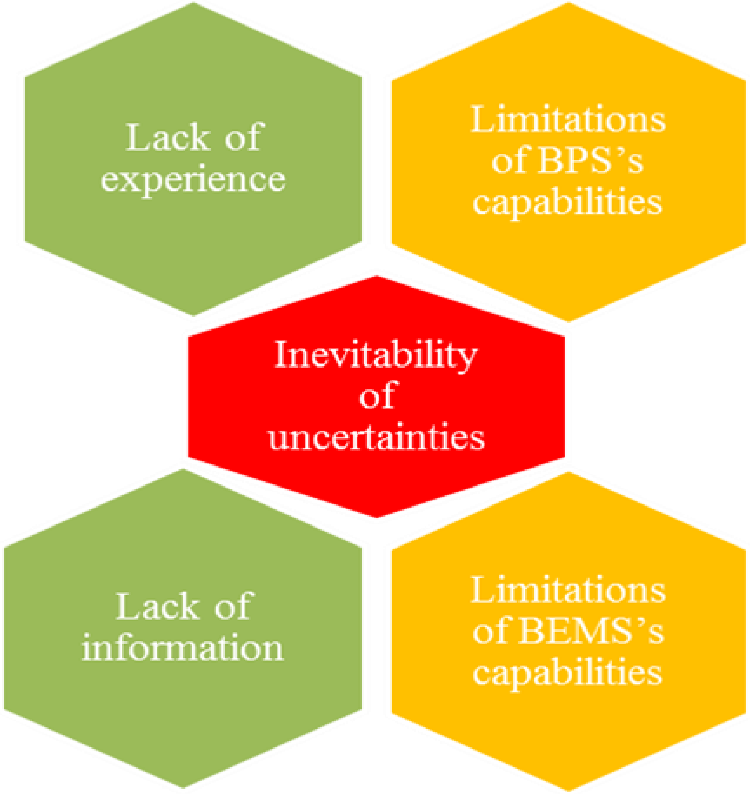
index

New generation computational tools for building and community energy systems based on the Modelica and Functional Mockup Interface standards

Annex 60 overview.

Annex 60 will share, further develop and deploy free open-source contributions of currently uncoordinated activities in modeling and simulation of energy systems of buildings and communities, based on the Modelica and Functional Mockup Interface standards.

Trust is the biggest challenge


Lack of experience

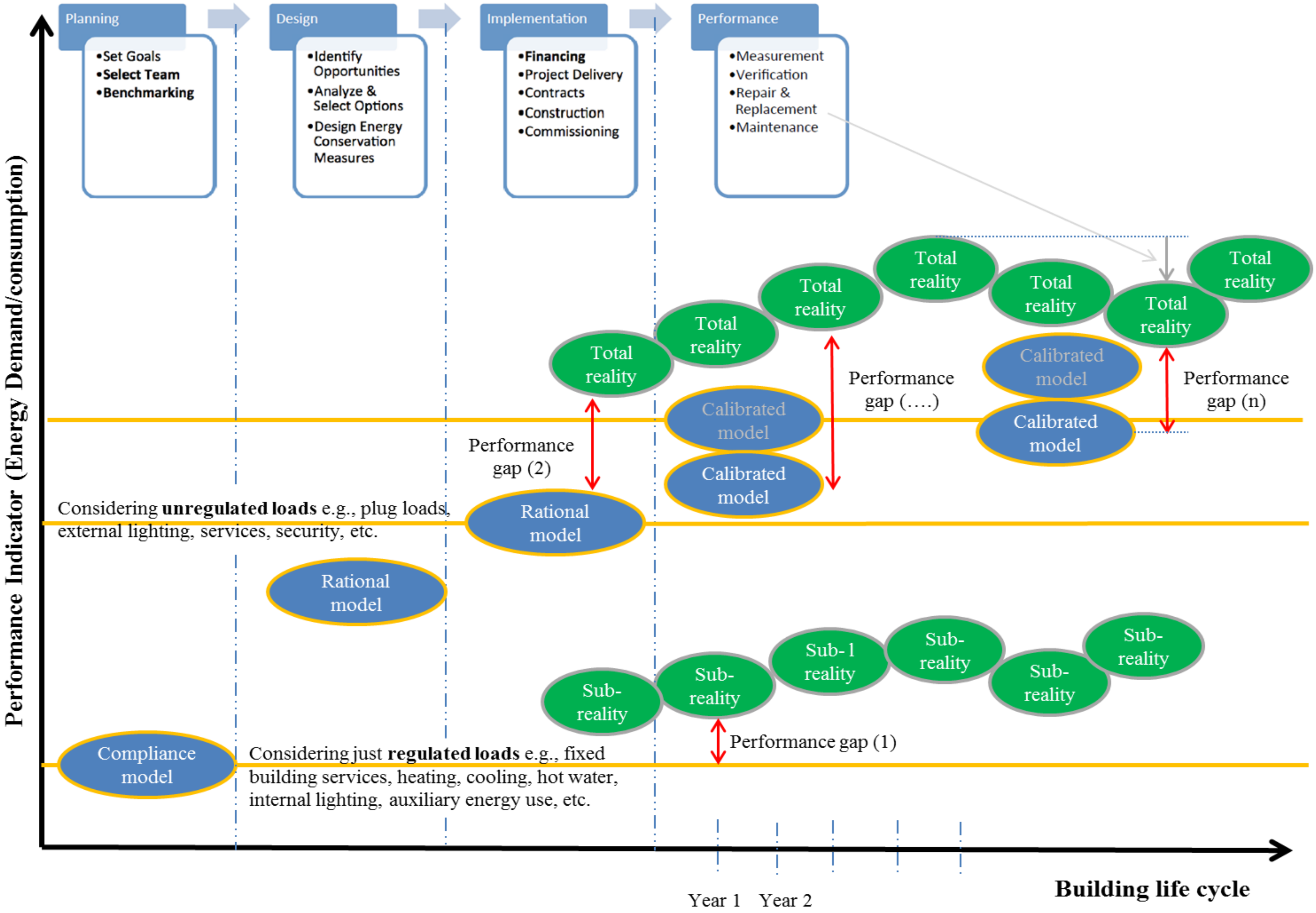
Limitations of BPS's capabilities

Inevitability of uncertainties

Lack of information

Limitations of BEMS's capabilities

Figure 2 the main challenges of implementing the proposed discrepancies identification approach



Planning
- Set Goals
- **Select Team**
- **Benchmarking**

Design
- Identify Opportunities
- Analyze & Select Options
- Design Energy Conservation Measures

Implementation
- **Financing**
- Project Delivery
- Contracts
- Construction
- Commissioning

Performance
- Measurement
- Verification
- Repair & Replacement
- Maintenance

Performance Indicator (Energy Demand/consumption)

Compliance model

Considering just **regulated loads** e.g., fixed building services, heating, cooling, hot water, internal lighting, auxiliary energy use, etc.

Rational model

Considering **unregulated loads** e.g., plug loads, external lighting, services, security, etc.

Rational model

Performance gap (2)

Total reality

Sub-reality

Sub-reality

Performance gap (1)

Calibrated model

Calibrated model

Total reality

Total reality

Sub-1 reality

Performance gap (….)

Total reality

Sub-reality

Calibrated model

Calibrated model

Total reality

Sub-reality

Total reality

Sub-reality

Performance gap (n)

Total reality

Year 1 Year 2

Building life cycle

PhD proposal - ZEN

A Comprehensive Optimization Platform for Accelerating Robust Zero Emission Neighborhoods in Practice.

- Integrated neighbourhood design is inherently a multi-objective optimization problem where two or more conflicting objectives must be minimized (i.e., carbon foot print, life cycle cost) and/or maximized (i.e., indoor environmental quality, energy flexible buildings).

- The complexity of finding compromises towards cost-effective net zero carbon neighbourhood (ZEN) has been dramatically increased, because the significant growth in energy-efficiency measures.

- The optimization problem become incredibly complex when different sources of uncertainty (i.e., financial, technical, climatic, and occupant behaviour assumptions/scenarios) are considered.

PhD proposal - ZEN

A Comprehensive Optimization Platform for Accelerating Robust Zero Emission Neighborhoods in Practice.

- This proposal aims at developing a comprehensive optimization platform to support robust optimal decisions for future-proof net zero carbon neighbourhood.
- The platform will be customized based on the financial, technical, climatic, and occupant behaviour patterns in Norway for achieving predefined target such ‘’reducing embodied CO_2 emissions in buildings by 50% while reducing the energy demand for operation by 20% for new buildings and 60% for retrofitted buildings, compared to current Norwegian Building Codes’’

Complexity-components

The cost-optimal solution is function of :

- 1- Solutions Space
- 2- assumptions/ scenarios

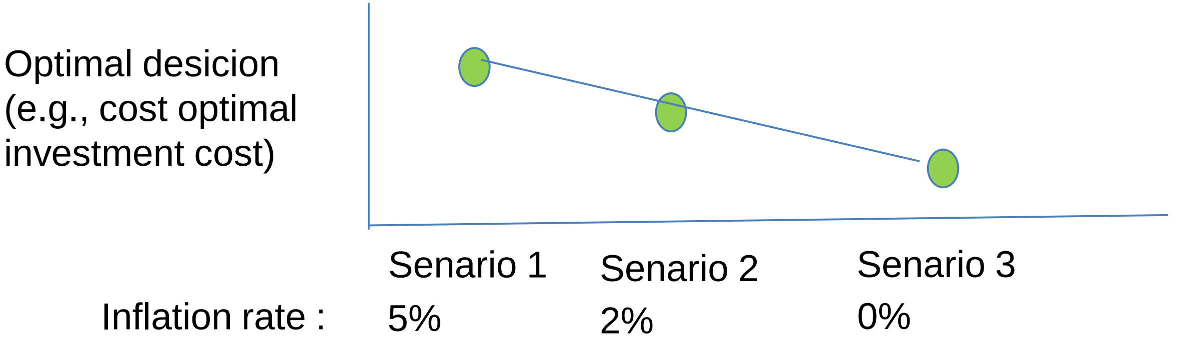
The complexity of finding a cost-optimal solution increases as long as :

- the solution-space expands because of the new technogies
- the scenarios increase seeking for robust cost-optimal solution

Optimization-based

Sensitivity Analysis

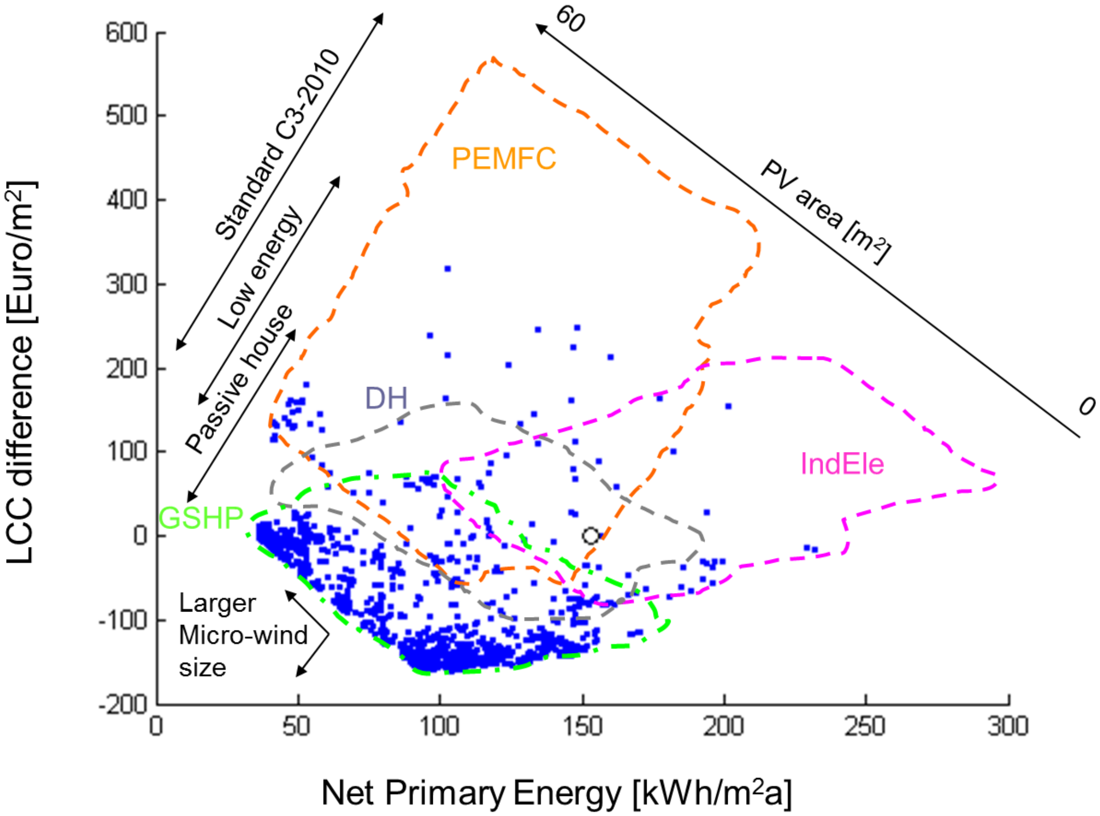
Optimization-based Sensitivity Analysis



Complexity-components

The cost-optimal solution is function of

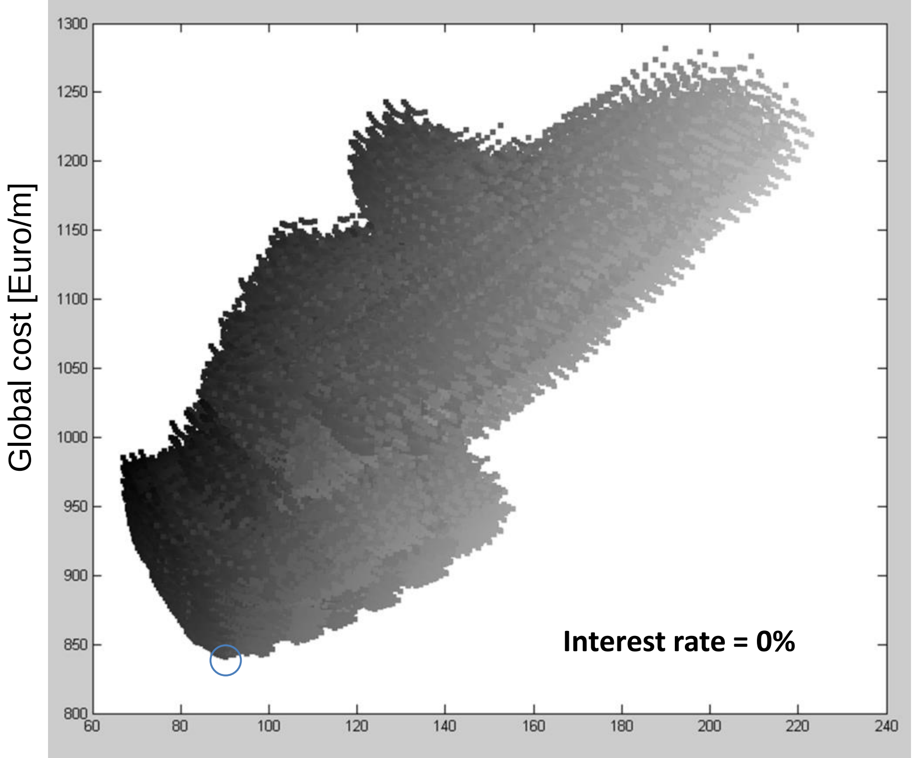
1- The possible design/operation options (Solution-Space)



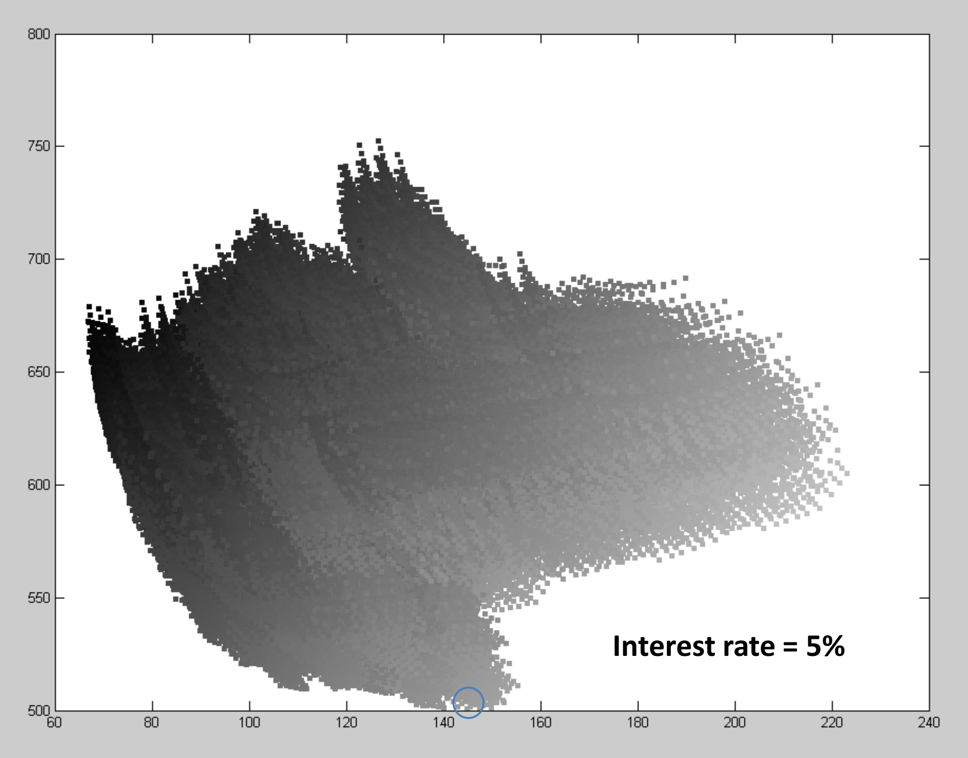
Complexity-components

The cost-optimal solution is function of

2- technical assumptions as well as financial and climate scenario (e.g., lifespan and interest rate)

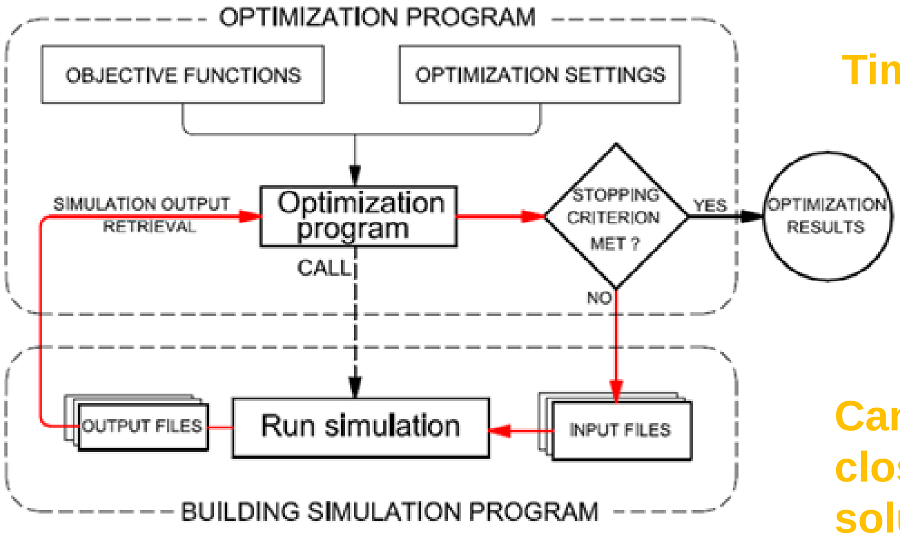


Primary Energy [kWh/m^{2}a]



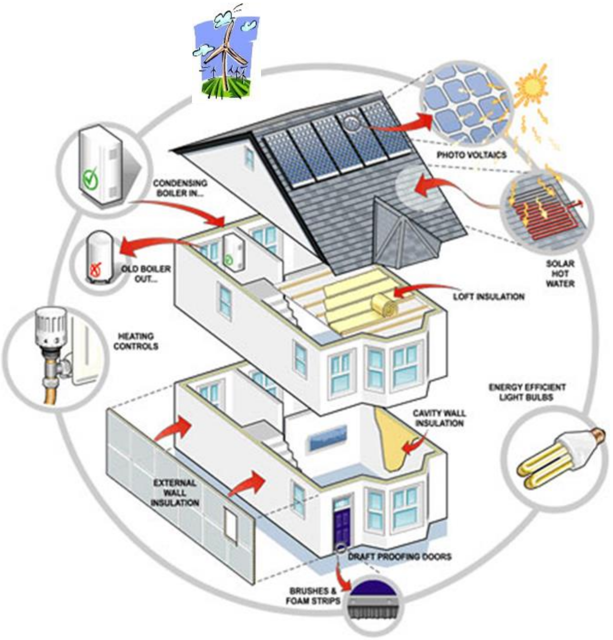
Primary Energy [kWh/m^{2}a]

Traditional Simulation-Based Optimization

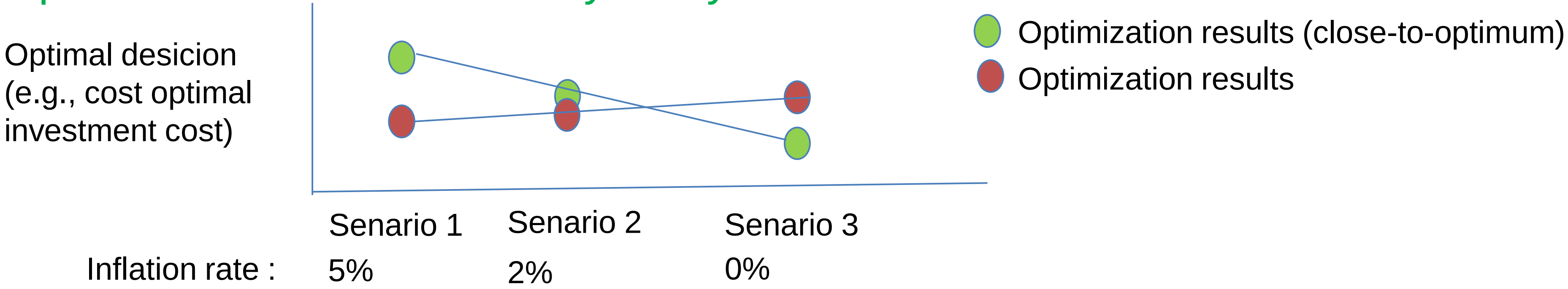


Time consuming

Can not guarantee close-to optimal solution for all the studied senarios



Optimization-based Sensitivity Analysis



Robustness of optimization

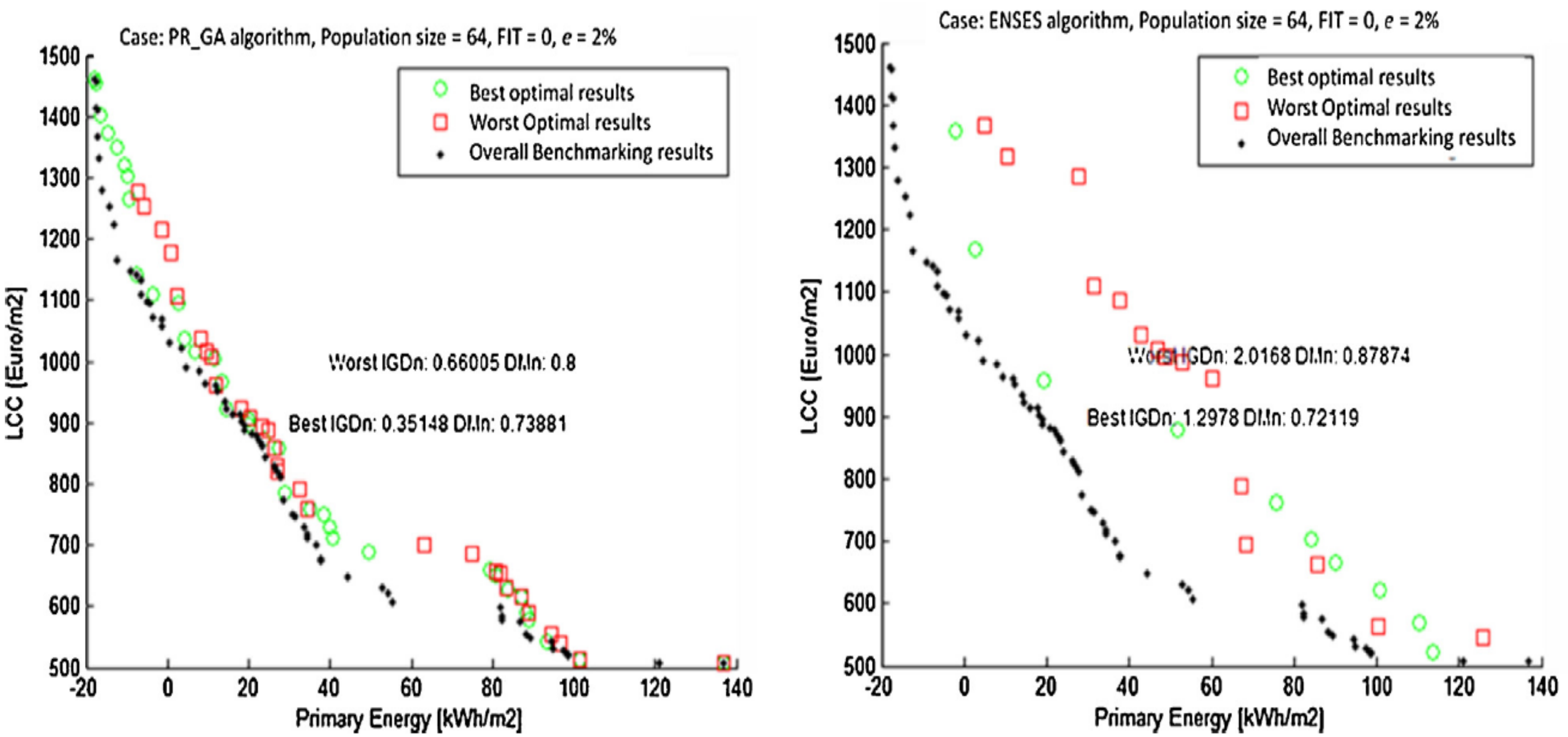
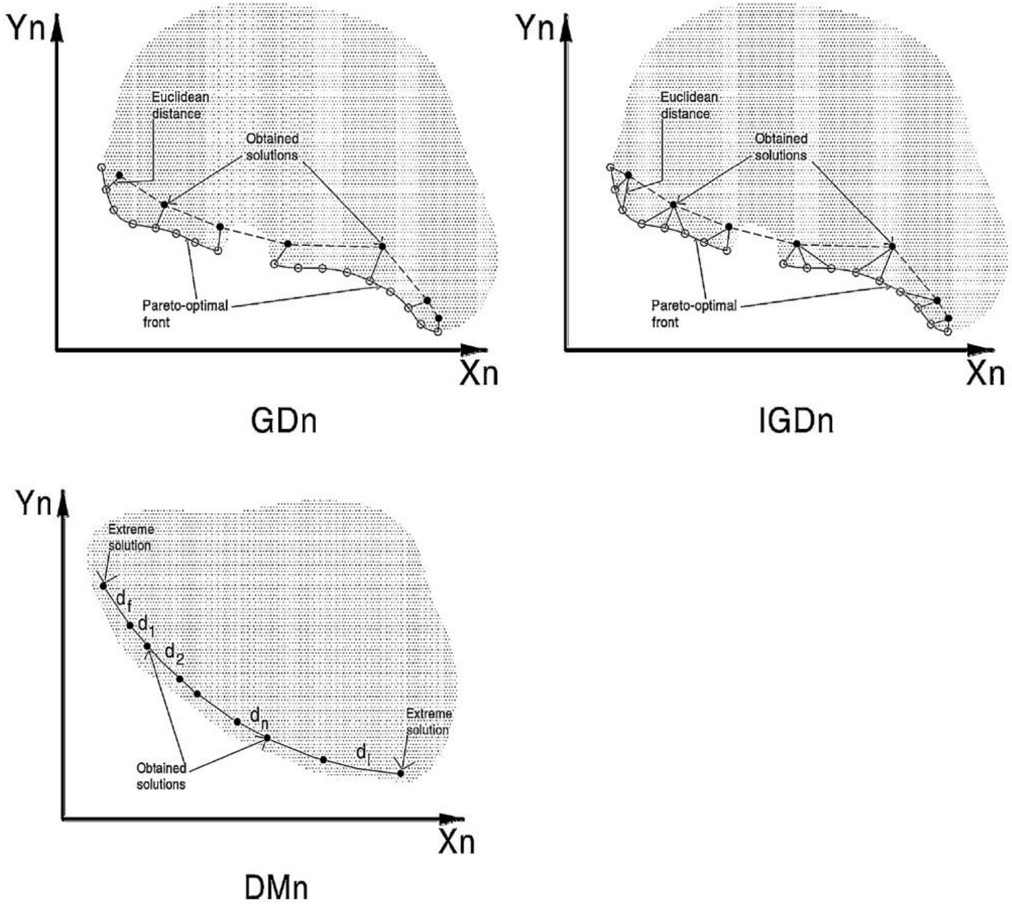


Fig. 7. The best and the worst obtained tradeoff solutions of the PR_GA and the ENSES, in terms of IGDn and DMn, compared with the benchmarking Pareto (Case A2—after 27 generations).

Robustness of optimization



GDn

IGDn

DMn

Fig. 4. The concept of the GDn, IGDn, and DMn (adapted from [45,46]).

Robustness of optimization

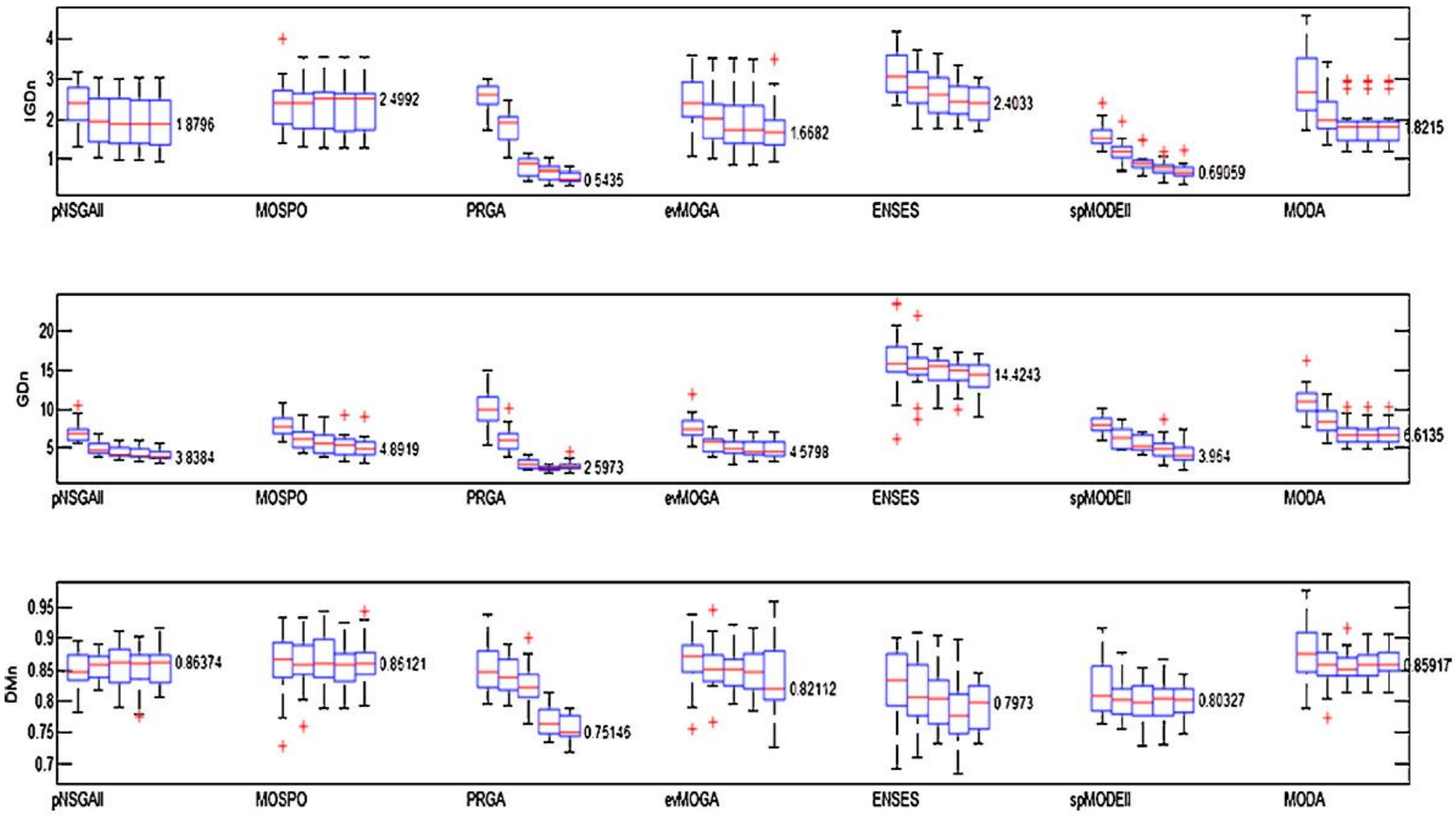
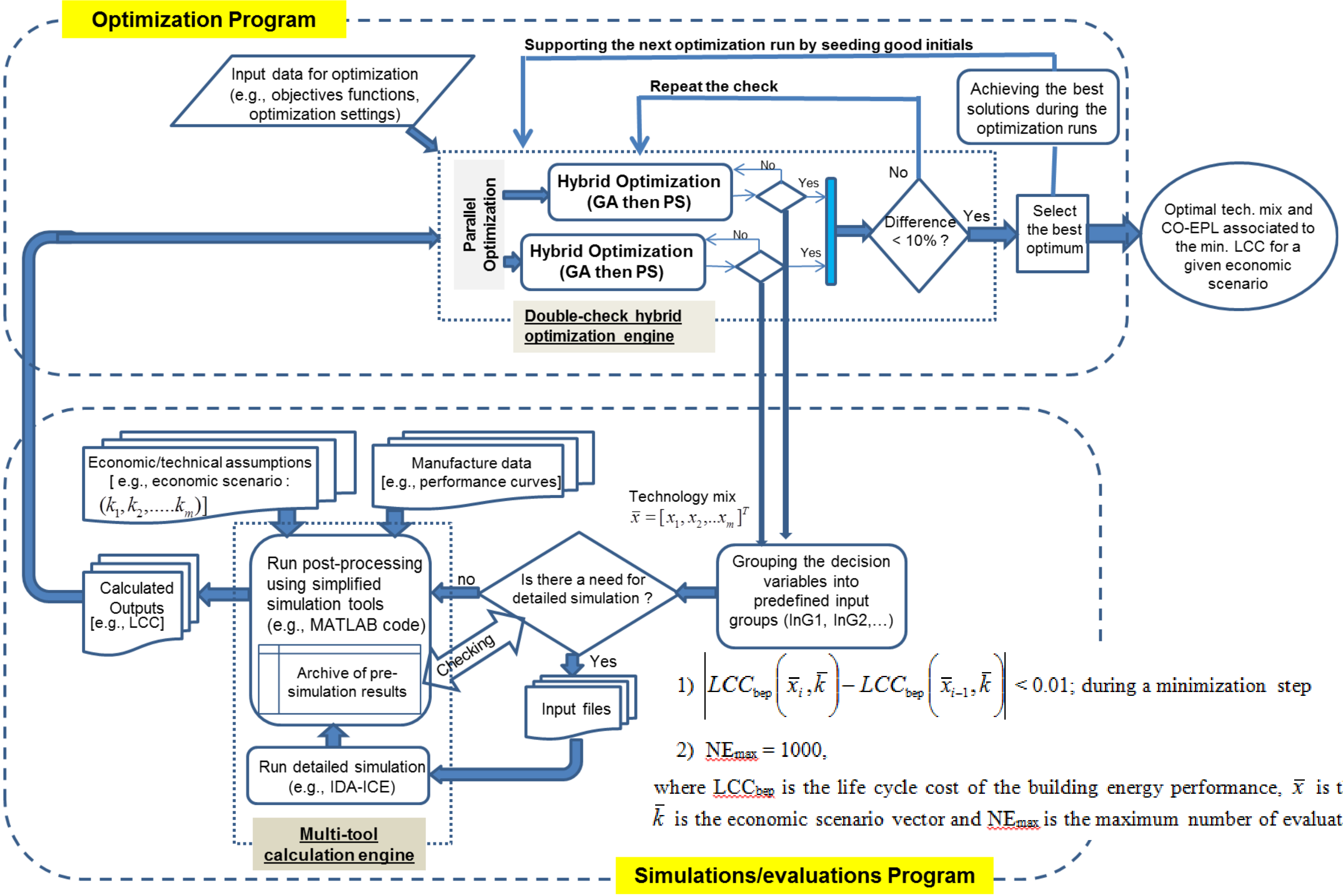


Fig. 9. The IGDn, GDn and DMn of the tested algorithms—Test case A2: population size = 64 individuals; financial assumption: FIT = 0, e = 2%. For each algorithm, optimization was executed 20 times, then the number of generations jumped from one to another value, i.e. from 3 to 9, 15, 21, 27 generations (≈200, 600, 1000, 1400, 1800 evaluations), respectively.

A Multi-aid Optimization Scheme (MAOS)



Optimization Program

Supporting the next optimization run by seeding good initials

Input data for optimization (e.g., objectives functions, optimization settings)

Repeat the check

Achieving the best solutions during the optimization runs

Parallel Optimization

Hybrid Optimization (GA then PS)

Hybrid Optimization (GA then PS)

No

Yes

No

Yes

No

Difference < 10% ?

Yes

Select the best optimum

Optimal tech. mix and CO-EPL associated to the min. LCC for a given economic scenario

Double-check hybrid optimization engine

Economic/technical assumptions [e.g., economic scenario : $(k_1, k_2, ...k_m)$]

Manufacture data [e.g., performance curves]

Technology mix $\bar{x} = [x_1, x_2, ...x_m]^T$

Calculated Outputs [e.g., LCC]

Run post-processing using simplified simulation tools (e.g., MATLAB code)

Archive of pre-simulation results

no

Is there a need for detailed simulation ?

Grouping the decision variables into predefined input groups (InG1, InG2,…)

Checking

Yes

Input files

Run detailed simulation (e.g., IDA-ICE)

Multi-tool calculation engine

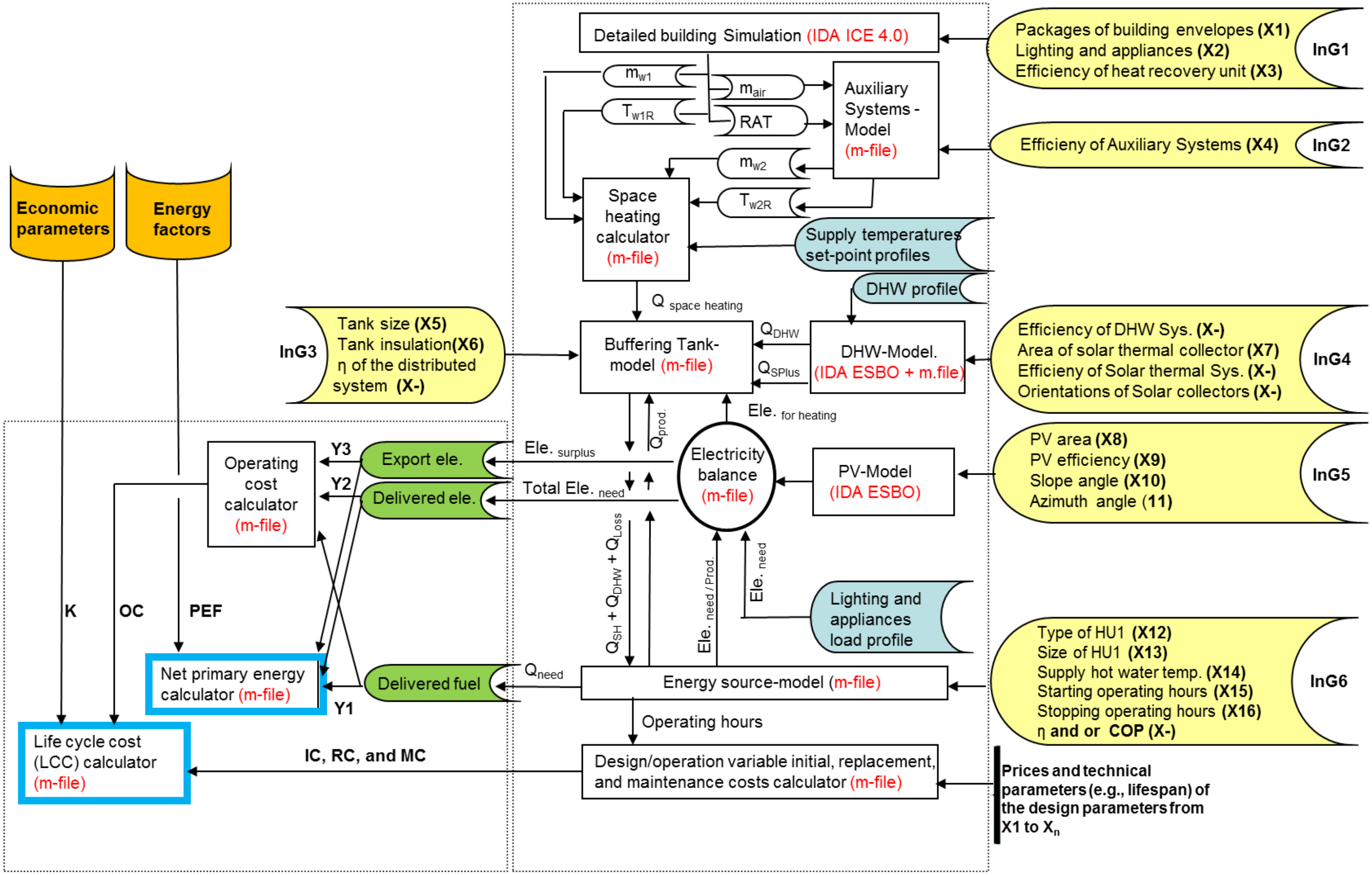
1) $\left| LCC_{bep}\left(\bar{x}_i, \bar{k}\right) - LCC_{bep}\left(\bar{x}_{i-1}, \bar{k}\right) \right| < 0.01$; during a minimization step

2) $NE_{max} = 1000$,

where LCC_{bep} is the life cycle cost of the building energy performance, $\bar{x}$ is the design variable vector, $\bar{k}$ is the economic scenario vector and NE_{max} is the maximum number of evaluations.

Simulations/evaluations Program

The multi-tool calculation engine



Detailed building Simulation (IDA ICE 4.0)

Packages of building envelopes **(X1)**
Lighting and appliances **(X2)**
Efficiency of heat recovery unit **(X3)**
InG1

m_{w1}
T_{w1R}
m_{air}
RAT
m_{w2}
T_{w2R}

Auxiliary Systems - Model (m-file)

Efficieny of Auxiliary Systems **(X4)**
InG2

Space heating calculator (m-file)

Supply temperatures set-point profiles

DHW profile

$Q_{\text{space heating}}$

Economic parameters

Energy factors

Tank size **(X5)**
Tank insulation**(X6)**
η of the distributed system **(X-)**
InG3

Buffering Tank-model (m-file)

Q_{DHW}
Q_{SPlus}

DHW-Model. (IDA ESBO + m.file)

Efficiency of DHW Sys. **(X-)**
Area of solar thermal collector **(X7)**
Efficieny of Solar thermal Sys. **(X-)**
Orientations of Solar collectors **(X-)**
InG4

$Q_{prod.}$
$\text{Ele.}_{\text{for heating}}$
$\text{Ele.}_{\text{surplus}}$
$\text{Total Ele.}_{\text{need}}$

Electricity balance (m-file)

PV-Model (IDA ESBO)

PV area **(X8)**
PV efficiency **(X9)**
Slope angle **(X10)**
Azimuth angle **(11)**
InG5

Operating cost calculator (m-file)

Y3
Y2
Export ele.
Delivered ele.

$Q_{SH} + Q_{DHW} + Q_{Loss}$
$\text{Ele.}_{\text{need / Prod.}}$
$\text{Ele.}_{\text{need}}$

Lighting and appliances load profile

K
OC
PEF

Net primary energy calculator (m-file)

Y1

Delivered fuel

Q_{need}

Energy source-model (m-file)

Type of HU1 **(X12)**
Size of HU1 **(X13)**
Supply hot water temp. **(X14)**
Starting operating hours **(X15)**
Stopping operating hours **(X16)**
η **and or COP (X-)**
InG6

Operating hours

Life cycle cost (LCC) calculator (m-file)

IC, RC, and MC

Design/operation variable initial, replacement, and maintenance costs calculator (m-file)

Prices and technical parameters (e.g., lifespan) of the design parameters from X1 to X_n

A Case Study / The Building

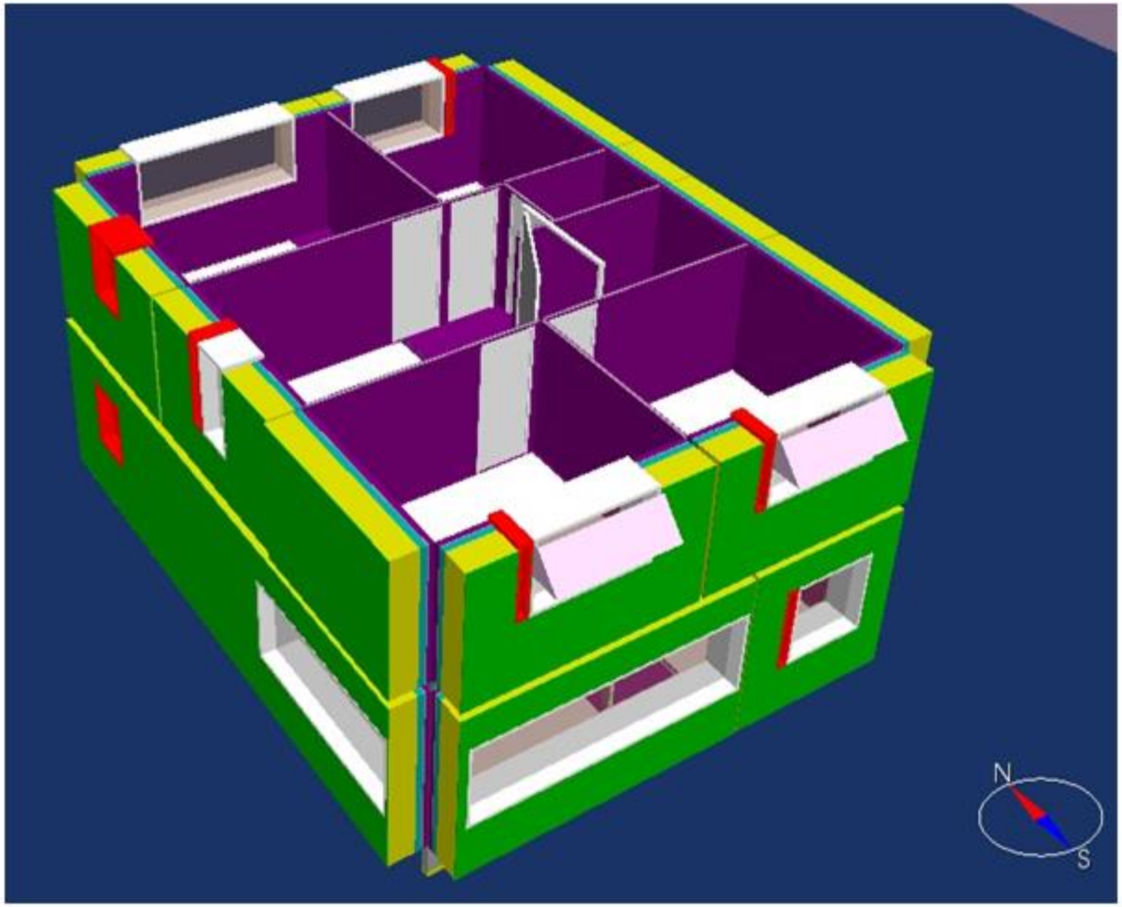
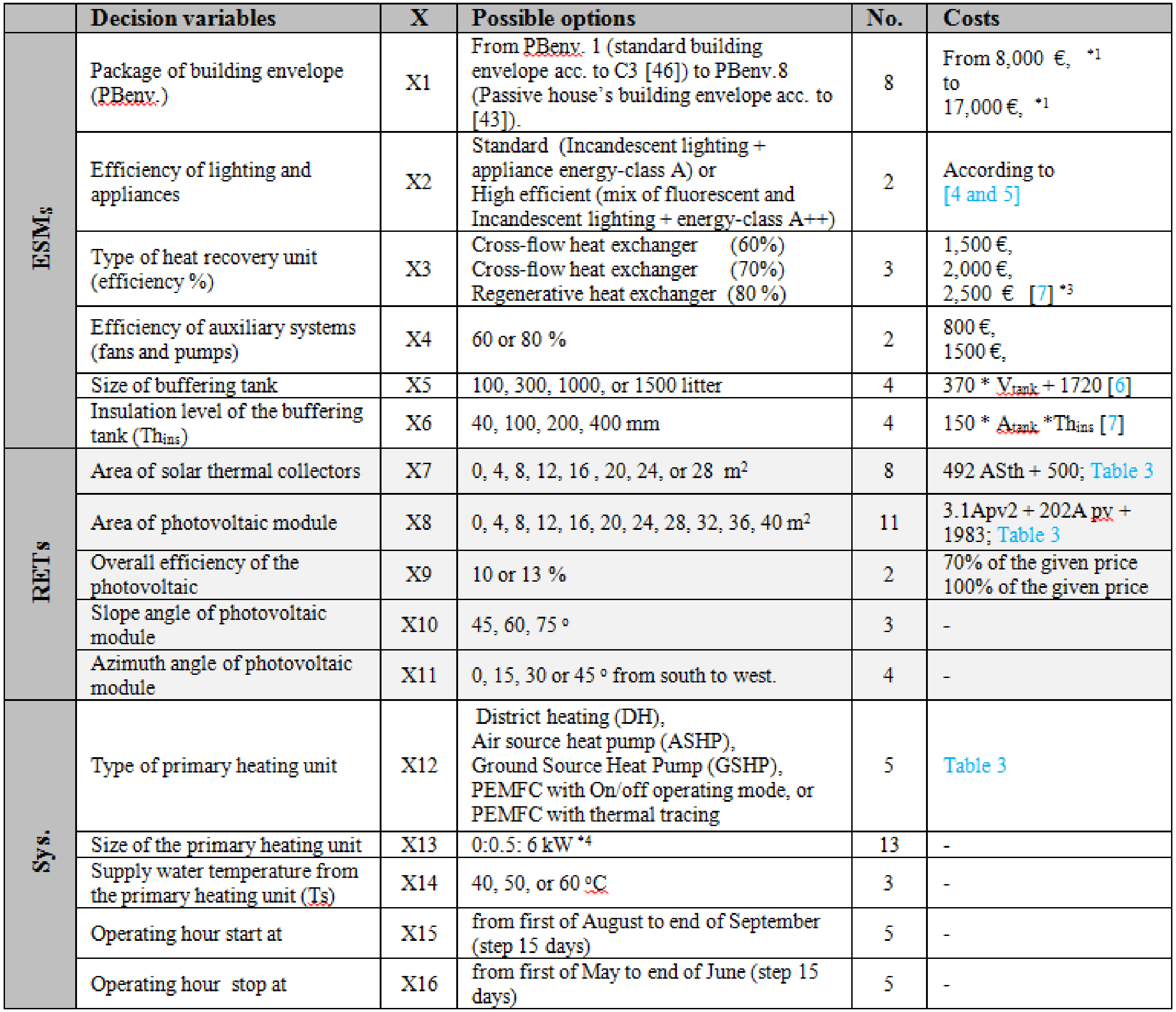


Figure 5 The studied single-family house. The small windows (red) are operable for free cooling to provide natural ventilation in summer.

A Case Study / Solution-Space



	Decision variables	X	Possible options	No.	Costs
ESMs	Package of building envelope (PBenv.)	X1	From PBenv. 1 (standard building envelope acc. to C3 [46]) to PBenv.8 (Passive house's building envelope acc. to [43]).	8	From 8,000 €, ^{*1} to 17,000 €, ^{*1}
	Efficiency of lighting and appliances	X2	Standard (Incandescent lighting + appliance energy-class A) or High efficient (mix of fluorescent and Incandescent lighting + energy-class A++)	2	According to [4 and 5]
	Type of heat recovery unit (efficiency %)	X3	Cross-flow heat exchanger (60%) Cross-flow heat exchanger (70%) Regenerative heat exchanger (80 %)	3	1,500 €, 2,000 €, 2,500 € [7] ^{*3}
	Efficiency of auxiliary systems (fans and pumps)	X4	60 or 80 %	2	800 €, 1500 €,
	Size of buffering tank	X5	100, 300, 1000, or 1500 litter	4	370 * V_{tank} + 1720 [6]
	Insulation level of the buffering tank (Th_{ins})	X6	40, 100, 200, 400 mm	4	150 * A_{tank} *Th_{ins} [7]
RETs	Area of solar thermal collectors	X7	0, 4, 8, 12, 16 , 20, 24, or 28 m^2	8	492 ASth + 500; Table 3
	Area of photovoltaic module	X8	0, 4, 8, 12, 16, 20, 24, 28, 32, 36, 40 m^2	11	3.1Apv2 + 202A py + 1983; Table 3
	Overall efficiency of the photovoltaic	X9	10 or 13 %	2	70% of the given price 100% of the given price
	Slope angle of photovoltaic module	X10	45, 60, 75 °	3	-
	Azimuth angle of photovoltaic module	X11	0, 15, 30 or 45 ° from south to west.	4	-
Sys.	Type of primary heating unit	X12	District heating (DH), Air source heat pump (ASHP), Ground Source Heat Pump (GSHP), PEMFC with On/off operating mode, or PEMFC with thermal tracing	5	Table 3
	Size of the primary heating unit	X13	0:0.5: 6 kW ^{*4}	13	-
	Supply water temperature from the primary heating unit (Ts)	X14	40, 50, or 60 ºC	3	-
	Operating hour start at	X15	from first of August to end of September (step 15 days)	5	-
	Operating hour stop at	X16	from first of May to end of June (step 15 days)	5	-

A Case Study / Economic Scenarios

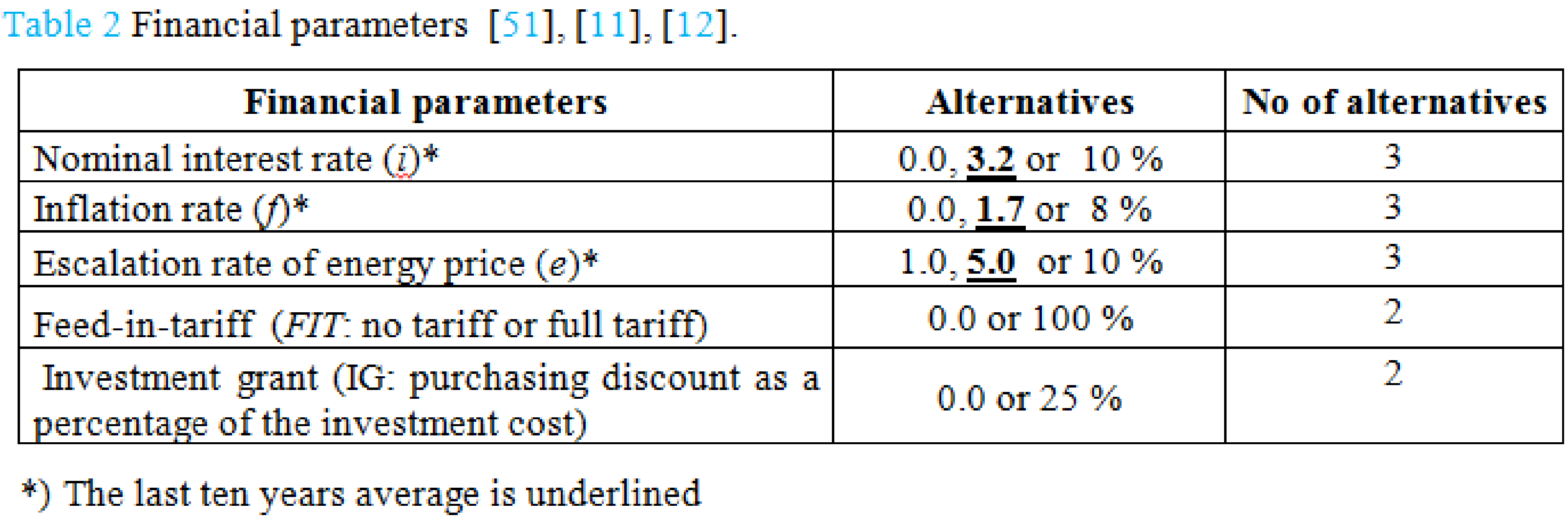


Table 2 Financial parameters [51], [11], [12].

Financial parameters	Alternatives	No of alternatives
Nominal interest rate (*i*)*	0.0, **3.2** or 10 %	3
Inflation rate (*f*)*	0.0, **1.7** or 8 %	3
Escalation rate of energy price (*e*)*	1.0, **5.0** or 10 %	3
Feed-in-tariff (*FIT*: no tariff or full tariff)	0.0 or 100 %	2
Investment grant (IG: purchasing discount as a percentage of the investment cost)	0.0 or 25 %	2

*) The last ten years average is underlined

Results / Time-Saving

In this example MAOS is reducing the time needed for full simulations during one optimisation run from 303 hours (0.6 hour * 505 building simulations) to ~19 hours (0.6 hour * 31 simulations). This results to 284 h time-saving on a Windows-based PC with a 2.83 GHz processor and 8 GB of RAM.

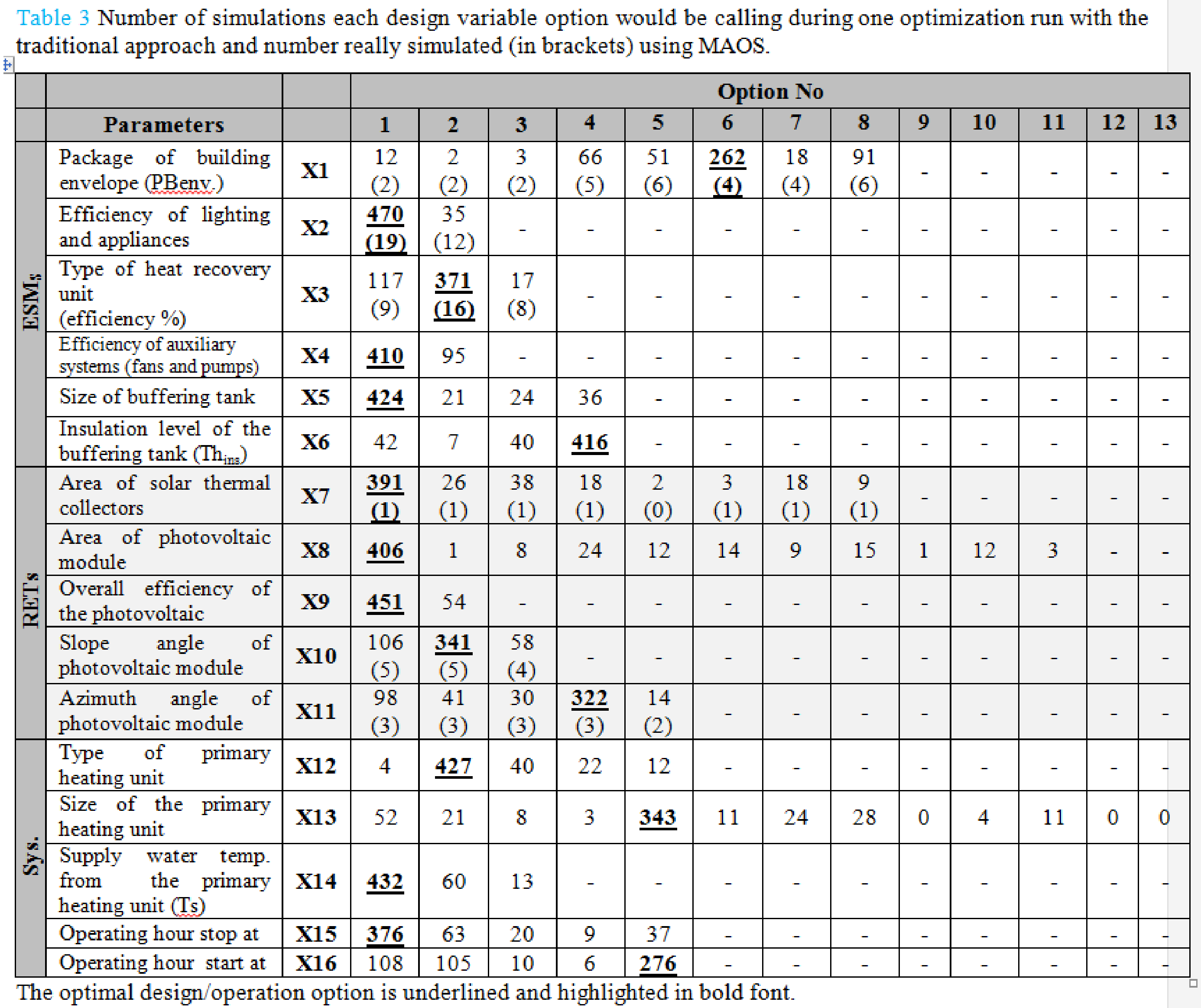


Table 3 Number of simulations each design variable option would be calling during one optimization run with the traditional approach and number really simulated (in brackets) using MAOS.

			Option No												
	Parameters		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
ESMs	Package of building envelope (PBenv.)	**X1**	12 (2)	2 (2)	3 (2)	66 (5)	51 (6)	**262** **(4)**	18 (4)	91 (6)	-	-	-	-	-
	Efficiency of lighting and appliances	**X2**	**470** **(19)**	35 (12)	-	-	-	-	-	-	-	-	-	-	-
	Type of heat recovery unit (efficiency %)	**X3**	117 (9)	**371** **(16)**	17 (8)	-	-	-	-	-	-	-	-	-	-
	Efficiency of auxiliary systems (fans and pumps)	**X4**	**410**	95	-	-	-	-	-	-	-	-	-	-	-
	Size of buffering tank	**X5**	**424**	21	24	36	-	-	-	-	-	-	-	-	-
	Insulation level of the buffering tank (Th_{ins})	**X6**	42	7	40	**416**	-	-	-	-	-	-	-	-	-
RETs	Area of solar thermal collectors	**X7**	**391** **(1)**	26 (1)	38 (1)	18 (1)	2 (0)	3 (1)	18 (1)	9 (1)	-	-	-	-	-
	Area of photovoltaic module	**X8**	**406**	1	8	24	12	14	9	15	1	12	3	-	-
	Overall efficiency of the photovoltaic	**X9**	**451**	54	-	-	-	-	-	-	-	-	-	-	-
	Slope angle of photovoltaic module	**X10**	106 (5)	**341** **(5)**	58 (4)	-	-	-	-	-	-	-	-	-	-
	Azimuth angle of photovoltaic module	**X11**	98 (3)	41 (3)	30 (3)	**322** **(3)**	14 (2)	-	-	-	-	-	-	-	-
Sys.	Type of primary heating unit	**X12**	4	**427**	40	22	12	-	-	-	-	-	-	-	-
	Size of the primary heating unit	**X13**	52	21	8	3	**343**	11	24	28	0	4	11	0	0
	Supply water temp. from the primary heating unit (Ts)	**X14**	**432**	60	13	-	-	-	-	-	-	-	-	-	-
	Operating hour stop at	**X15**	**376**	63	20	9	37	-	-	-	-	-	-	-	-
	Operating hour start at	**X16**	108	105	10	6	**276**	-	-	-	-	-	-	-	-

The optimal design/operation option is underlined and highlighted in bold font.

Table 4 Number of each combination of the first three decision variables (X1, X2, and X3) required to be evaluated during one optimization run using the traditional approach and number of really executed simulations (in brackets) using MAOS.

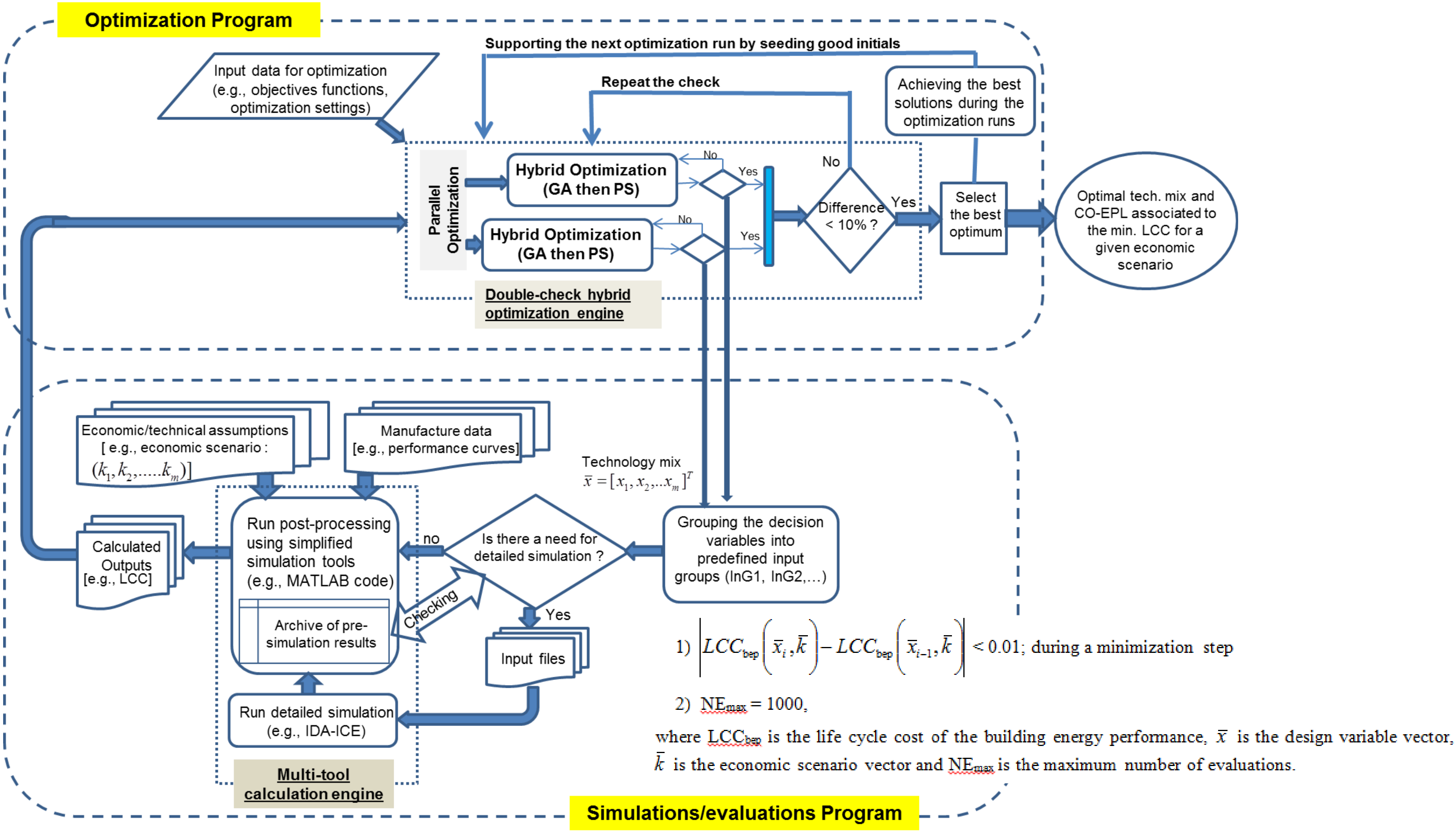
Lighting and appliances	Heat recovery option No	Building envelope option No								**Sum**
		1	2	3	4	5	6	7	8	
Standard lighting and appliances	1	8(1)	0(0)	0(0)	47 (1)	11(1)	4(1)	5(1)	32(1)	107(6)
	2	4(1)	1(1)	1(1)	12(1)	31(1)	**255(1)**	6(1)	43(1)	353(8)
	3	0(0)	0(0)	0(0)	1(1)	3(1)	2(1)	2(1)	2(1)	10(5)
High-efficient lighting and appliances	1	0(0)	0(0)	0(0)	2(1)	1(1)	0(0)	0(0)	7(1)	10(3)
	2	0(0)	0(0)	2(1)	4(1)	3(1)	1(1)	5(1)	3(1)	18(6)
	3	0(0)	1(1)	0(0)	0(0)	2(1)	0(0)	0(0)	4(1)	7(3)
Sum		12(2)	2(2)	3(2)	66(5)	51(6)	262(4)	18(4)	91(6)	505(31)

The optimal combination is underlined.

Table 5 Number of each combination of PV module azimuth and slope angles (X10 and X11) required to be evaluated during one optimization run and number really simulated (in brackets) using MAOS.

Slope angle of photovoltaic module option No	**Azimuth angle of photovoltaic module option No**					**Sum**
	1	2	3	4	5	
1	74 (1)	9 (1)	5 (1)	12 (1)	6 (1)	106 (5)
2	14 (1)	18 (1)	6 (1)	**296 (1)**	7 (1)	341(5)
3	10 (1)	14 (1)	19 (1)	15 (1)	0 (0)	58 (4)
Sum	98 (3)	41(3)	30 (3)	323 (3)	14 (2)	505(14)

A Multi-aid Optimization Scheme (MAOS)



1) $\left| LCC_{bep}\left(\bar{x}_i, \bar{k}\right) - LCC_{bep}\left(\bar{x}_{i-1}, \bar{k}\right) \right| < 0.01$; during a minimization step

2) $NE_{max} = 1000$,

where LCC_{bep} is the life cycle cost of the building energy performance, $\bar{x}$ is the design variable vector, $\bar{k}$ is the economic scenario vector and NE_{max} is the maximum number of evaluations.

Double-check test

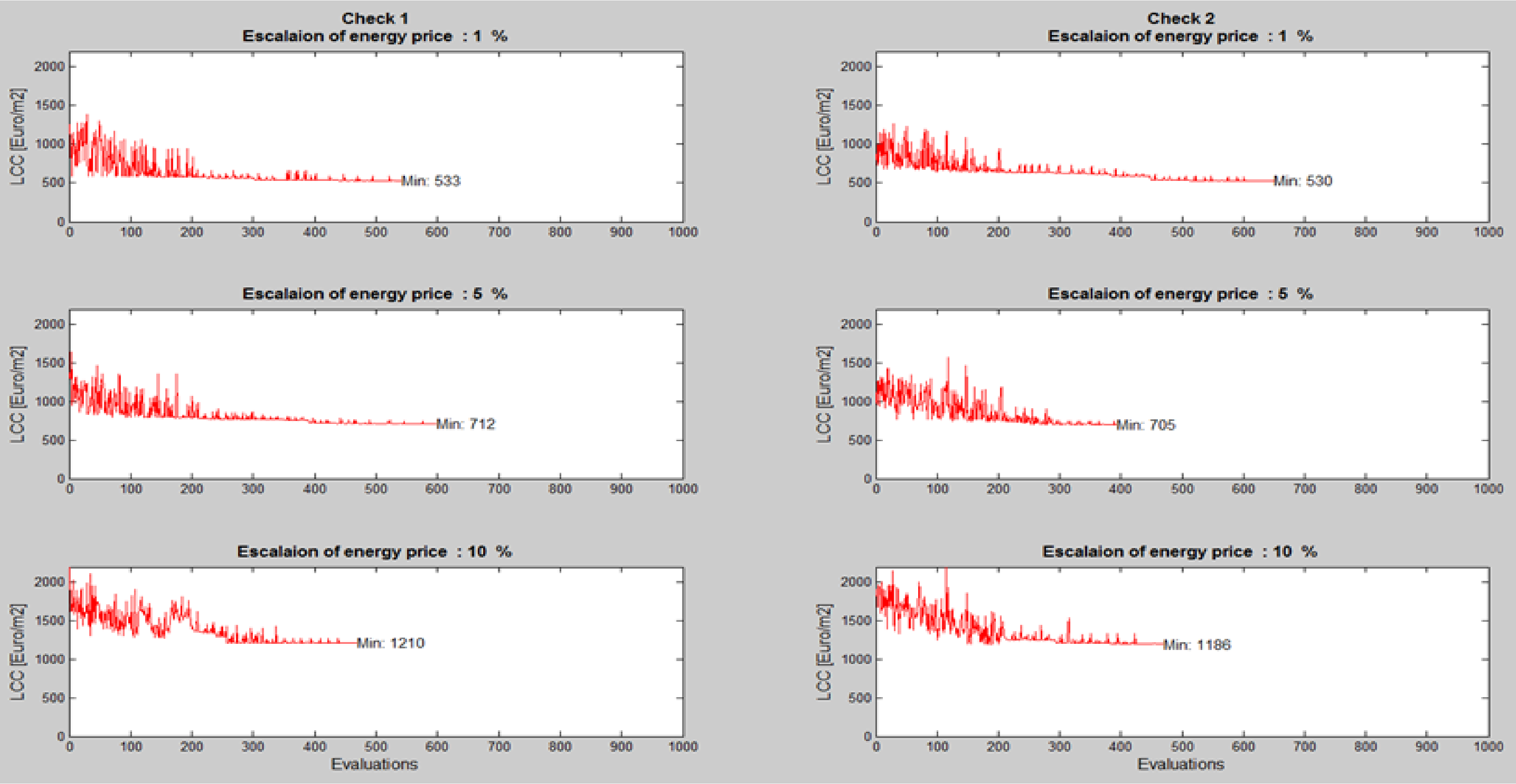


Figure 6 Three repeated optimization runs assuming 1%, 5%, and 10% escalation rates, respectively, where $i = 3.2\%$, $f = 1.7\%$, FiT=0%, iG=0%.

Repeatability of optimization results

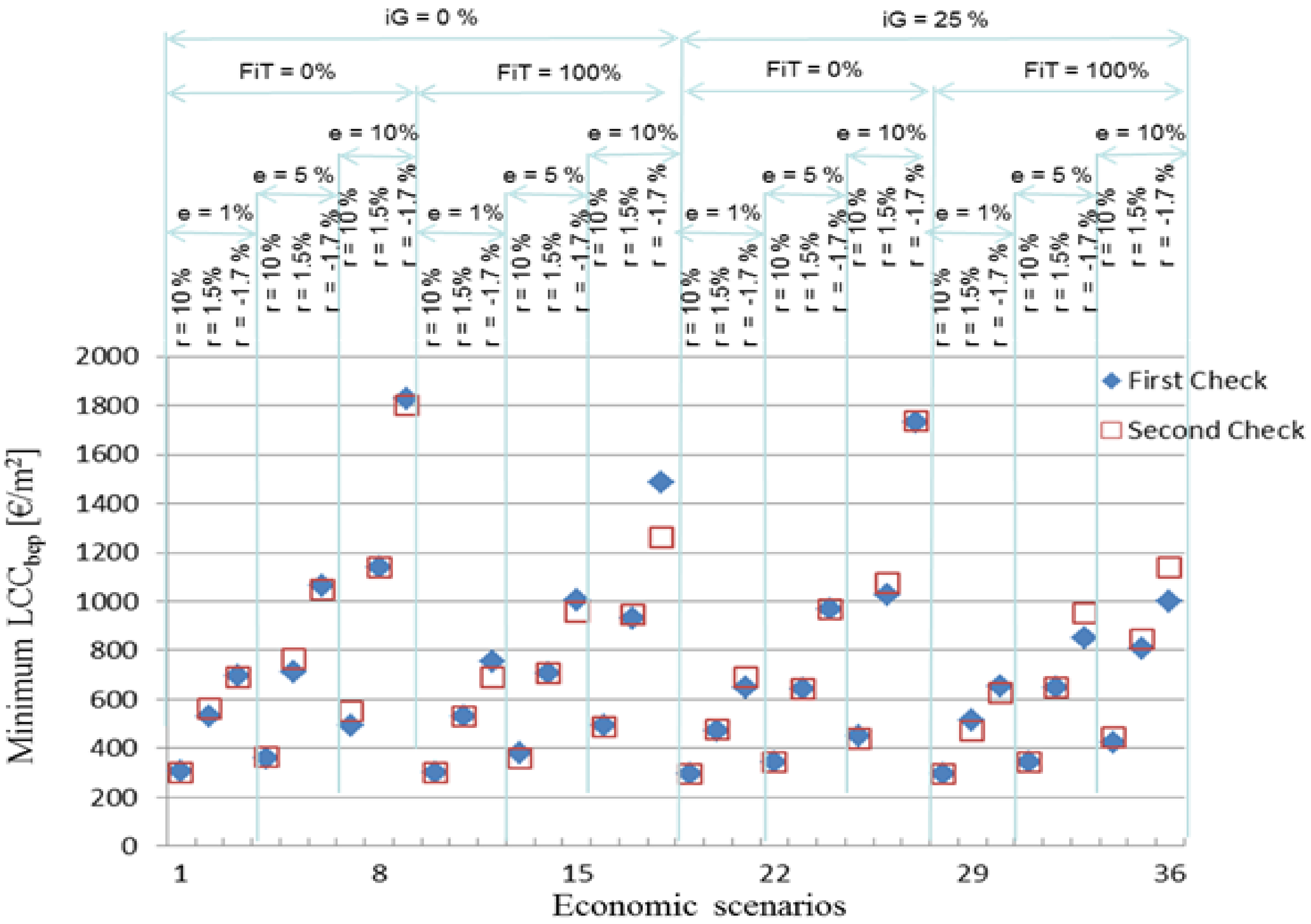
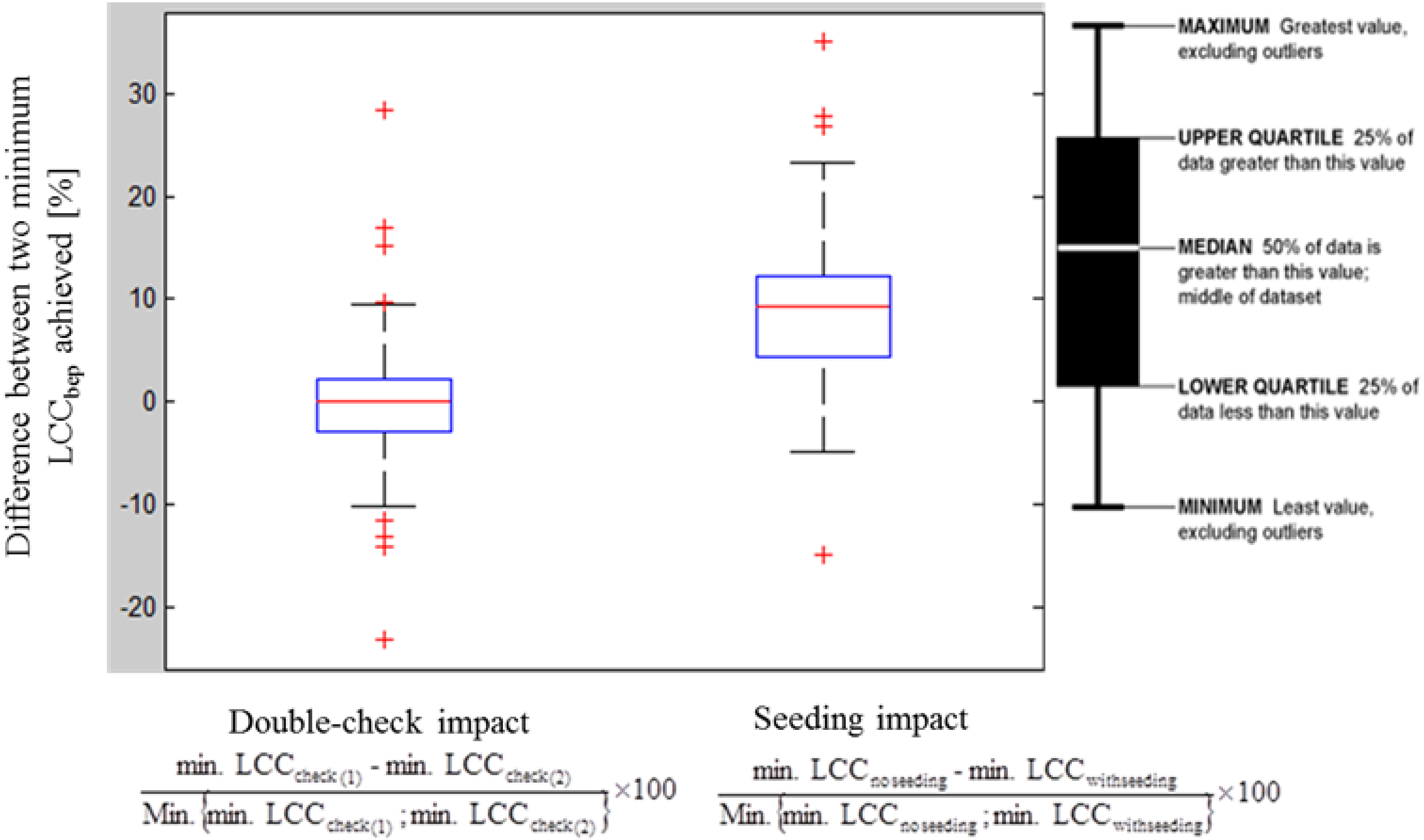


Figure 7 A sample for testing the repeatability of the optimization results. Optimization results of the first and second run for 36 economic scenarios.

Repeatability of optimization results



$$\frac{\text{min. } LCC_{check(1)} - \text{min. } LCC_{check(2)}}{\text{Min.}\{\text{min. } LCC_{check(1)} ; \text{min. } LCC_{check(2)}\}} \times 100$$

$$\frac{\text{min. } LCC_{no\,seeding} - \text{min. } LCC_{with\,seeding}}{\text{Min.}\{\text{min. } LCC_{no\,seeding} ; \text{min. } LCC_{with\,seeding}\}} \times 100$$

Figure 8. The impact of using the double-checking and seeding techniques.

Repeatability of optimization results

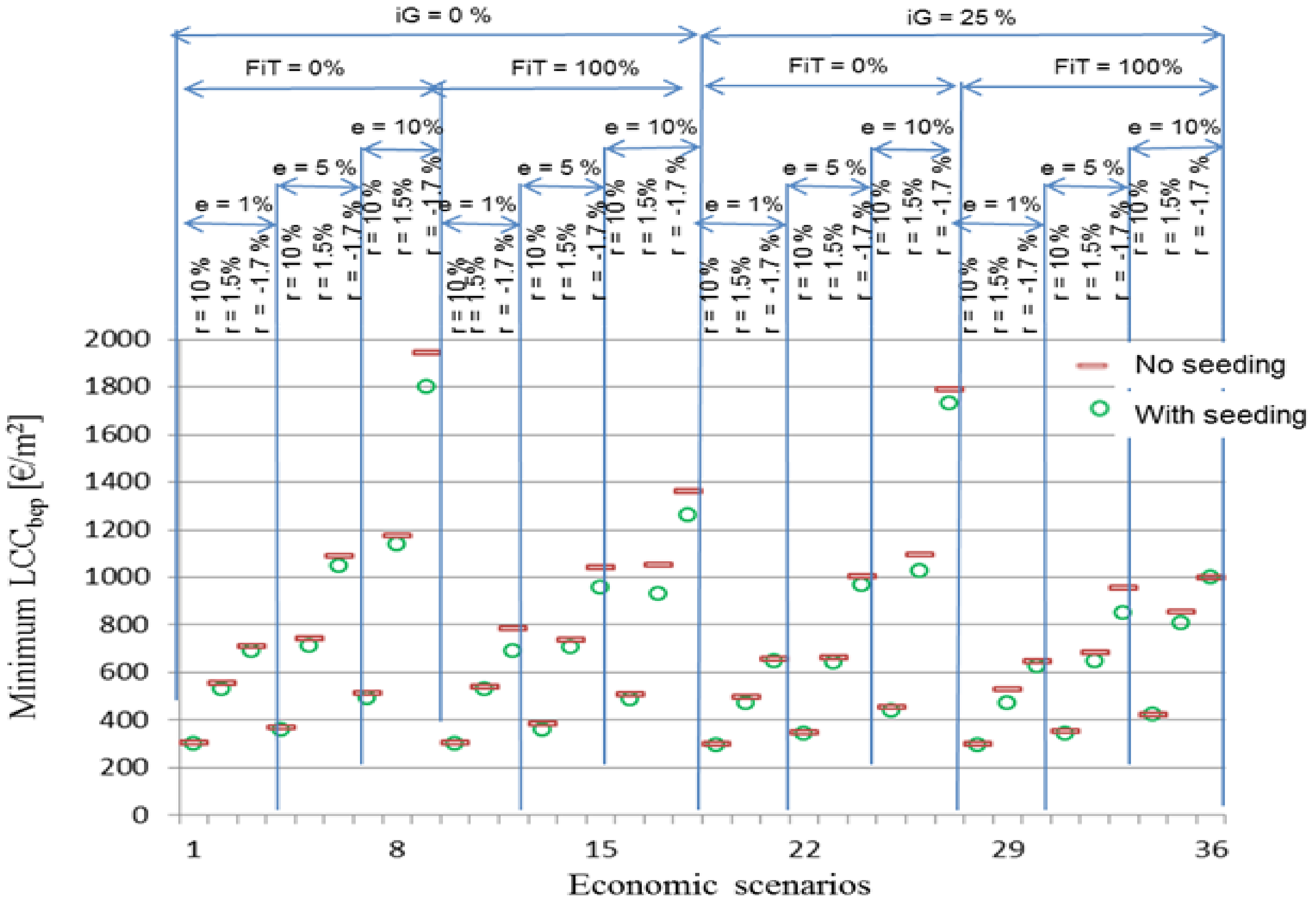


Figure 9 Comparison of the optimization performance when the hybrid optimization algorithm (*GA-PS*) is used with and without good initial population from previous optimization runs. 36 economic scenarios are shown.

Advantages of the seeding technique

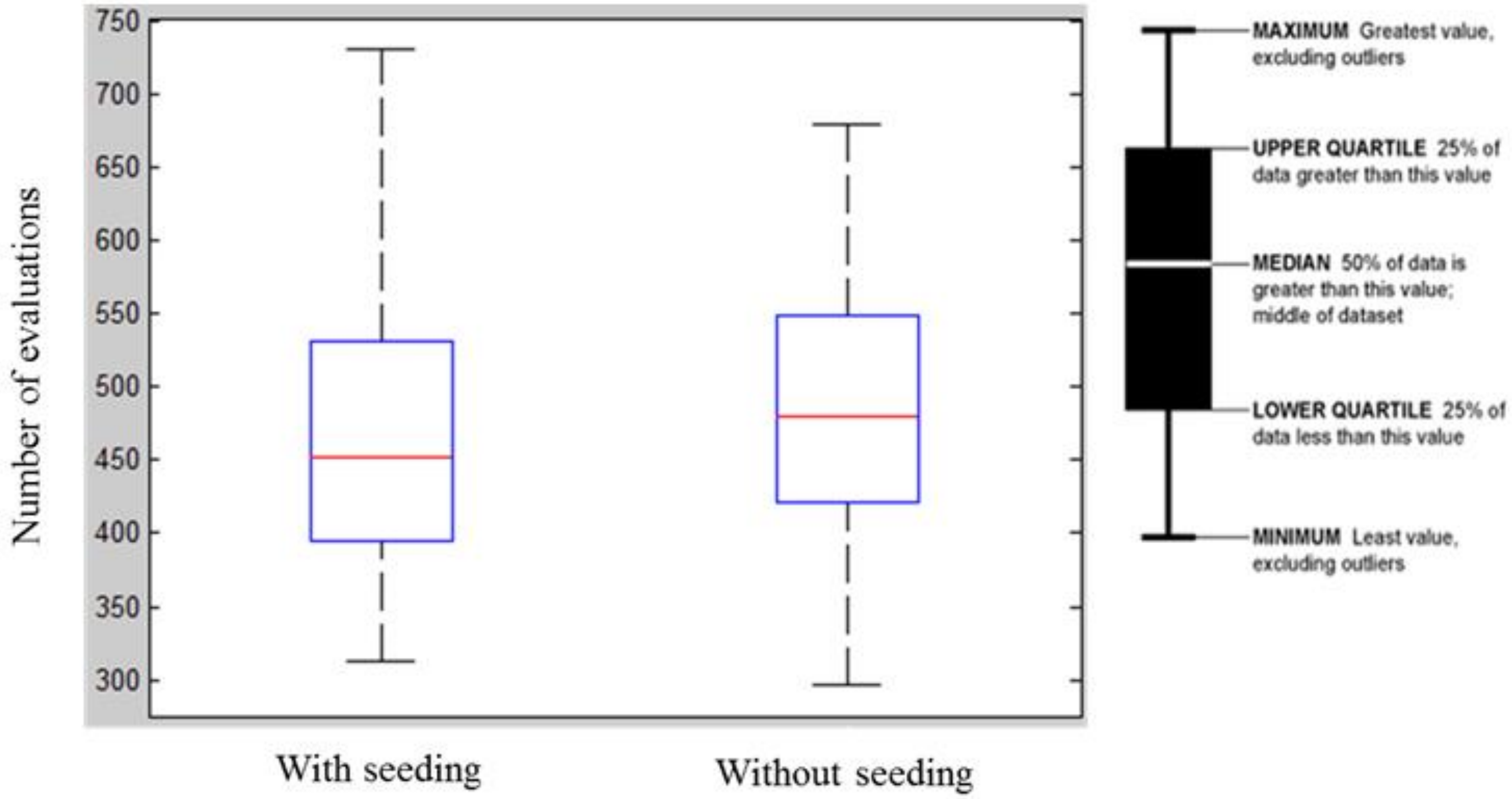


Figure 10 Boxplot presents the range of number of evaluations used for optimizing the 108 cases with and without applying the seeding technique.

At the same investment, the distance between the red (□) and green (x) points presents the gap between the net primary energy (NPE) with and without energy credit.

The cost-optimal solution does not include surplus energy to be exported to the grid (the generated energy from RES is used on-site or no RES)

Figure 11 cost-optimal investment versus cost-optimal energy performance level for all addressed economic scenarios leading to EPL_{co} less than the reference (~150 kWh/m2a). □CHP solutions circumscribed.

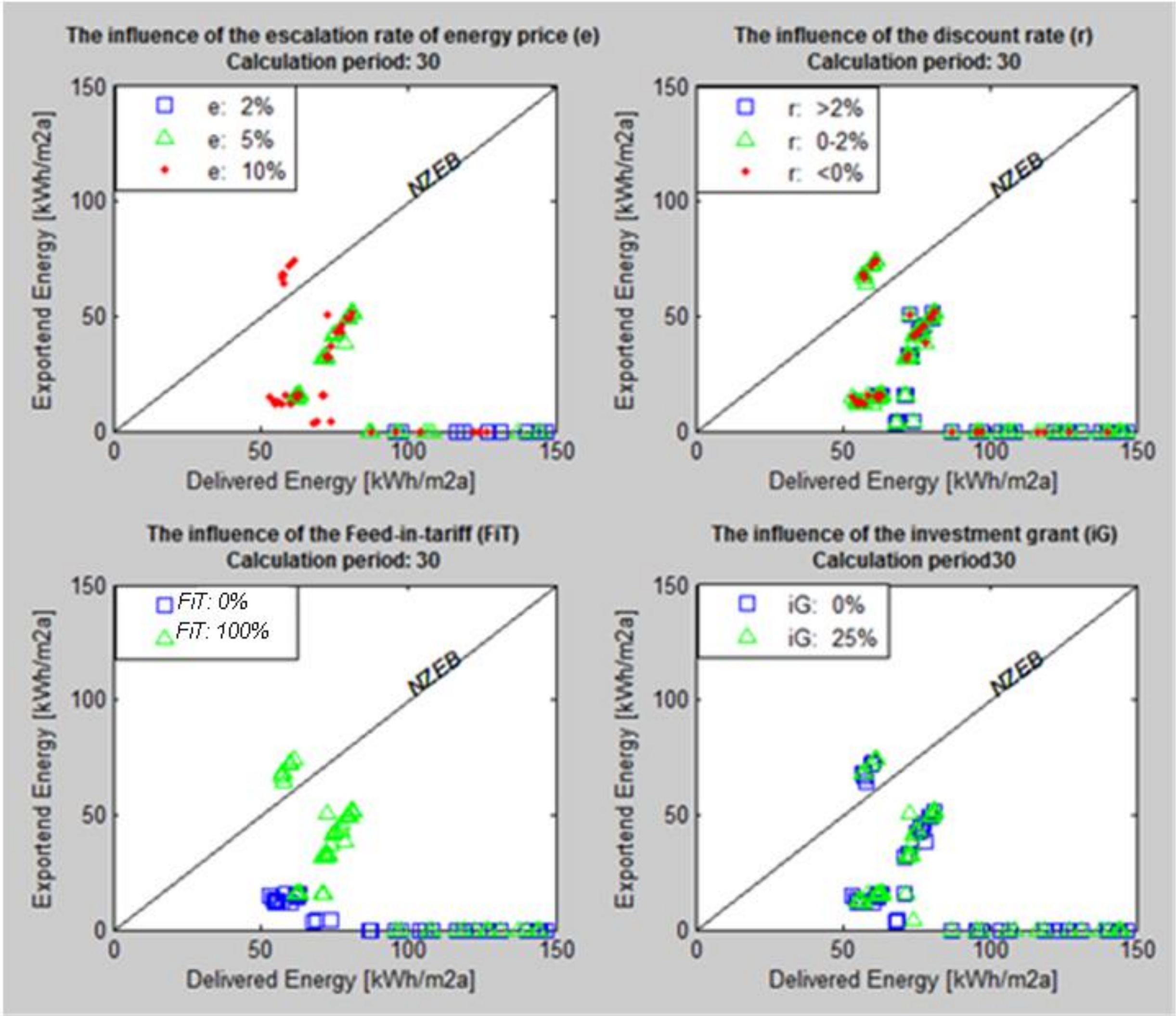
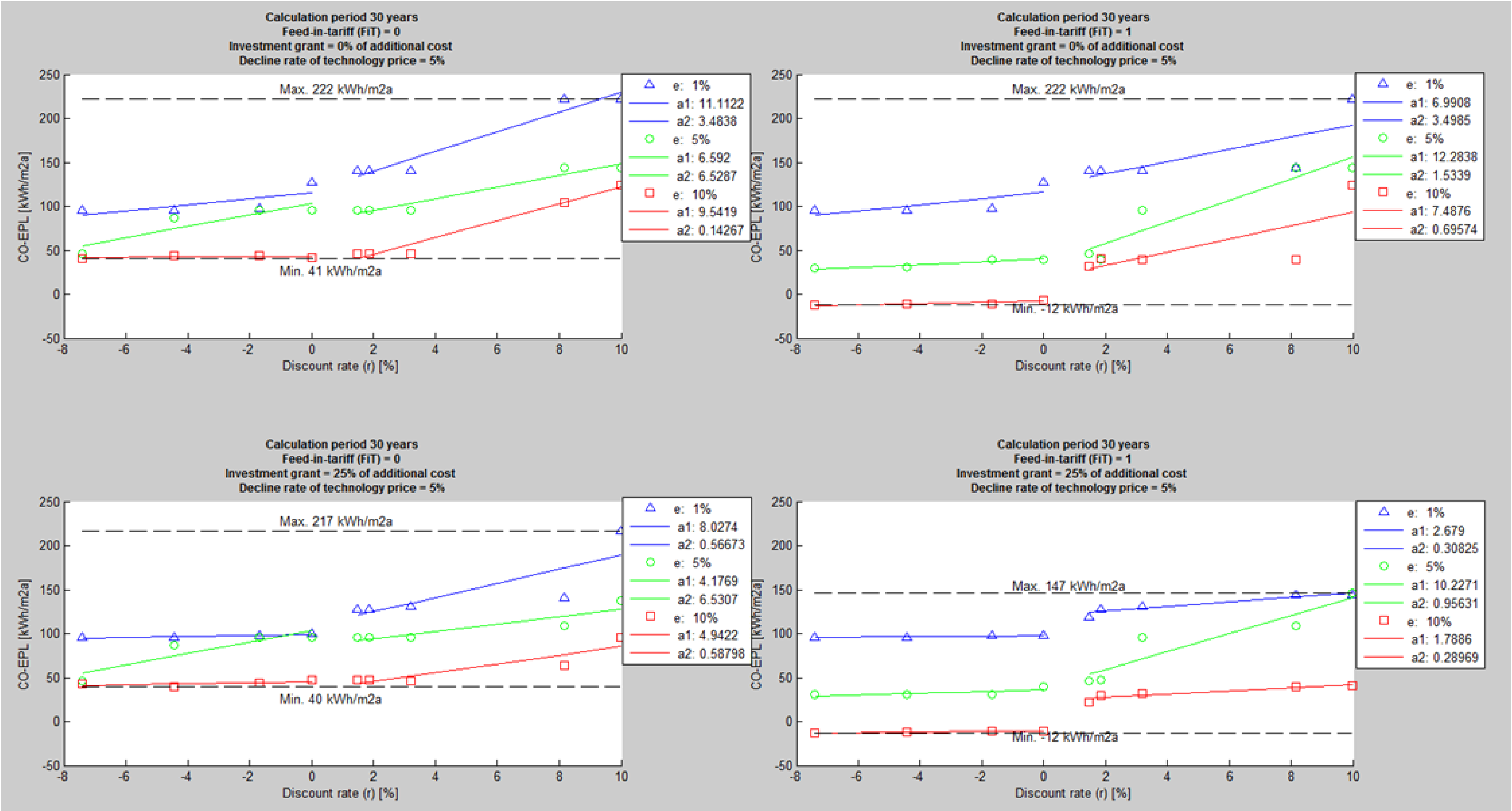


Figure 12 The influence of the economic parameters on the delivered versus exported yearly primary energy balance of the cost-optimal solutions for all addressed economic scenarios which lead to EPLco less than the reference value (150 kWh/m2a).

Optimization-based Sensitivity Analysis



Calculation period 30 years
Feed-in-tariff (FiT) = 0
Investment grant = 0% of additional cost
Decline rate of technology price = 5%

Calculation period 30 years
Feed-in-tariff (FiT) = 1
Investment grant = 0% of additional cost
Decline rate of technology price = 5%

Calculation period 30 years
Feed-in-tariff (FiT) = 0
Investment grant = 25% of additional cost
Decline rate of technology price = 5%

Calculation period 30 years
Feed-in-tariff (FiT) = 1
Investment grant = 25% of additional cost
Decline rate of technology price = 5%

Figure 13 cost-optimal energy performance level (*CO-EPL*) versus discount rate (r) assuming: 1%, 5% and 10% energy price escalation rates (*e*) for each subplot; *FiT*=0 and *FiT* =1 for the left and right hand side subplots, respectively; and *iG* = 0% of additional investment and *iG* = 25% of additional investment for the top and bottom subplots, respectively. Where **30-year** calculation period is assumed. Energy credit (100% credit) is given for exporting the surplus energy to the grid.

Optimization-based Sensitivity Analysis

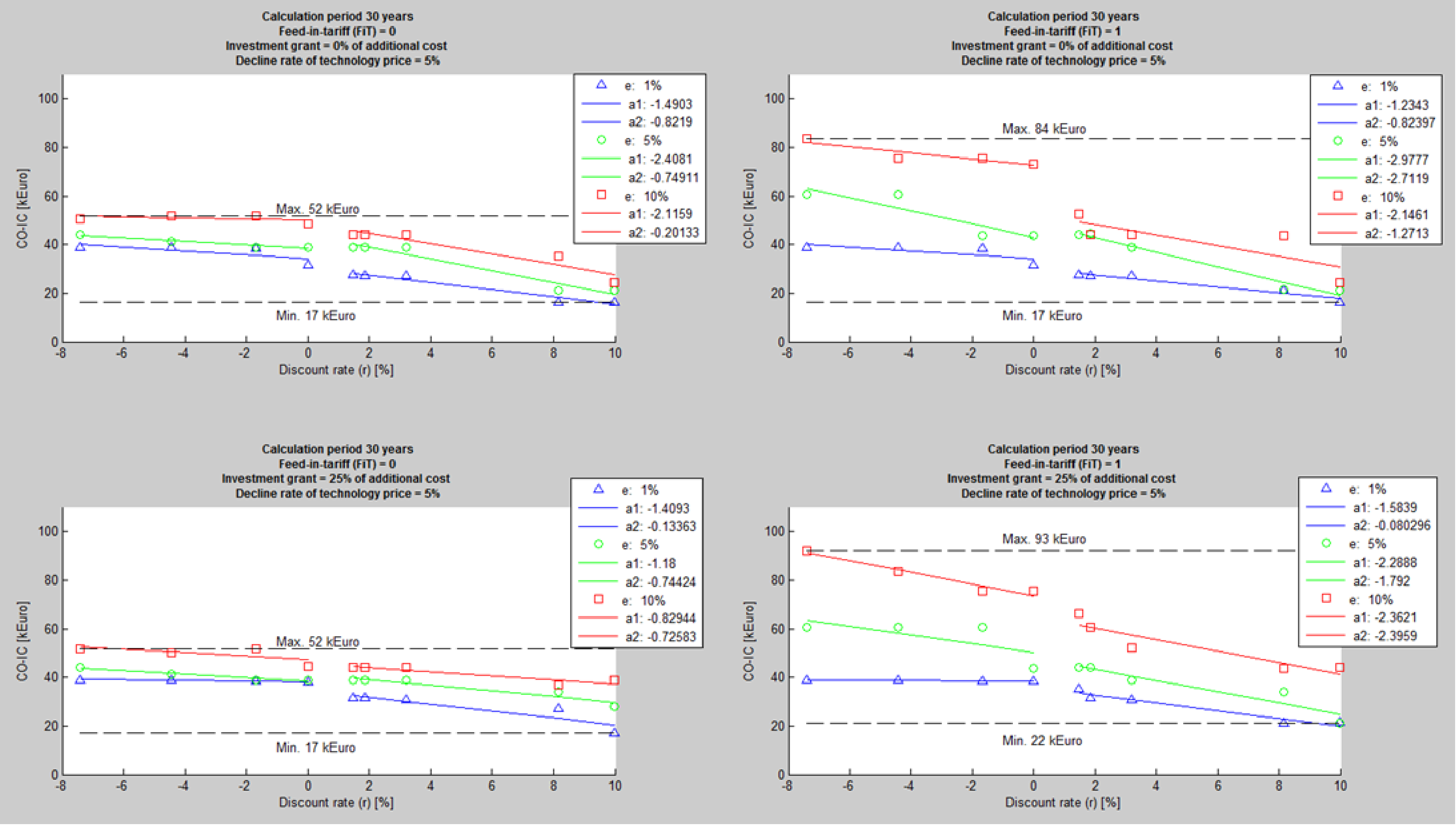


Figure 15 cost-optimal investment (*CO-IC*) versus discount rate (r) assuming: 1%, 5% and 10% energy price escalation rates (e) for each subplot; *FiT*=0 and *FiT* =1 for the left and right hand side subplots, respectively; and *iG* = 0% of additional investment and *iG* = 25% of additional investment for the top and bottom subplots, respectively. Where **30-year** calculation period is assumed.

Conclusions

- The complexity of our optimization problems is increasing dramatically.

- The execution time of simulation-based optimization can be reduced significantly (possibility 90%) by using smart optimization approach.

- The double-checking test is important for ensuring high quality of the optimised minima.

- Seeding good initials for the combined Genetic Algorithm and Pattern Search is improving the quality of the results by finding deeper minima than without seeding and by reducing the required number of computational evaluations.

- As a final conclusion, the introduced scheme (MAOS) can be considered as practical tool to increase the investors' confidence and trust in investment towards nZBs by providing fast and comprehensive analysis.

NTNU – Trondheim
Norwegian University of
Science and Technology

Thank You

Mohamed Hamdy, **Phd, M.Sc., Eng.,**
Associate professor – [my LinkedIn]

Department of Civil and Transport Engineering

Mobile : (+47) 92 05 28 76
Fax : (+47) 73 59 70 21
Email : Mohamed.Hamdy@ntnu.no
Skype : MHamdy82

Mohamed Hamdy
Eindhoven University of Technology
Energy, HVAC, Building, Simulation, Optimization.
Verified email at tue.nl - Homepage
My profile is public

Title	Cited by	Year
☐ A multi-stage optimization method for cost-optimal and nearly-zero-energy building solutions in line with the EPBD-recast 2010 M Hamdy, A Hasan, K Siren Energy and Buildings 56, 189-203	114	2013

Citation indices	All
Citations	507
h-index	9
i10-index	9