ENERGY 4.0 – ARE WE READY FOR IT?

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Abstract

Improving energy performance of building stock requires a systemic approach based on inclusivity of all economic and social actors that can be achieved mostly effectively by digitalization. Digitalization offers potential to increase energy efficiency through technologies that gather and analyze data before making changes to the physical environment, thus expanding the view of energy efficiency: from end-use to system efficiency.

A precondition is producing digital twins of the assets, including information affecting its energy performance. Application of digital modelling tools (BIM) has been confirmed to leverage generation of sustainable energy systems and solutions, reduce gaps and enable continuous improvement of operational energy, thorugh systemic engagement of all stakeholders.

Digitalization used in all stages of a building life cycle leverages exchange of information, enables simulation of energy behavior and optimization of consumption patterns. One of the basic features is enabling digital collaborative environment for efficient share of data, which includes energy system operators, construction sector and a wide community of buildings' users.

Digital energy twins enable inclusion of buildings in the energy system of the future, not only as smart, rational consumers, but also as new clean energy producers.

The paper presents the methodological and mathematical model for evaluation of impacts of application of digitalization on improvement of energy performance and sustainability indicators of buildings, throughout their life cycle.

Key words: Digitalization – energy nexus, improvement of energy performance, measurable indicators

1. INTRODUCTION

Reforms of energy sector require tools for simulation and optimization of the largest energy consumers – buildings. Achieving NZEBs is very difficult without technologies such as BIM. It becomes more evident in the exploitation phase where consumption patterns need to be observed, adjusted and optimized permanently, by using digital sensors and acquisition data and their processing.

Improving energy performance of building stock requires a systemic approach based on inclusivity of all economic and social actors, that can be achieved mostly effectively by digitalization. Digitalization offers potential to increase energy efficiency through technologies that gather and analyze data before making changes to the physical environment, thus expanding the view of energy efficiency: from end-use to system efficiency.

A precondition is producing digital twins of the assets, including information affecting its energy performance. Application of digital modelling tools (BIM) has been confirmed to leverage generation of sustainable energy systems and solutions, reduce gaps and enable continuous improvement of operational energy, thorugh systemic engagement of all stakeholders.

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Digital energy twins enable inclusion of buildings in the energy system of the future, not only as smart, rational consumers, but also as new clean energy producers.

2. BACKGROUND

The model has been developed and tested in two H2020 funded (BIMcert, ARISE) and three Erasmus funded projects (All4RD, BEWARE, BIMAhead), in period 2018 – 2022.

3. RESEARCH OBJECTIVE

The objective of research was development and validation of a methodology and a calculation model for quantification of impact of digitalization on energy performance of buildings throughout their life cycle. For that purpose, digital prototypes of a new and a renovated building were produced, to demonstrate how BIM can be used for calculation and optimization of energy consumption in a building with a focus on creating sustainable and energy efficient buildings and collaborative environment. Comparison to traditional method was applied, pointing out advantages of BIM in achieving optimal energy performance.

For the purposes of the H2020 funded BIMcert project, a BIM architectural model of a residential building was developed in Autodesk Revit, which was used as a basis for development of the building energy model in Insight 360.

4. METHODOLOGY

The assumptions of the rates of improvement due to implementation of digitalization were based on empirical and statistical data, and confirmed by experimental measurements carried out through the projects, applying thereby a novel approach for comparison of traditional (2D CAD) and a new method of work based on 3D geometric and energy model, using digital prototypes of a new and renovated building for that purpose

The model enables forecast and calculation of rate of improvement of energy efficiency and of the mix of supply by clean and renewable energy sources, by using digital simulation models and optimization tools, towards buildings of high energy performance, such as NZEBs.
The mathematical representation of the model of evaluation of impacts of digitalization on energy performance of buildings is the following:

$$\Delta \mathrm{E} = \sum_{i=1}^{12} \{\{(1+\mathrm{a}) * \mathrm{Et} * \{1+(1-b)^{-1} * [1+(1+\mathrm{c})] - \mathrm{K1}\} * \mathrm{Et} * \mathrm{A} * \mathrm{ti}\} * \mathrm{K2}\}_{\bar{i}} * 10^{\underline{-3}} \text{ [MWh/year]}$$

Whereas:
ΔE is the total additional energy saving per year, due to implementation of digital models
I is the year month
a is the coefficient of saving due to digitalization in the design stage (10 – 15% for new and 15 – 20 % for renovated buildings); *a = f(type of building)*
b is the coefficient of reduction of gap between the designed and constructed energy performance (5 to 10%)
c= is the reduction of energy consumption due to optimization of consumption patterns in operation stage
A is the area of building [m^2]
t_i [hours] is the time of average energy use during a month
K_1 is the mix of clean and renewable energy sources supply
K_2 is conversion factor of final to primary energy
K_3 is the coefficient of reduction of GHG emissions due to energy savings achieved by digital models and tools

The mathematical representation of the model resulted in an algorithm, as a pre step of a software tool development.

The algorithm is based on the following sequence of model application:

1. Enter the type of a building (residential, not residential, new, renovated, etc.)
2. Enter the size of useful area of the building [m^2]
3. Enter the country and geographic location
4. Read the data base on climate parameters
5. Read the data base for targeted level of energy performance (regular building, NZEB, passive building) on a country - based level
6. Calculate final energy consumption
7. Calculate energy supply mix
8. Calculate primary energy consumption
9. Calculate the additional values of parameters of energy performance as an impact of digital technologies:
   - In the design stage
   - In the construction stage
   - In the operation stage
   - In the demolition / renovation stage
10. Present the additional savings in primary energy consumption, in kWh/ m^2, GWh/year/, EUR/ year
11. Present the optimized mix of clean energy generation sources for the building
12. Calculate the additional investment cost (due to improved clean energy sources mix)
13. Calculate the BCR (Benefit Cost Ratio) and payback time
14. Calculate the reduction of GHG emissions [tons/ year]

The model that has been developed and tested, first up to TRL 3 and then up to TRL5 (including work in digitally simulated physical environment). is ready to be further tested and confirmed in a physical environment up to level TRL8. Method of verification will be comparison of specific stages of work operations, that directly affect energy performance, with and without digitalization applied.
Calibration against outputs of similar projects, in innovation domain, was also considered, to provide comparison of coefficients of impacts obtained empirically and confirmed experimentally, to measured / observed / achieved values in the completed physical demonstrations.

4. RESULTS

This chapter presents the results produced during the model development and validation.

Stage I: Development of an architectural model

The architectural model was previously developed exclusively for the research purposes in Autodesk Revit 2018 software.

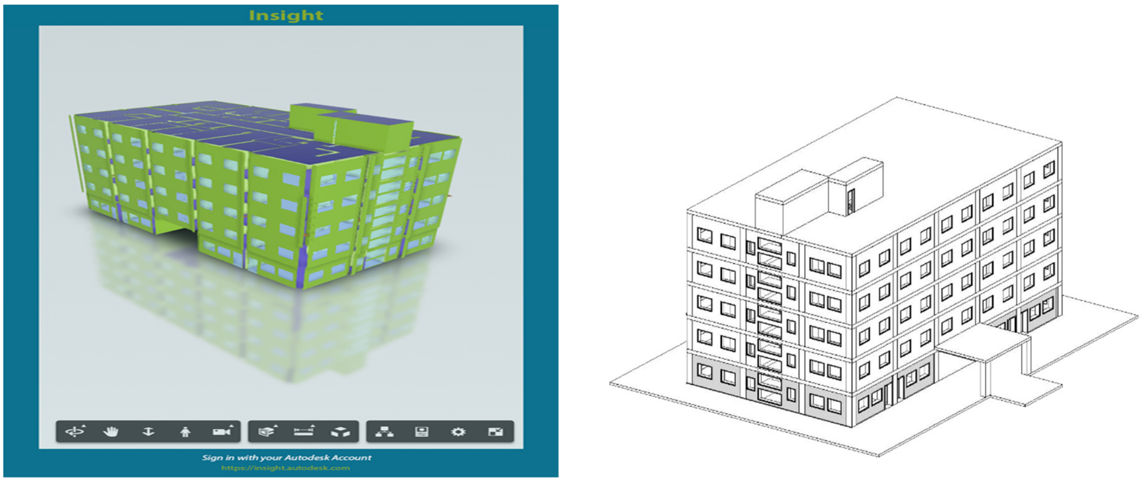


Figure 1: 3D Model of the building

Stage II: Calculation of energy required for the building operation

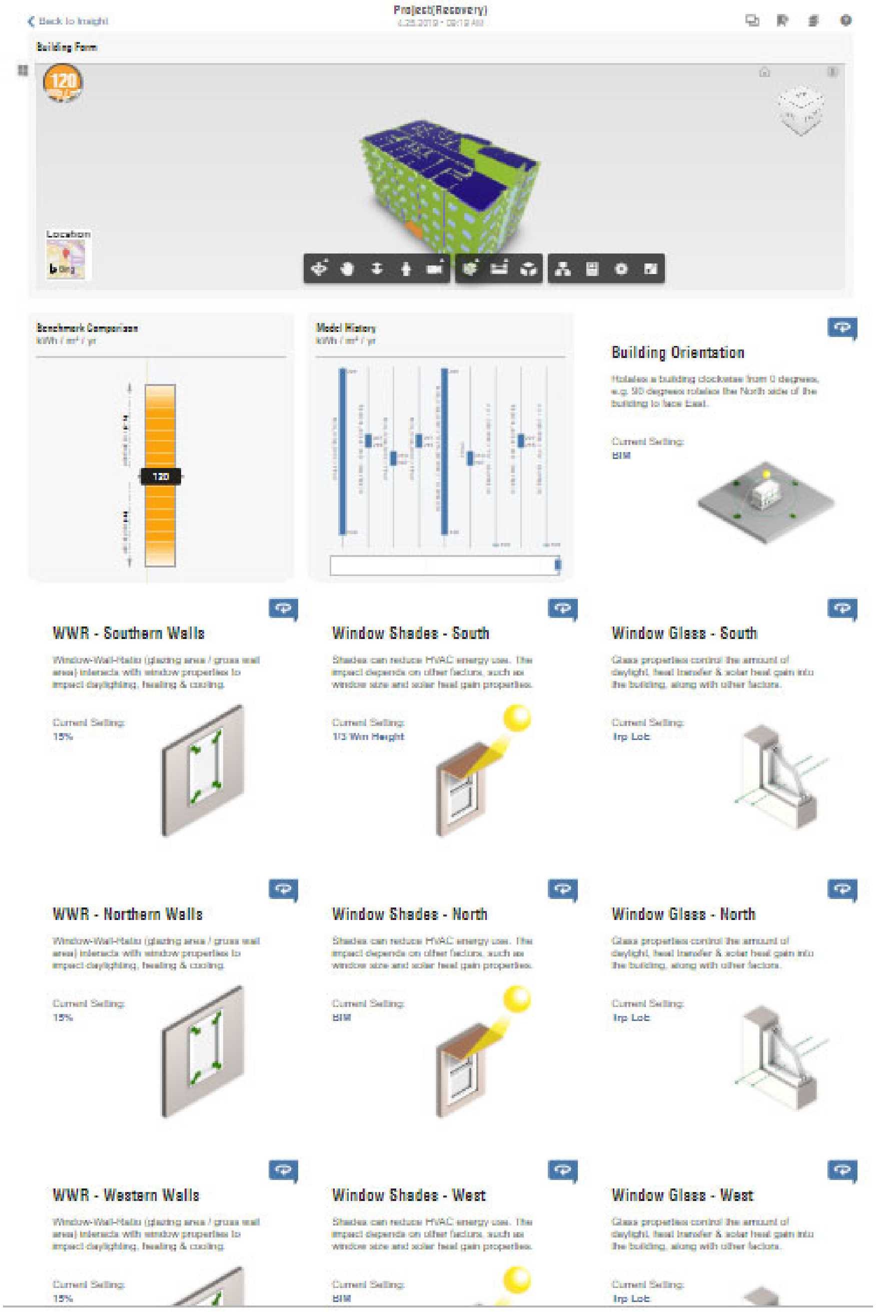
Calculation of energy required for the building operation is carried out in the following steps
Step 2.1: Start creation of the building energy model
Step 2.2: Specify location of the building and therefore local climate conditions
Step 2.3: Transfer data from the architectural model
Step 2.4: Create the energy model

Stage III: Comparison of alternatives and optimization

Optimization of energy performance is carried out by comparison of costs of annual energy consumption and investment costs of analyzed design alternatives.
As the optimal one, the alternative for which the sum of annual energy costs (respectively the energy demand) and annual operational costs is minimal. The operational costs are usually calculated as a percentage of investment costs. The investment costs are taken over from the architectural model.

Step III.1: Energy Cost Range with Performance Factors

The AutoDesk tool Insight 360 was used to get access to building's performance during the design process by directly revealing a spectrum of potential design outcomes (Figure 1) through the Energy Cost Range factors that enable to quickly identify key energy performance drivers such as:Building Orientation, Window-Wall-Ratio, Window Shades, Window Glass, Wall Construction, Roof Construction, Infiltration, Lighting Efficiency, Daylighting and Occupancy Controls, HVAC, Operating Schedule, PV - Panel Efficiency



Building Orientation

Rotates a building clockwise from 0 degrees, e.g. 90 degrees rotates the North side of the building to face East.

Current Setting:
BIM

WWR - Southern Walls

Window-Wall-Ratio (glazing area / gross wall area) interacts with window properties to impact daylighting, heating & cooling.

Current Setting:
15%

Window Shades - South

Shades can reduce HVAC energy use. The impact depends on other factors, such as window size and solar heat gain properties.

Current Setting:
1/3 Win Height

Window Glass - South

Glass properties control the amount of daylight, heat transfer & solar heat gain into the building, along with other factors.

Current Setting:
Trp LoE

WWR - Northern Walls

Window-Wall-Ratio (glazing area / gross wall area) interacts with window properties to impact daylighting, heating & cooling.

Current Setting:
15%

Window Shades - North

Shades can reduce HVAC energy use. The impact depends on other factors, such as window size and solar heat gain properties.

Current Setting:
BIM

Window Glass - North

Glass properties control the amount of daylight, heat transfer & solar heat gain into the building, along with other factors.

Current Setting:
Trp LoE

WWR - Western Walls

Window-Wall-Ratio (glazing area / gross wall area) interacts with window properties to impact daylighting, heating & cooling.

Current Setting:
15%

Window Shades - West

Shades can reduce HVAC energy use. The impact depends on other factors, such as window size and solar heat gain properties.

Current Setting:
BIM

Window Glass - West

Glass properties control the amount of daylight, heat transfer & solar heat gain into the building, along with other factors.

Current Setting:
Trp LoE

Figure 2. Variable building envelope parameters in Insight 360

Step III.2 Comparing Design Scenarios

Using this software enables to specify the factor ranges for selected design alternatives. The energy calculation performance can be easily measured facing Architecture 2030 and ASHRAE 90.1 criterion, allowing to save and compare design scenarios (Figure 2), adapted to the Basic Model that derives from Revit, for tracking performance extending the building lifecycle, allowing to specifically perceive the differences in price and in the required amount of energy in various alternatives.

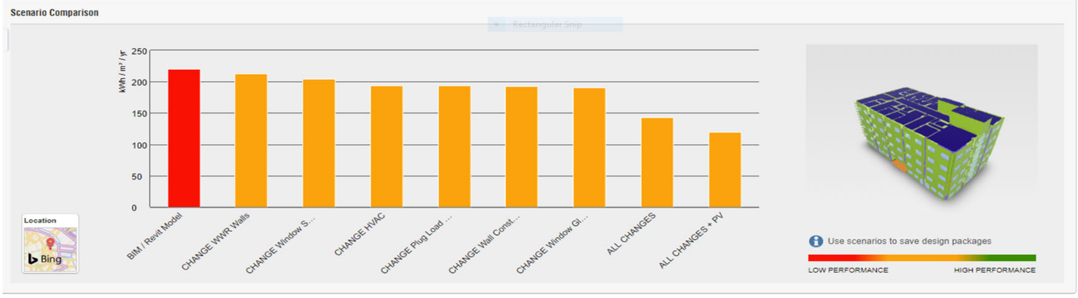
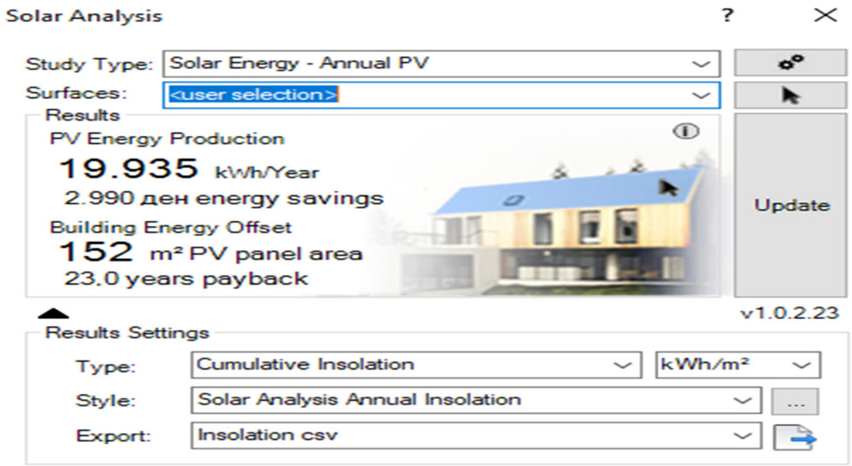


Figure 3. Comparison of Energy Savings Scenarios

Step III.3: Clean Energy Generation: Solar Radiation & Photovoltaic Energy Production

Solar Analysis for Revit is also a part of Insight 360. It allows visualizing solar radiation on building element surfaces in Revit model (Figure 4). The panel type, percent of roof area coverage and payback period settings make it simple to evaluate the performance assumptions. PV energy production is accessible in Revit as well as through the Insight 360 web interface (Figure 5).



Study Type: Solar Energy - Annual PV

Surfaces: <user selection>

Results

PV Energy Production

19.935 kWh/Year

2.990 ден energy savings

Building Energy Offset

152 m² PV panel area

23.0 years payback

Results Settings

Type: Cumulative Insolation kWh/m²

Style: Solar Analysis Annual Insolation

Export: Insolation csv

Figure 4. Solar Settings available in Revit

Step III.4: Varying parameters to set different scenarios

The following 9 alternatives were analysed:
Alternative 0: Baseline scenario derived from the Revit Model (BIM); Base geometry and features of the building envelope
Alternative 1: Window / Wall ratio *Changes adapted to the Baseline scenario
Alternative 2: Window Shades – South Wall; *Changes adapted to the Baseline

Alternative 3: HVAC system; *Changes adapted to the Baseline scenario
Alternative 4: Plug Load Efficiency; *Changes adapted to the Baseline scenario
Alternative 5: Wall Construction ;
Alternative 6: Window Glass type;
Alternative 7A: All changes – Alternatives 1,2,3,4,5,6
Alternative 7B: All changes – Alternatives 1,2,3,4,5,6
Alternative 8: Renewable energy sources included in the building energy consumption

Step III.5: Comparison of alternatives

Table 1: Comparison of alternatives

	EUI Min	EUI Mean	EUI Max	Cost Min	Cost Mean	Cost Max	Deviations	Deviations	Deviations
Alternative	[kWh/m^2/yr]	[kWh/m^2/yr]	[kWh/m^2/yr]	[EUR/m^2/yr]	[EUR/m^2/yr]	[EUR/m^2/yr]	[EUR/m^2/yr]	[kWh/m^2/yr]	%
Base Run	215	**220**	227	40.1	**41.5**	43.2	**0**	**0**	**0**
1	144	**213**	320	22.3	**29.5**	44	**-12,0**	**-7**	**3.3**
2	138	**205**	308	21.2	**28.1**	42	**-13,4**	**-15**	**6,8**
3	189	**204**	201	21.9	**23.2**	24.9	**-18,3**	**-16**	**7,8**
4	130	**194**	292	19.6	**26.2**	39.3	**-15,3**	**-26**	**13,4**
5	130	**193**	291	19.5	**26**	39	**-15,5**	**-27**	**14,0**
6	128	**191**	288	19.1	**25.6**	38.4	**-15,9**	**-19**	**15,2**
7A	165	**172**	178	13.8	**15.2**	16.9	**-26,3**	**-28**	**27,9**
7B	137	**143**	150	11.7	**13.1**	14.2	**-30,1**	**-77**	**52,8**
8	110	**110**	110	9.63	**9.63**	9.63	**-31,9**	**-110**	**100**

Explanation of parameters used in the table is given below:
EUI [kWh/m^2/yr] is **Energy Use Intensity** – building's total annual energy use per unit area required for the building operation (sum of heating energy and electrical energy for illumination).

- EUI Min [kWh/m^2/yr] is the minimum value of Energy Use Intensity required for the building operation.
- EU Mean [kWh/m^2/yr] is the average value of Energy Use Intensity required for the building operation.
- EU Mean [kWh/m^2/yr] is the maximum value of Energy Use Intensity required for the building operation.
- Cost Min [EUR/m2/yr] is the minimum value of annual cost required for the building operation.
- Cost Mean [EUR/m^2/yr] is the average value of annual energy cost required for the building operation.
- Cost Max [EUR/m^2/yr] is the maximum value of annual energy cost required for the building operation.

Step III.6: Selection of the optimal alternative
As the best alternative the last one **Alternative No. 8**, can be taken, which includes most of the changes on the existing model and represents the possibility of using the capacity of solar panels. This alternative has lower annual cost for energy consumption for **31.87 EUR/m^2/yr**, or **100 kWh/m^2/yr** in relation to the basic model.The following table presents several energy parameters

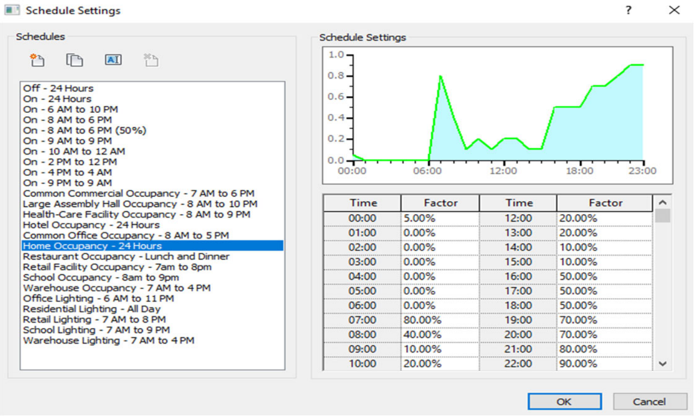
(Annual Energy Cost, Lifecycle Cost, EUI, Annual Energy: Electric / Fuel / Annual Peak Demand; Lifecycle Energy: Electric / Fuel) of the project base run and alternatives for the model

Table 2 – Selection of the optimal alternative

Alternative	Annual Energy Cost	Lifecycle Cost	Energy Use Intensity (EUI)	Annual Energy: Electric	Annual Energy: Fuel	Annual Energy:	Lifecycle Energy: Electric	Lifecycle Energy: Fuel
	[€]	[€]	kWh/m^2/y	[kWh]	[kWh]	[kW]	[kW]	[kWh]
Base Run	55,820.06	760,271.49	227.5	347,096	93,677.5	68.2	10,412,871	2,810,327.5
1	51,369.91	699,658.62	210.8	317,586	93,677.5	63.5	9,527,580	2,810,327
2	54,600.22	743,652.37	223.33	339,004	93,677.5	66.8	10,170,132	2,810,327.5
3	37,206.53	506,758.43	201.11	199,961	190,049.72	34.6	5,998,821	5,701,489.17
4	51,322.62	699,013.45	211.94	317,272	93,677.5	68.1	9,518,145	2,810,327.5
5	51,013.86	694,804.23	210.83	315,223	93,677.5	58	9,456,675	2,810,327.5
6	48,415.34	659,411.85	201.94	297,991	93,677.5	57.5	8,939,736	2,810,327.5

Stage IV: Simulation of varying consumption due to occupancy schedule of rooms

The best way to understand energy usage is having an energy demand profile of the building or facility. The profile shows the rate of energy use over a given time (Fig. 5).



Off - 24 Hours
On - 24 Hours
On - 6 AM to 10 PM
On - 8 AM to 6 PM
On - 8 AM to 6 PM (50%)
On - 9 AM to 9 PM
On - 10 AM to 12 AM
On - 2 PM to 12 PM
On - 4 PM to 4 AM
On - 9 PM to 9 AM
Common Commercial Occupancy - 7 AM to 6 PM
Large Assembly Hall Occupancy - 8 AM to 10 PM
Health-Care Facility Occupancy - 8 AM to 9 PM
Hotel Occupancy - 24 Hours
Common Office Occupancy - 8 AM to 5 PM
Home Occupancy - 24 Hours
Restaurant Occupancy - Lunch and Dinner
Retail Facility Occupancy - 7am to 8pm
School Occupancy - 8am to 9pm
Warehouse Occupancy - 7 AM to 4 PM
Office Lighting - 6 AM to 11 PM
Residential Lighting - All Day
Retail Lighting - 7 AM to 8 PM
School Lighting - 7 AM to 9 PM
Warehouse Lighting - 7 AM to 4 PM

Time	Factor	Time	Factor
00:00	5.00%	12:00	20.00%
01:00	0.00%	13:00	20.00%
02:00	0.00%	14:00	10.00%
03:00	0.00%	15:00	10.00%
04:00	0.00%	16:00	50.00%
05:00	0.00%	17:00	50.00%
06:00	0.00%	18:00	50.00%
07:00	80.00%	19:00	70.00%
08:00	40.00%	20:00	70.00%
09:00	10.00%	21:00	80.00%
10:00	20.00%	22:00	90.00%

Figure 5. Setting parameters in Revit with respect to the occupation of space

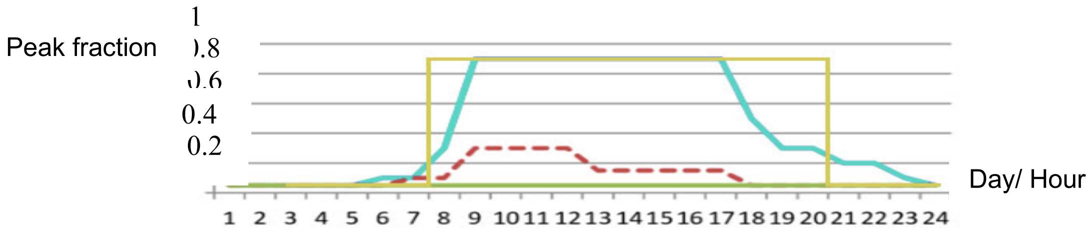


Figure 6. A 24 –hours simulation of energy consumption for a selected day

The energy consumption designed using a BIM model (the blue line in Figure 6) is lower for about 25% than energy calculated by traditional method (the yellow line), due to precise and very discrete (in small time intervals) simulation of consumption related to time of day and occupancy schedule. Energy management system designed upon this schedule of consumption will therefore provide reduction of gap between the designed and achieved energy performance during building's operation, for approximately the same ratio.

6. FINDINGS

The study demonstrates the following overall energy effects of application of BIM (compared to traditional method), due to the advantages specified previously:

1) **Increased energy savings by 16,86%**, compared to the best alternative that can be achieved by traditional method,
2) For the total area of the building (dwellings + offices) of 2558 m^2, total energy saving in this sample project equals to: **33 kWh/m^2/year × 2558 m^2 = 74.1 MWh** annual energy, savings due to applied energy calculations based on BIM model.
3) Total share of energy generated by on – site renewable sources is: **43,277 kWh annually**, or **33 kWh/m^2** per **year,** which is **30% of the total energy consumption** of the building.
4) The expected **reduction of gap** between designed and actual energy performance is over **25%**, due to accurately designed energy consumption and management system supported by BIM model (as presented in the simulation of 24-hour consumption)

7. CONCLUSIONS

The developed methodological and mathematical model confirms that Impacts of applying digital technologies in buildings, on improving energy performance, are measurable, in energy and monetary units, on annual and cumulative basis.

Digital technologies improve energy features and reduce performance gaps in operational stage, in a more reliable and effective way than the traditional method of construction projects delivery. Digital twins of buildings enable a more accurate evaluation of large number of alternatives in early design stages, in aspect of cost – energy optimal performance of buildings.

8. FUTURE WORK

The foreseen improvements of the model will include:
1) extension of the list of sustainability indicators measurable by the model,
2) variations of building parameters to increase climate resilience and,
3) increase of economic efficiency through a specific optimization method based on an LCA, taking in consideration and exploiting recycling potential of construction.

The ultimate ambition, after reaching TRL8, is creation of a software tool with capacity of big data analytics (e.g. output data sets from BIM energy models and SCADA systems. data bases for regulatory settings of energy performance, climate simulation data series, etc.), carrying out analysis and calculations for further improvement of performance, especially in operation stage and when deciding on optimal renovation strategies.It will be useful for: investors, building owners and operators, educational institutes, policy makers on national and European level, to plan and decide on measures for integration of digitalization in building processes, as well as for researchers exploring digitalization – energy nexus. It will also enable forecast and development of skills and competences for future requirements addressed to construction workforce.

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