NTNU – Trondheim
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Towards Practical Optimization Approach for Investigating Computationally-Expensive Integrated Building Designs

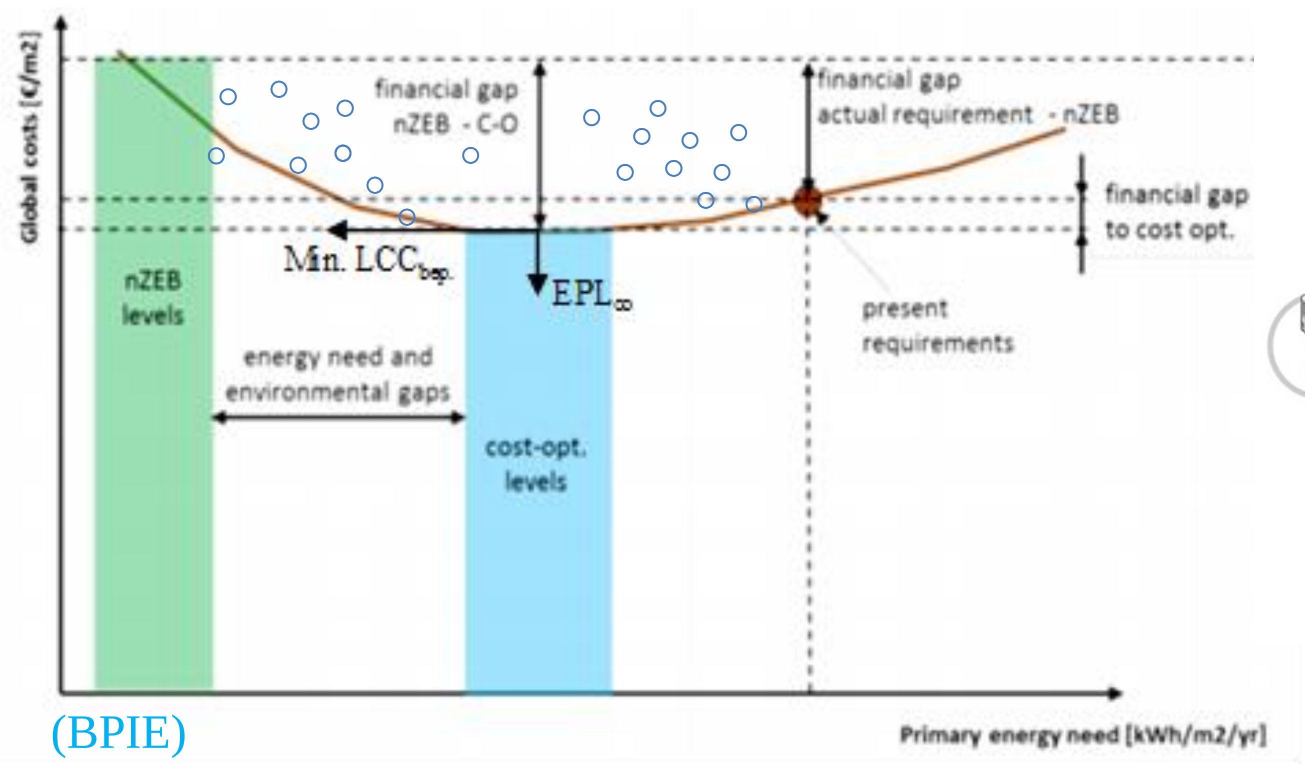
Mohamed Hamdy, **Phd, M.Sc., Eng.,**
Associate professor – my LinkedIn

Department of Civil and Transport Engineering
Visiting address: Høgskoleringen 7A, Room 2-236

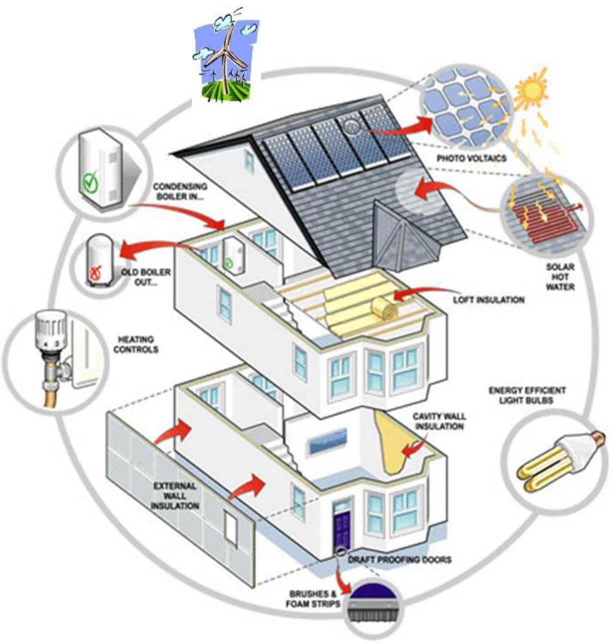
Mobile : (+47) 92 05 28 76
Fax : (+47) 73 59 70 21
Email : Mohamed.Hamdy@ntnu.no
Skype : MHamdy82

Background and Motivation

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).

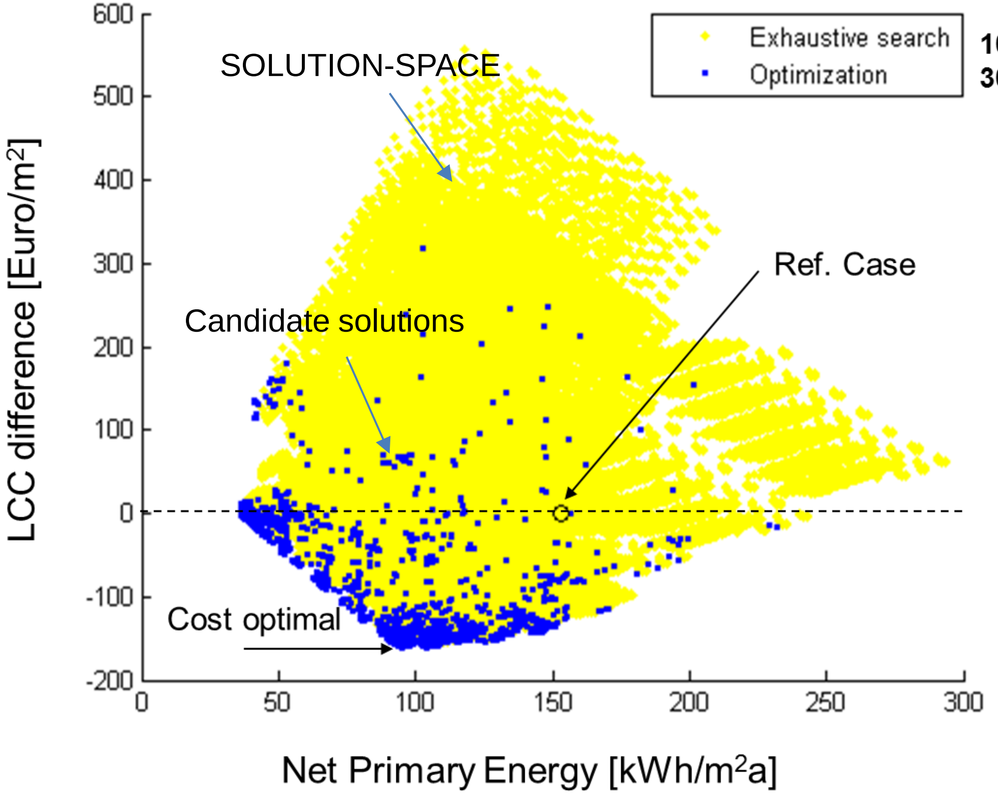


(BPIE)

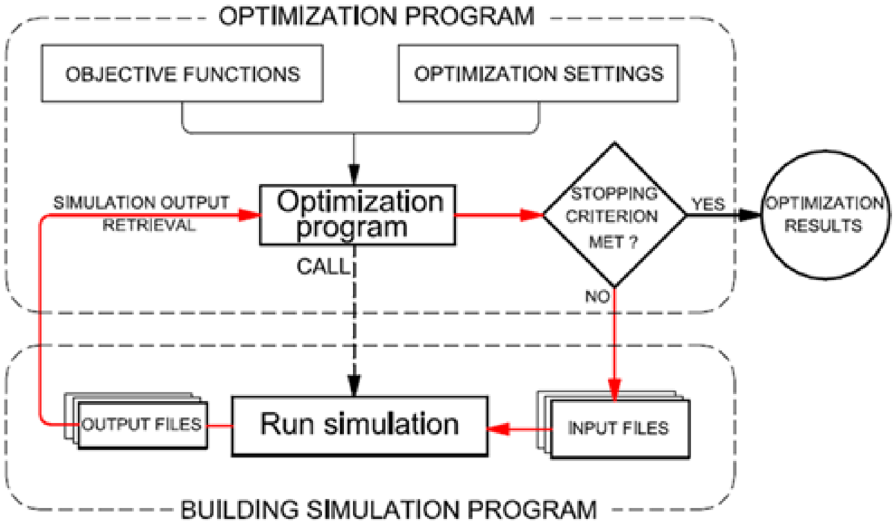


Design variables

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) .

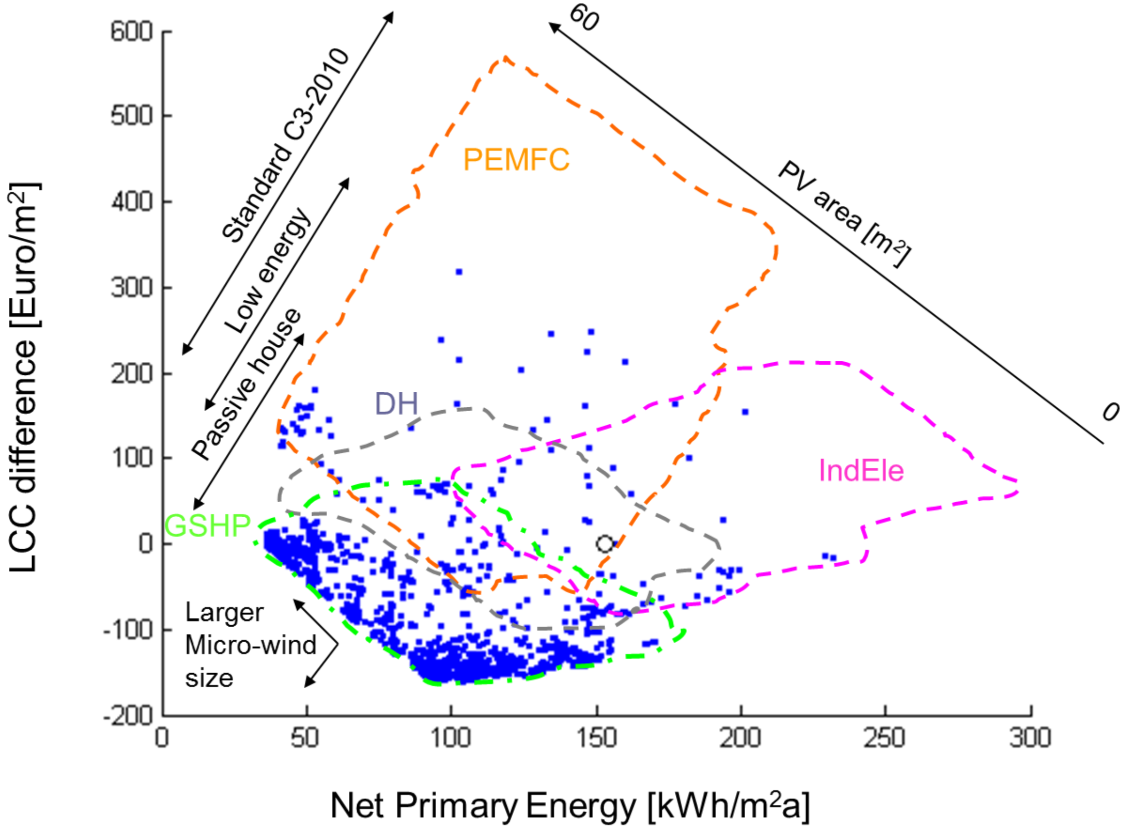
Source: Hamdy M., Hasan A. (2013). A Holistic Simulation-Based Optimization Approach for Dimentioning Cost Optimal and nearly-Zero-Energy Buildings. 1st IBPSA-Egypt Conference, Building Simulation Cairo 2013. 23rd- 24th June 2013.

A Question

The cost-optimal solution depends on ……. ??

The Cost-Optimal Solution Depends on…….?

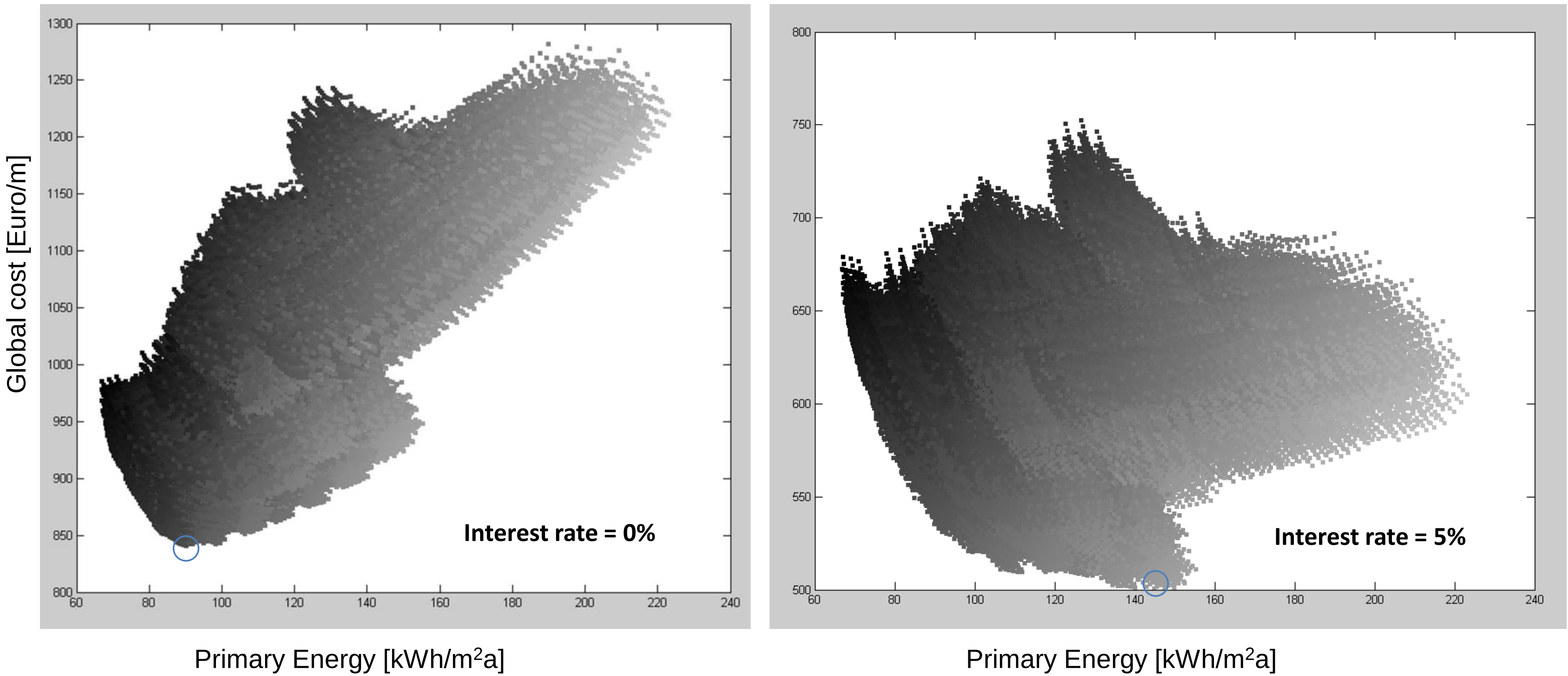
1- The possible design/operation options (Solution-Space)



Source: Hasan, Ala; Palonen, M.; Hamdy, M. (2014). Simulation-based optimization for energy and buildings. World Renewable Energy Congress XIII, WREC 2014, 3 - 8 August 2014, London, United Kingdom. World Renewable Energy Network WREN (2014), 7 p.

The Cost-Optimal Solution Depends on…….?

2- technical assumptions as well as financial and climate scenario (e.g., lifespan, interest rate, decline rate of technology price, etc.,)



The Cost-Optimal Solution Depends on…….?

The cost-optimal solution is function of :

- 1- Solutions Space
- 2- assumptions/ scenario

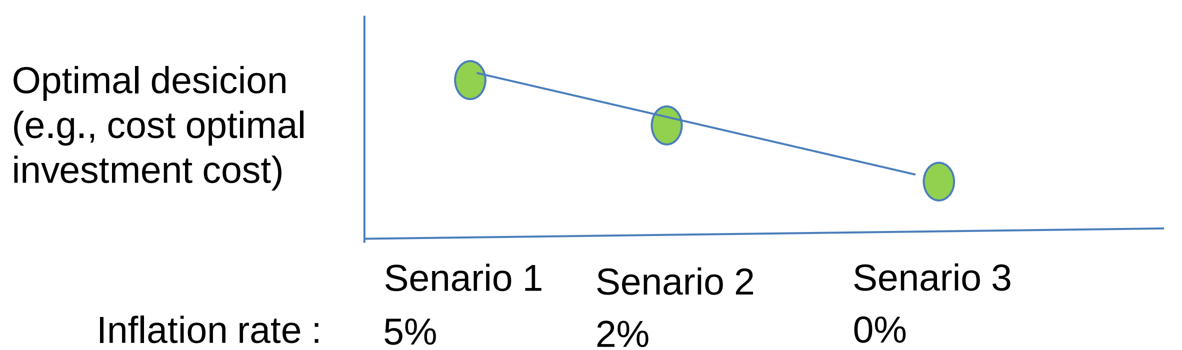
The complexity of finding robust cost-optimal solution increases as long as :

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

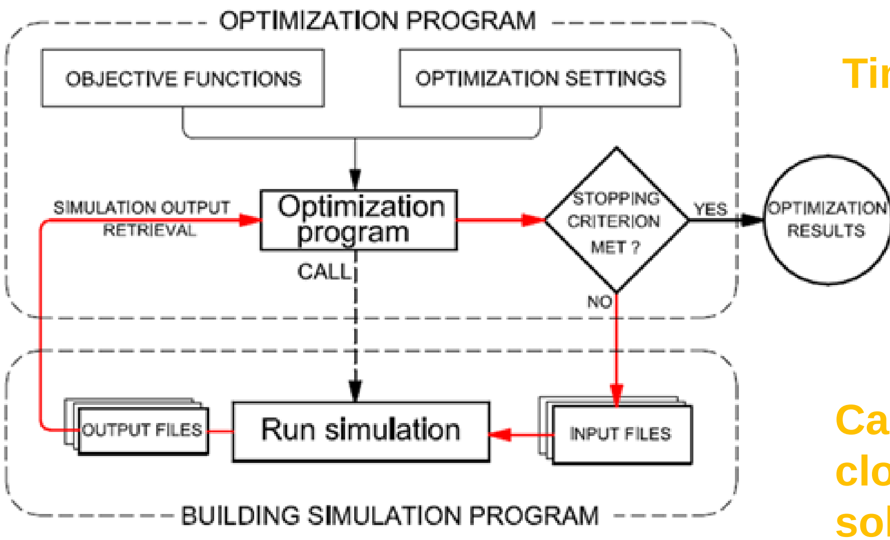
Optimization-based

Sensitivity Analysis

Optimization-based Sensitivity Analysis

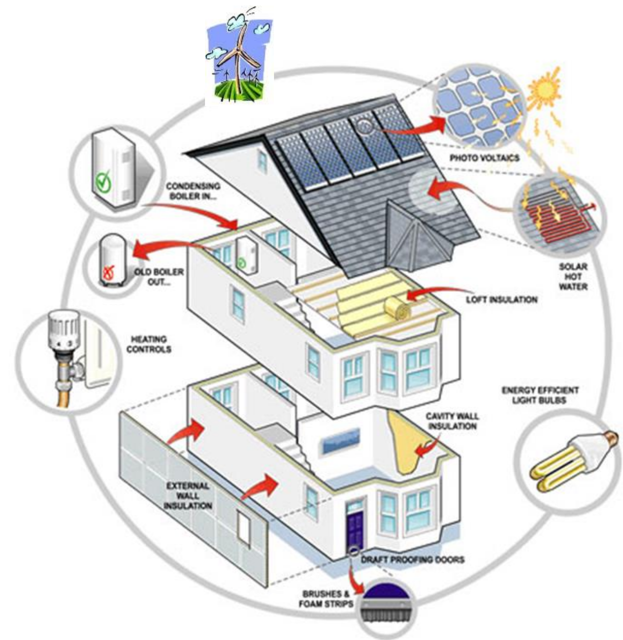


Traditional Simulation-Based Optimization



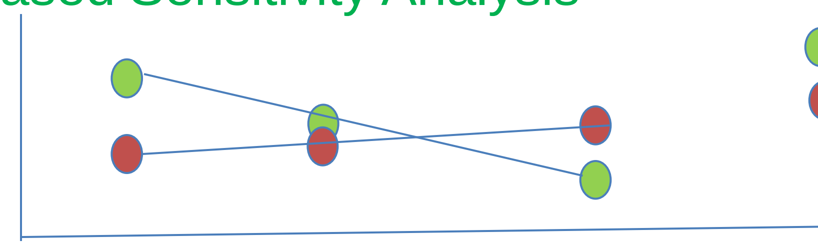
Time consuming

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



Optimization-based Sensitivity Analysis

Optimal desicion (e.g., cost optimal investment cost)



Optimization results (close-to-optimum)

Optimization results

	Senario 1	Senario 2	Senario 3
Inflation rate :	5%	2%	0%

A Multi-aid Optimization Scheme (MAOS)

Journal

Journal of Building Performance Simulation ›

Volume 9, 2016 - Issue 4

Enter keywords, authors, DOI

Research article

A multi-aid optimization scheme for large-scale investigation of cost-optimality and energy performance of buildings

Mohamed Hamdy & Kai Sirén

Pages 411-430 | Received 14 Apr 2015, Accepted 01 Jul 2015, Published online: 07 Aug 2015

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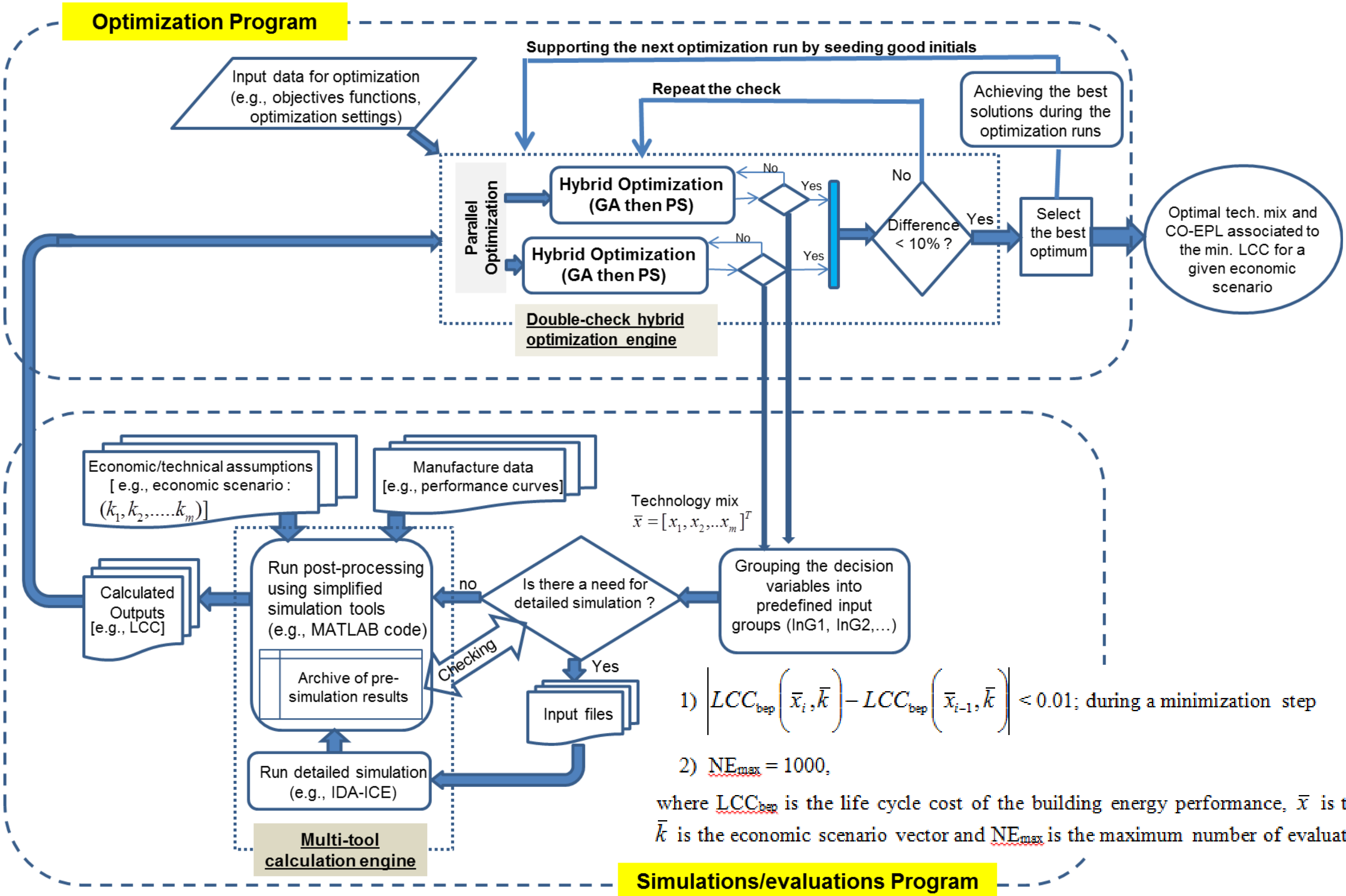
A Multi-aid Optimization Scheme (MAOS)



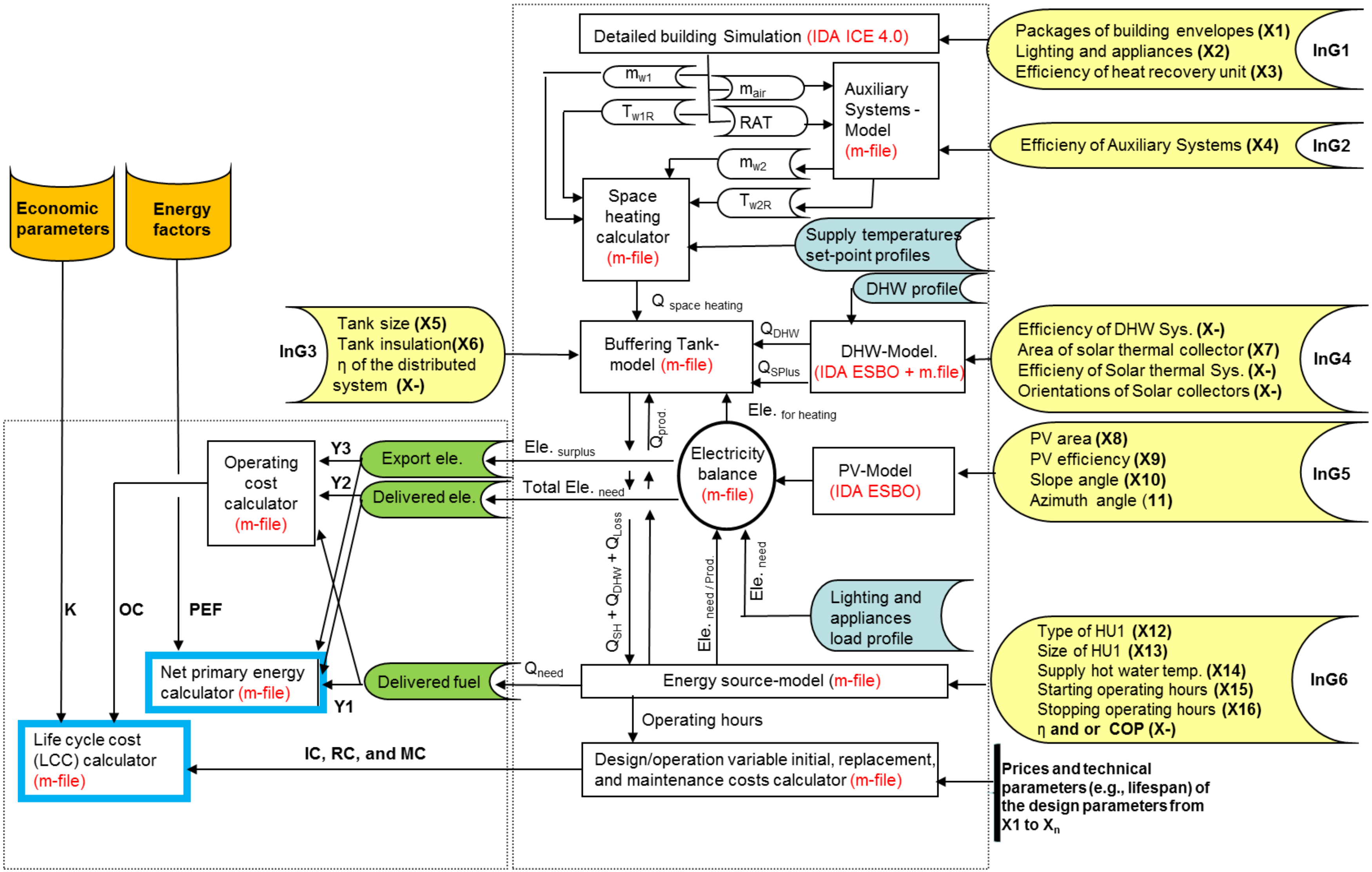
1) $\left| LCC_{bep}\left(\bar{x}_i, \bar{k}\right) - LCC_{bep}\left(\bar{x}_{i-1}, \bar{k}\right) \right| < 0.01$; during a minimization step

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.

Hamdy M., Sirén K**. (2015).** A Multi-Aid Optimization Scheme for Large-scale Investigation of Cost-optimality and Energy Performance of Buildings. Journal of Building Performance Simulation. ISSN: 1940-1493 (Print) 1940-1507 (Online)

The Multi-tool Calculation Engine (Grouping)



A Case Study / The Building

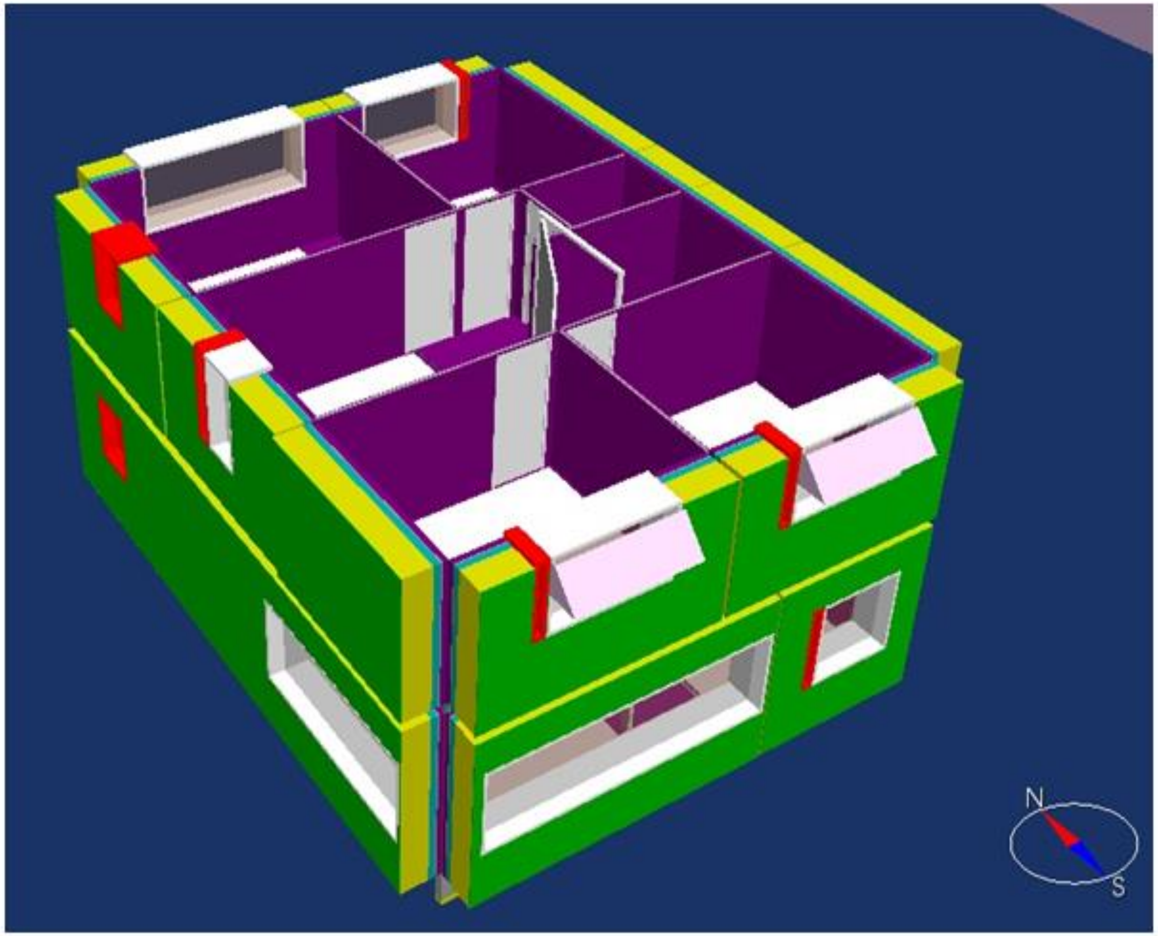


Figure 5 The studied single-family house. The small windows (red) are operable for free cooling to provide natural ventilation in summer.

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 pv + 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 °C	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 optimization 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.

	Parameters		Option No 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)	-	-	-	-	-
ESMs	Efficiency of lighting and appliances	X2	**470 (19)**	35 (12)	-	-	-	-	-	-	-	-	-	-	-
ESMs	Type of heat recovery unit (efficiency %)	X3	117 (9)	**371 (16)**	17 (8)	-	-	-	-	-	-	-	-	-	-
ESMs	Efficiency of auxiliary systems (fans and pumps)	X4	**410**	95	-	-	-	-	-	-	-	-	-	-	-
ESMs	Size of buffering tank	X5	**424**	21	24	36	-	-	-	-	-	-	-	-	-
ESMs	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)	-	-	-	-	-
RETs	Area of photovoltaic module	X8	**406**	1	8	24	12	14	9	15	1	12	3	-	-
RETs	Overall efficiency of the photovoltaic	X9	**451**	54	-	-	-	-	-	-	-	-	-	-	-
RETs	Slope angle of photovoltaic module	X10	106 (5)	**341 (5)**	58 (4)	-	-	-	-	-	-	-	-	-	-
RETs	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	-	-	-	-	-	-	-	-
Sys.	Size of the primary heating unit	X13	52	21	8	3	**343**	11	24	28	0	4	11	0	0
Sys.	Supply water temp. from the primary heating unit (Ts)	X14	**432**	60	13	-	-	-	-	-	-	-	-	-	-
Sys.	Operating hour stop at	X15	**376**	63	20	9	37	-	-	-	-	-	-	-	-
Sys.	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.

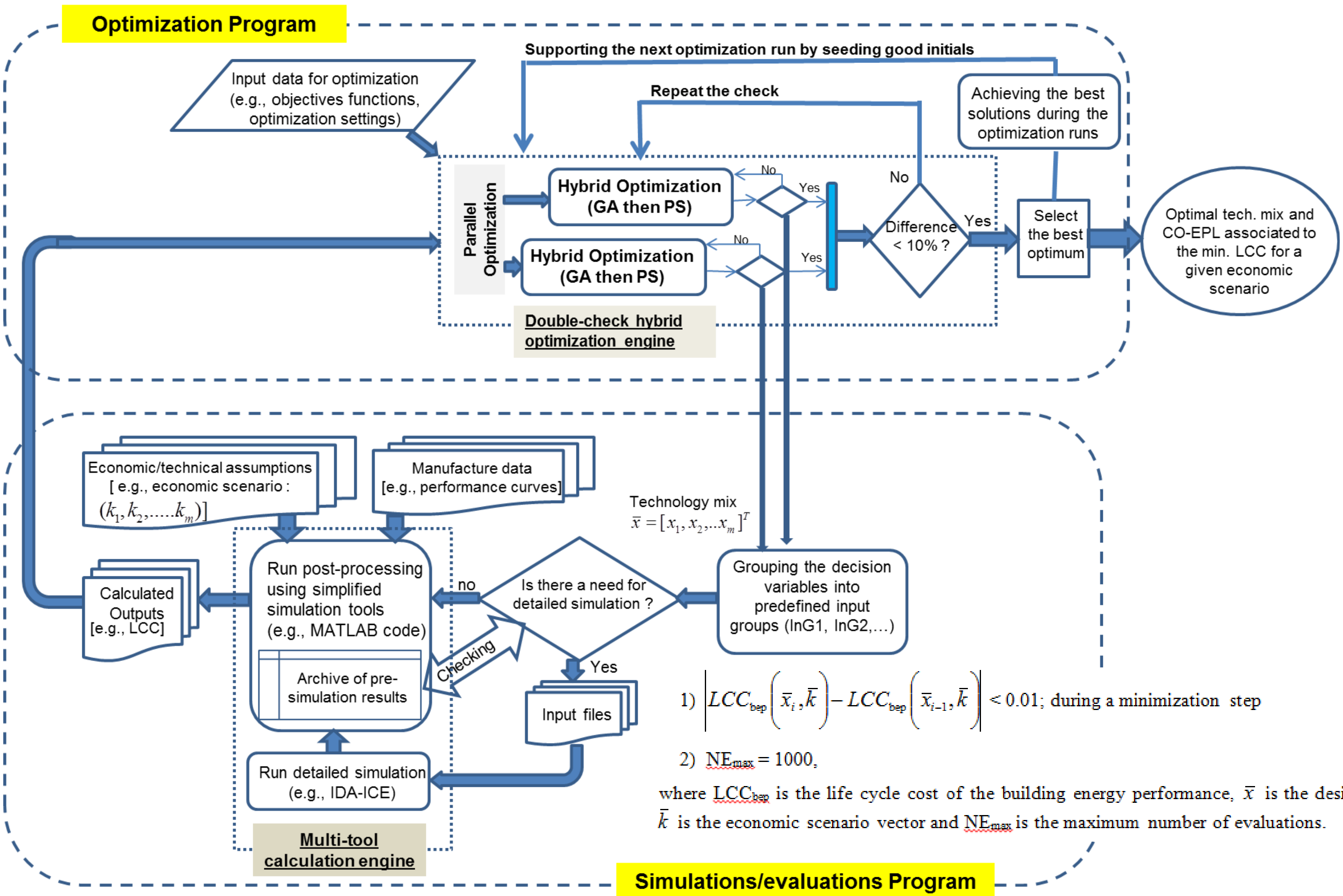
Lighting and appliances	Heat recovery option No	Building envelope option No								**Sum**
		1	2	3	4	5	6	7	8	
Standard lighting and appliances	1	8(1)	0(0)	0(0)	47 (1)	11(1)	4(1)	5(1)	32(1)	107(6)
	2	4(1)	1(1)	1(1)	12(1)	31(1)	**255(1)**	6(1)	43(1)	353(8)
	3	0(0)	0(0)	0(0)	1(1)	3(1)	2(1)	2(1)	2(1)	10(5)
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 Approach

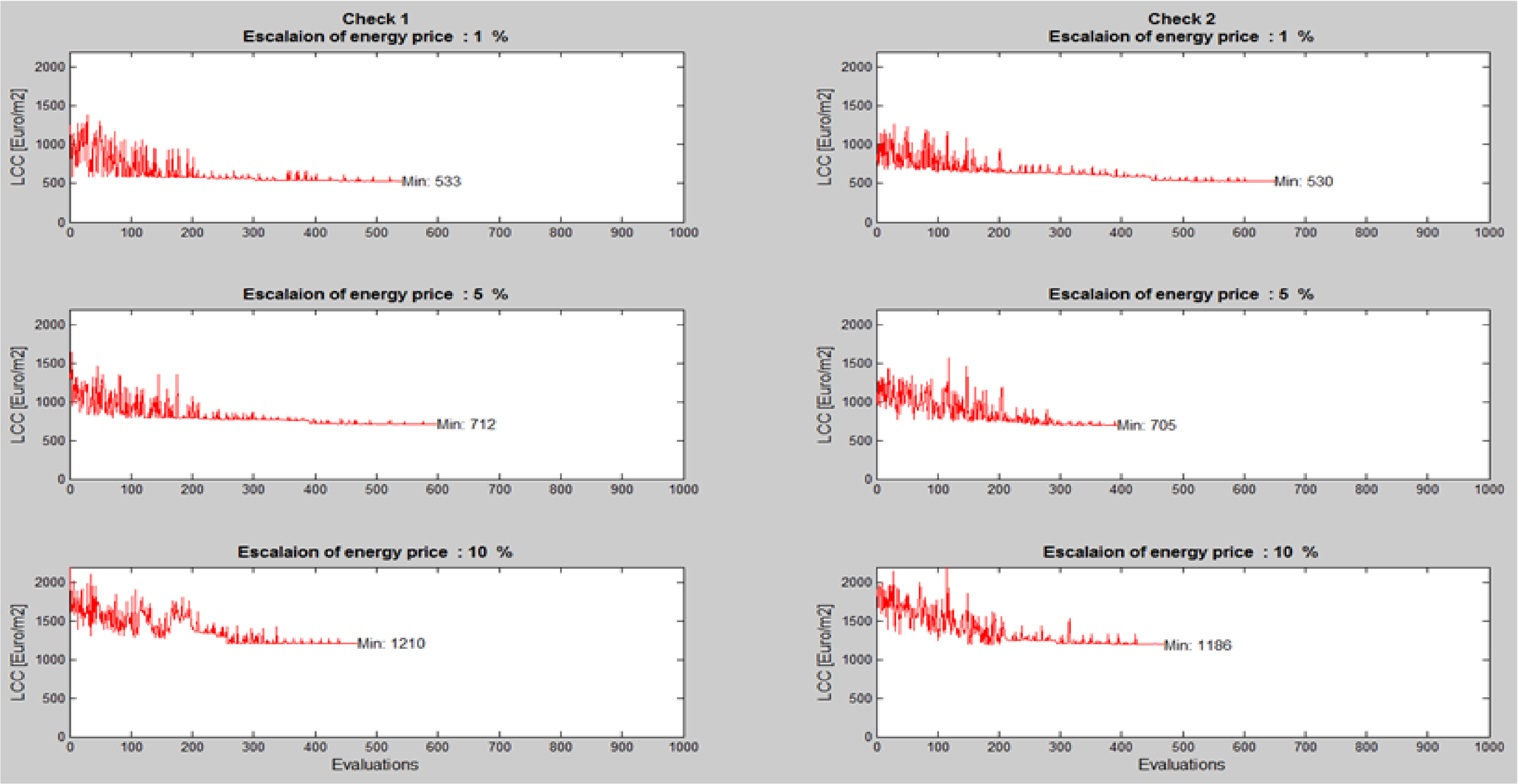


Figure 6 Three repeated optimization runs assuming 1%, 5%, and 10% escalation rates, respectively, where $i = 3.2\%$, $f = 1.7\%$, FiT=0%, iG=0%.

Double-check Approach

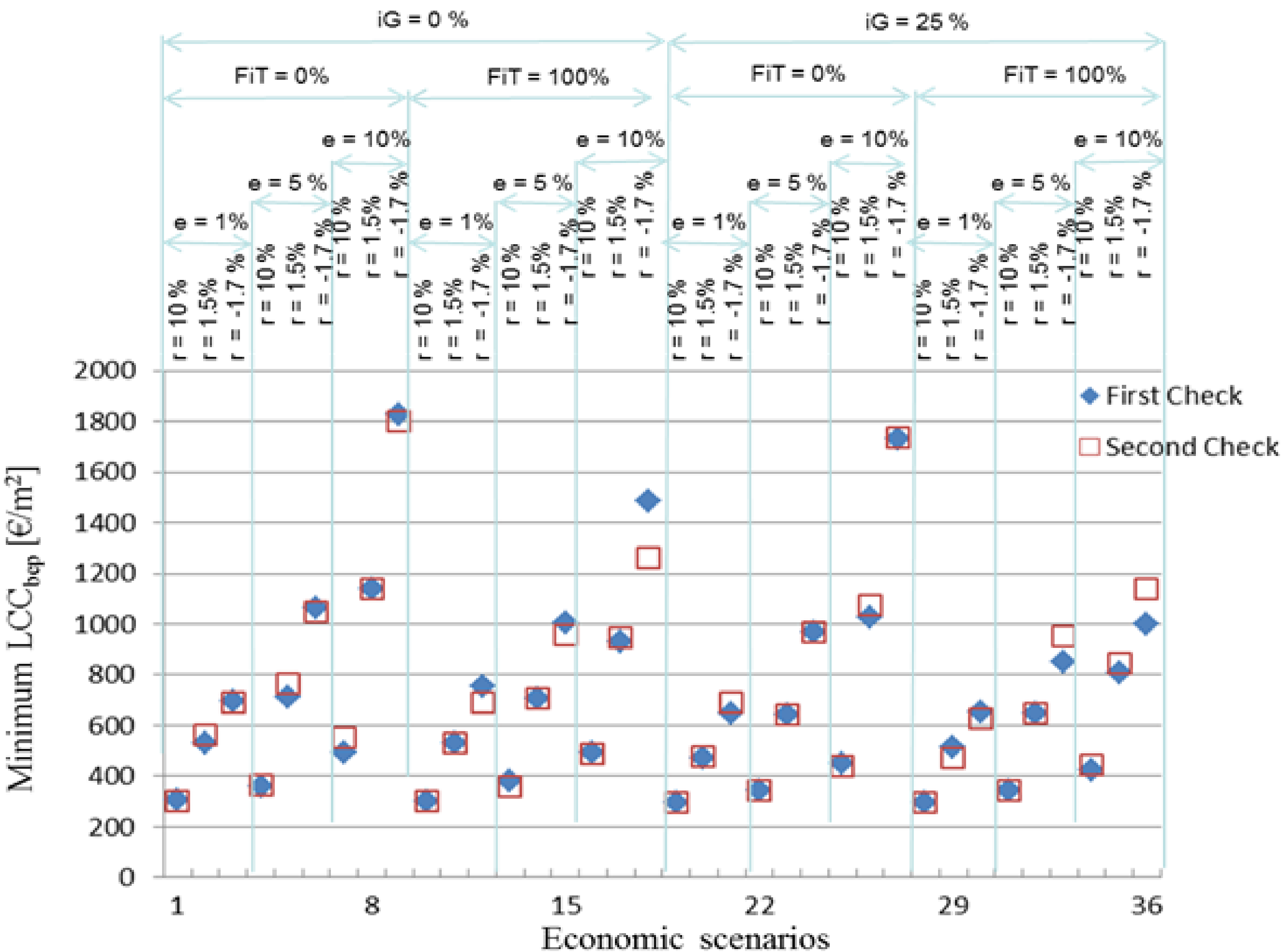


Figure 7 A sample for testing the repeatability of the optimization results. Optimization results of the first and second run for 36 economic scenarios.

Seeding Approach

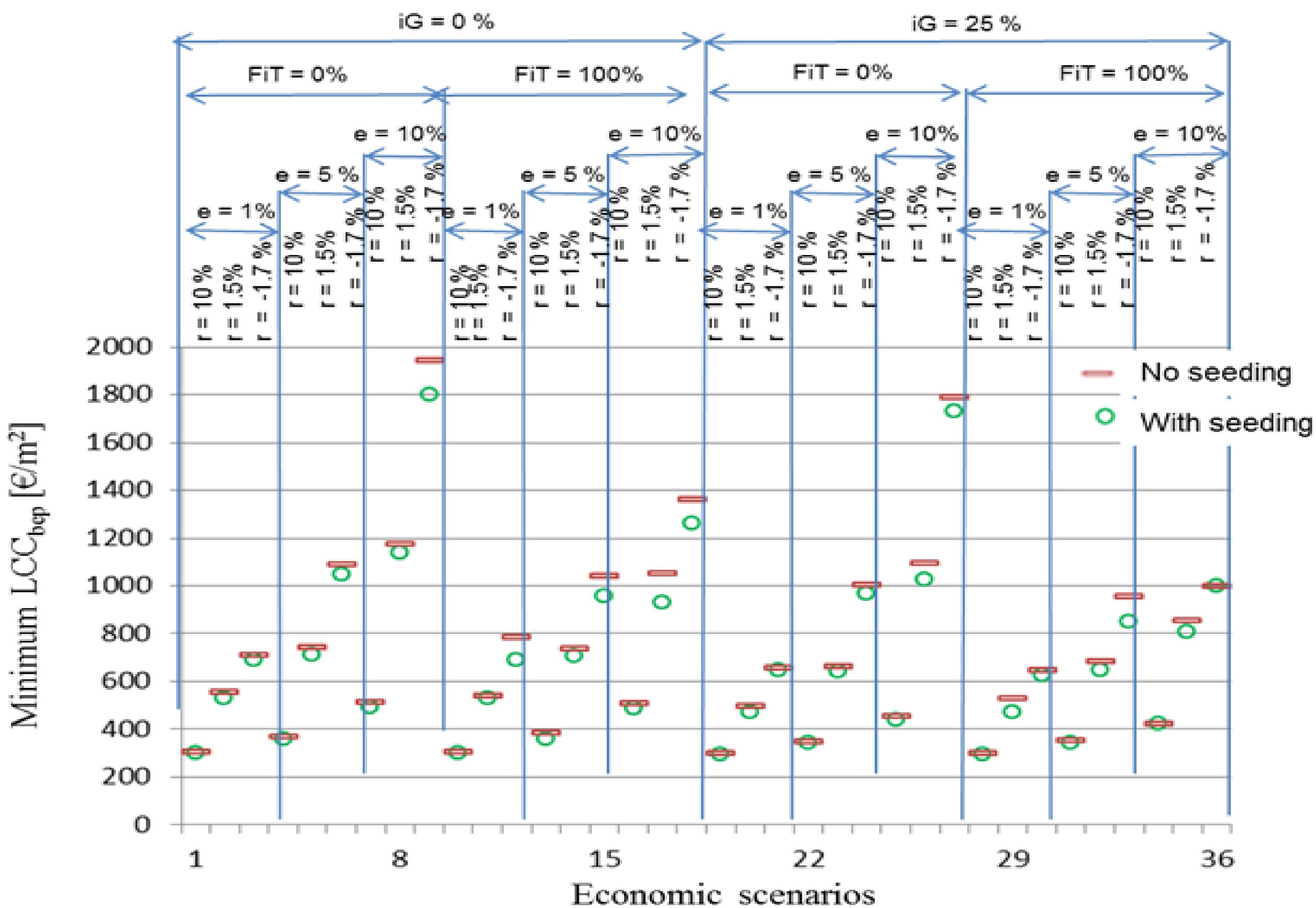
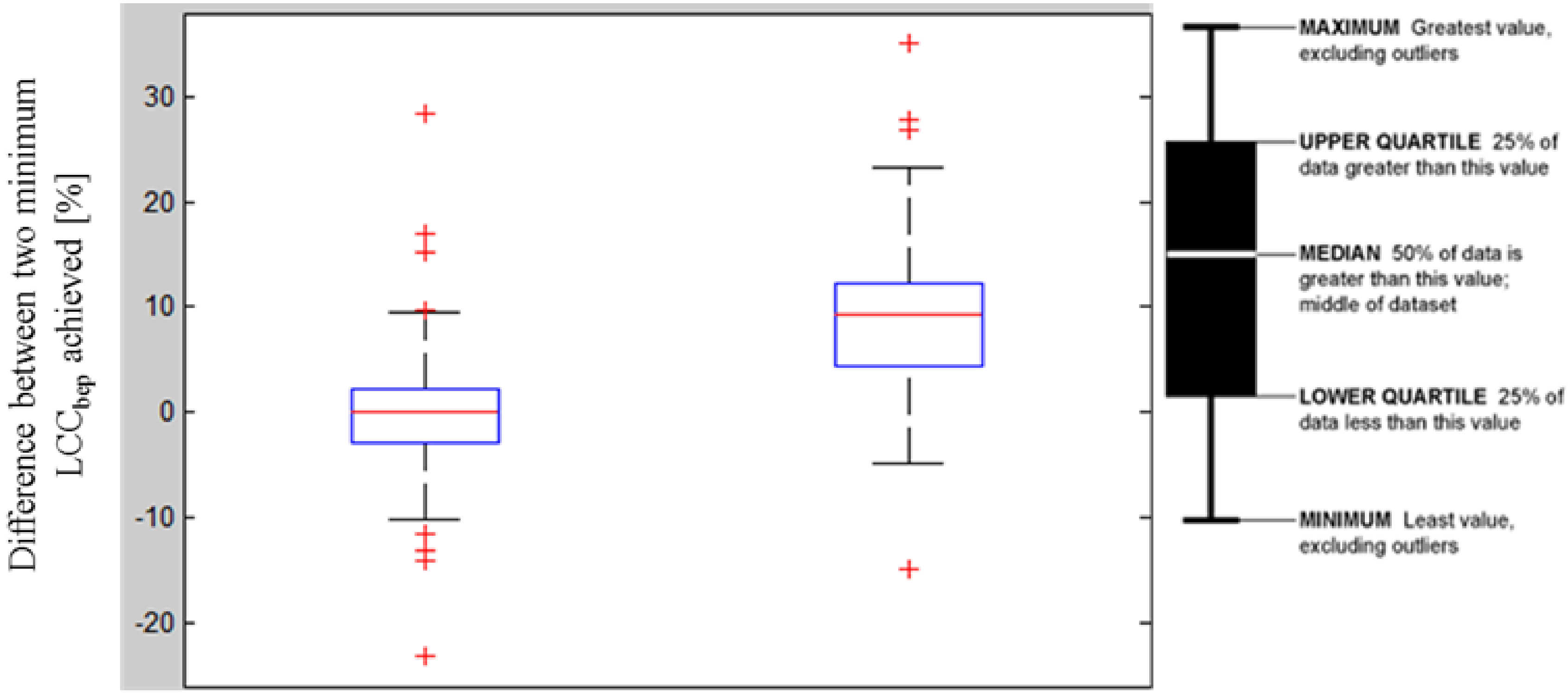


Figure 9 Comparison of the optimization performance when the hybrid optimization algorithm (*GA-PS*) is used with and without good initial population from previous optimization runs. 36 economic scenarios are shown.

The Impact of Using the Introduced Approaches (Double-check and Seeding) on the Results Accuracy



Double-check impact

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

Seeding impact

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

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

The Impact of Using the Introduced Approach (Seeding) on the Computational Cost

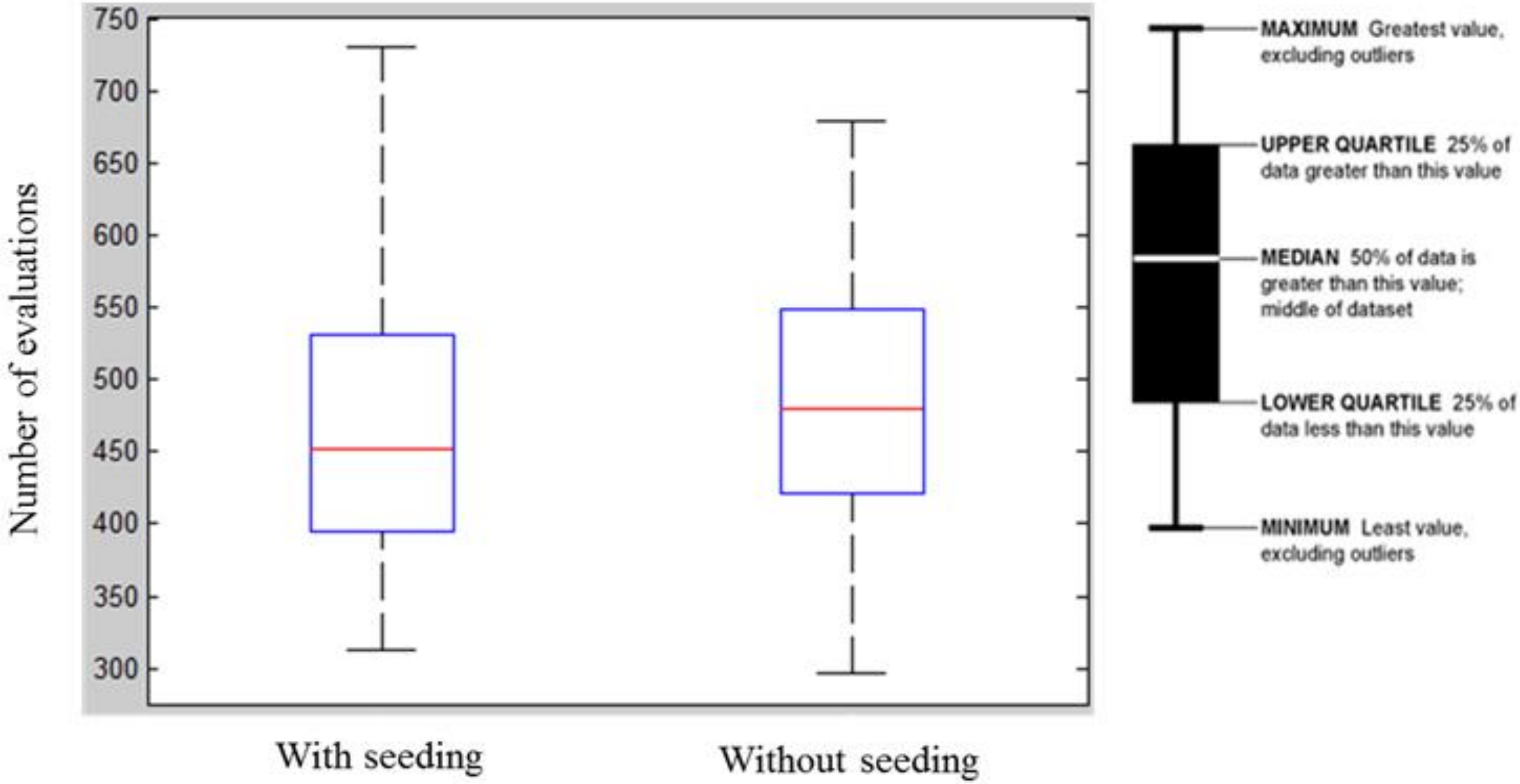


Figure 10 Boxplot presents the range of number of evaluations used for optimizing the 108 cases with and without applying the seeding technique.

The Impact of the Economic Scenario on the Cost Optimal Results

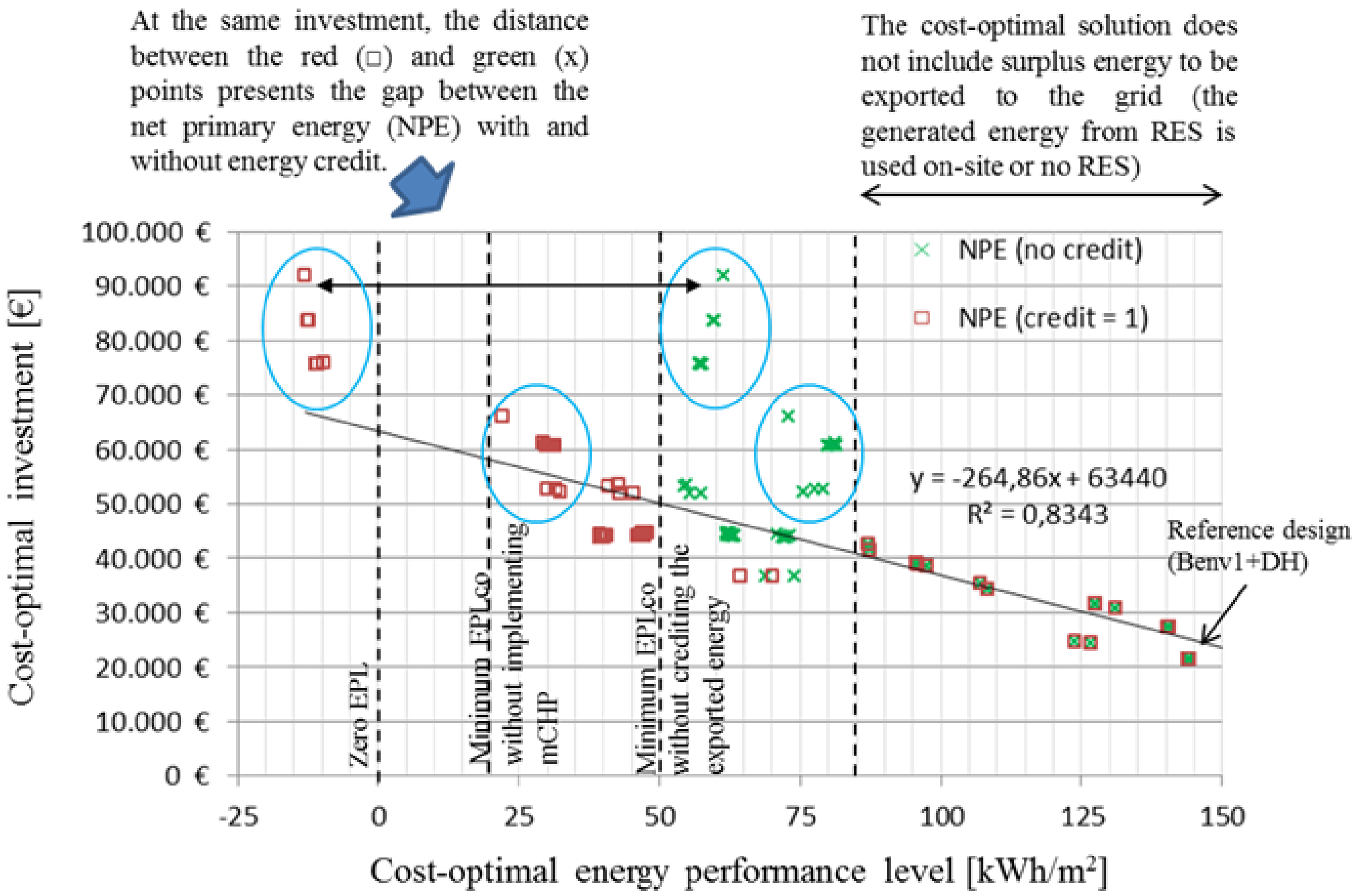


Figure 11 cost-optimal investment versus cost-optimal energy performance level for all addressed economic scenarios leading to *EPL_{co}* less than the reference (~150 kWh/m2a). □CHP solutions circumscribed.

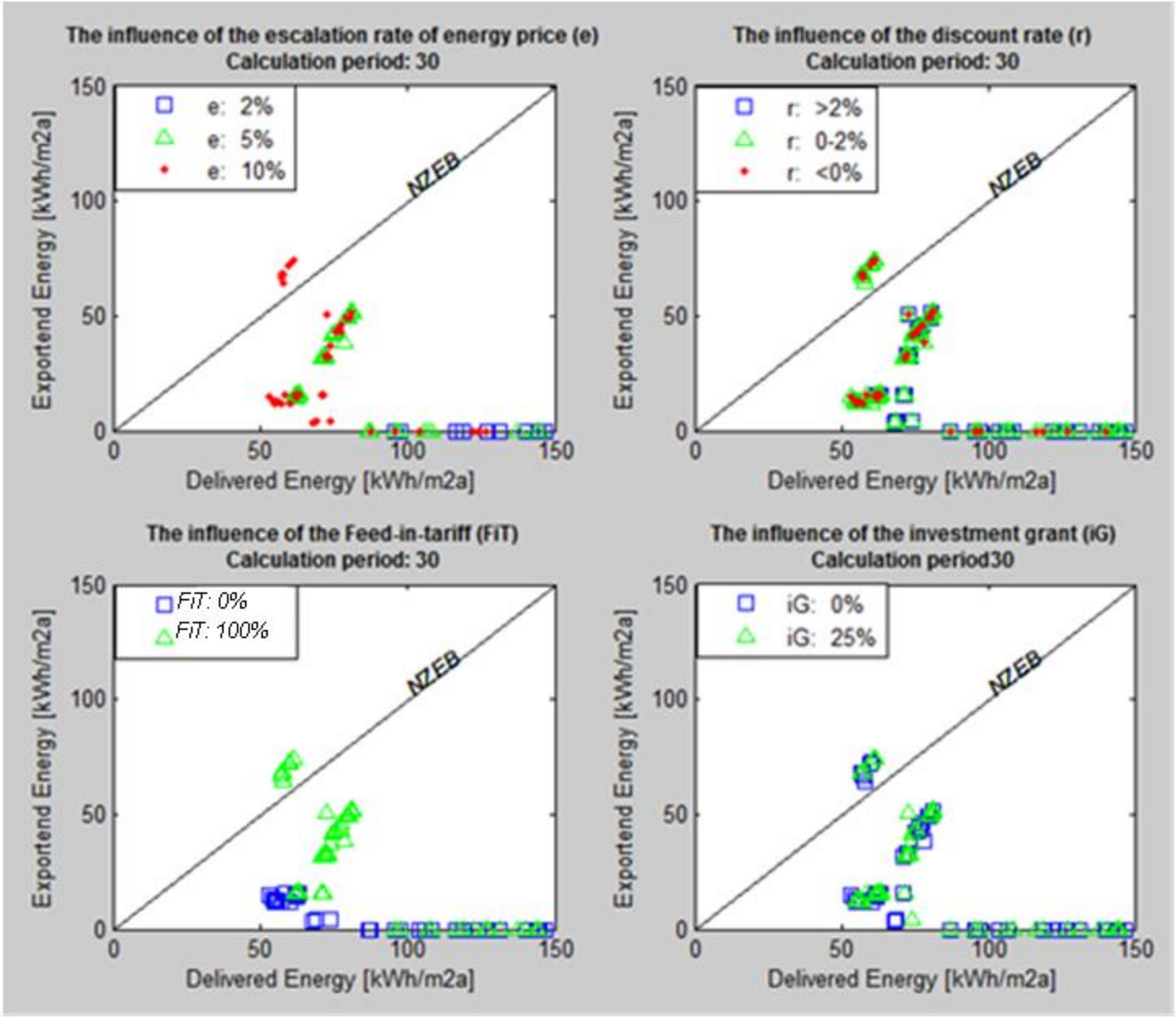


Figure 12 The influence of the economic parameters on the delivered versus exported yearly primary energy balance of the cost-optimal solutions for all addressed economic scenarios which lead to EPLco less than the reference value (150 kWh/m2a).

Optimization-based Sensitivity Analysis

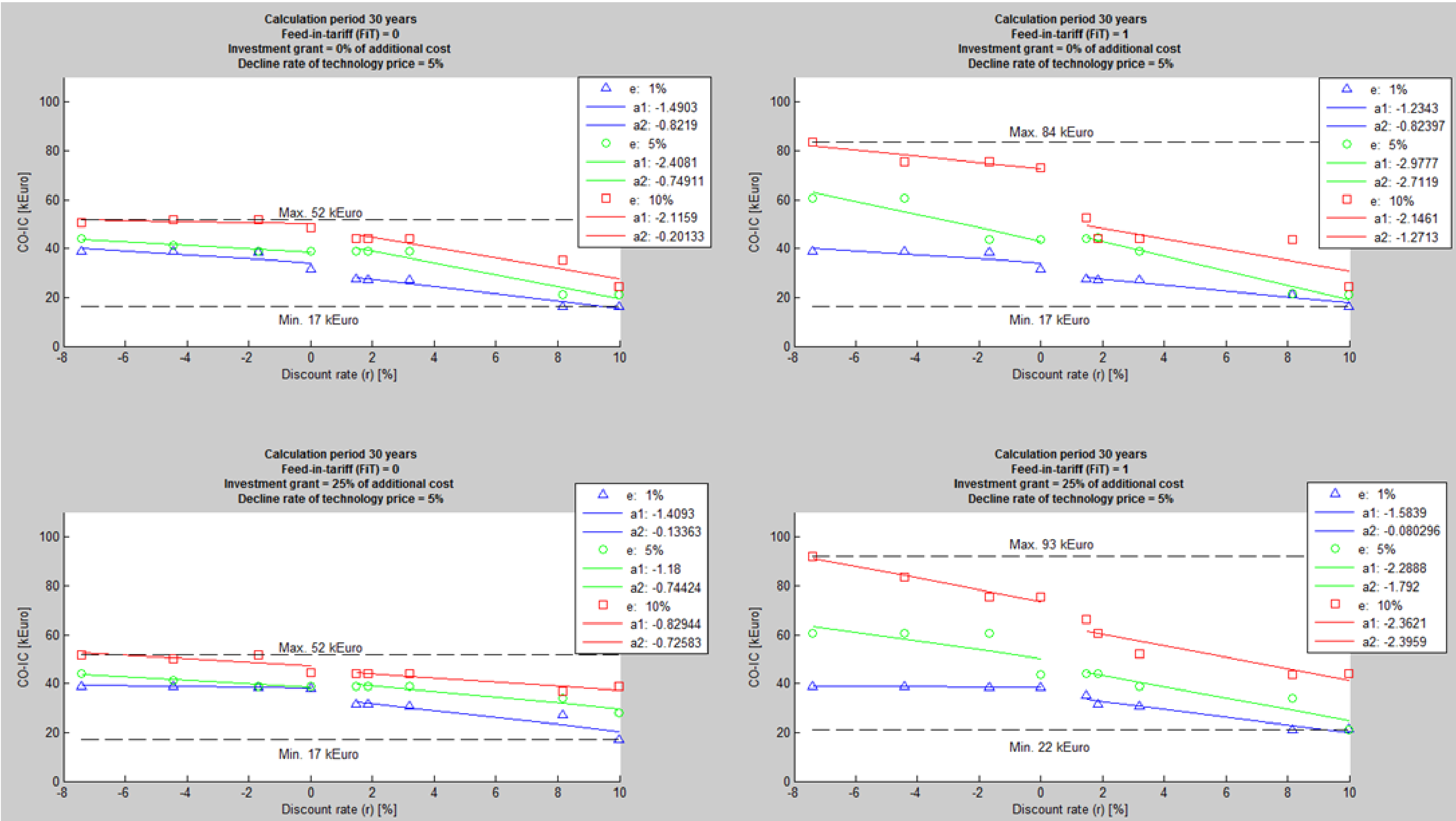


Figure 15 cost-optimal investment (*CO-IC*) versus discount rate (r) assuming: 1%, 5% and 10% energy price escalation rates (e) for each subplot; *FiT*=0 and *FiT* =1 for the left and right hand side subplots, respectively; and *iG* = 0% of additional investment and *iG* = 25% of additional investment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

Optimization-based Sensitivity Analysis

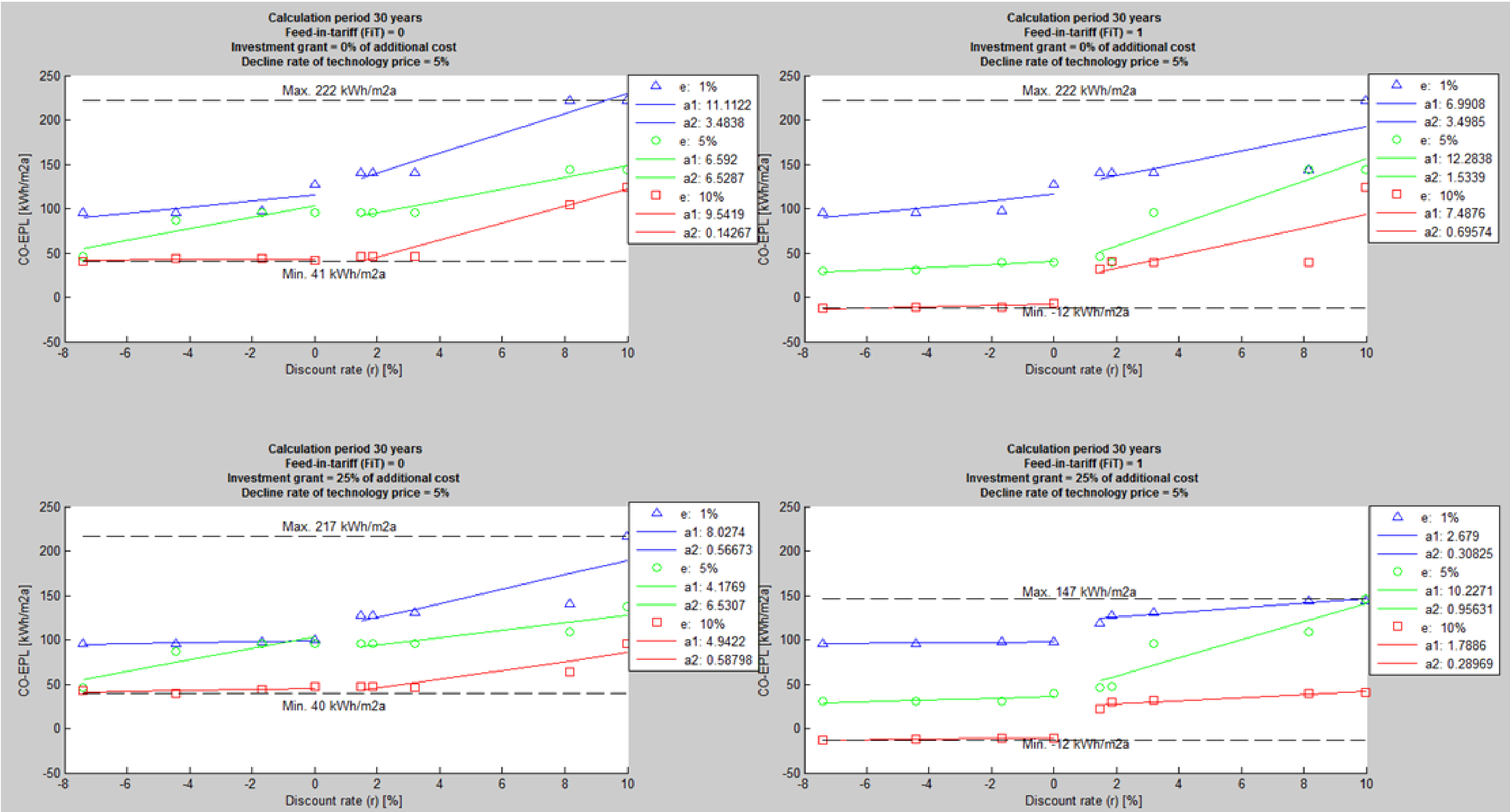


Figure 13 cost-optimal energy performance level (*CO-EPL*) versus discount rate (r) assuming: 1%, 5% and 10% energy price escalation rates (*e*) for each subplot; *FiT*=0 and *FiT* =1 for the left and right hand side subplots, respectively; and *iG* = 0% of additional investment and *iG* = 25% of additional 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.

Conclusions

The introduced MAOS scheme is a powerful tool for reducing the computational cost for large-scale investigation of cost-optimality and energy performance of buildings.

- The scheme is able to avoid the major part of full building simulations by a local system simulation or using archived results.

- In the demonstration case the number of full detailed simulations was reduced from 1515 (505 + 505 + 505) to 52 (31 + 14 + 7) saving roughly ~532 (474*0.6 + 491*0.25 + 498 * 0.25) hours in simulation time (~95% time-reduction).

Conclusions

- **The double-checking test** is important for ensuring high quality of the optimised minima. Even at a specific studied scenario/assumptions the probability of large difference (>10%) through the double-checking test seems to be small. If the calculated optima are not close enough to the true optimum, the sensitivity of the optimized objective might be captured falsely or not at all.

- **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.

Conclusions

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