Control and Optimization Tools for the Incorporation of Innovative Technologies in Net Zero Energy Settlement Design

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Abstract – This paper describes the development of a set of control and optimization tools that support the implementation of highly innovative energy technologies in the design of Net Zero Energy settlements. The incorporation of novel technologies in building and settlement design involves unique challenges, such as frequent design changes, the risk of cost overruns and the need to synchronize the work of different stakeholders who did not previously collaborate. Three tools were developed and implemented to cope with those challenges. A cost control tool tracks the technology's initial costs during the design phase, so that any cost overrun can be easily recognized and treated. A change management tool allows the project's designers to identify, examine and discuss the implications of every proposed change in the design before the change is executed, and prevent deviations from the project's cost and energy performance requirements. A third tool supports a life cycle cost analysis of each technology and an identification of their optimal configuration. In response to a tight schedule and the uncertainty regarding the users' exact requirements, an Evolutionary Prototyping methodology was adopted to develop the tools. They were implemented in a project involving the design of Net Zero Energy settlements in four different European countries.

Keywords –

Net Zero Energy; Cost control; Change management; Design optimization;

1 Introduction

The need to increase the energy efficiency of buildings and cities has been widely recognized. However, the challenges of managing projects in which novel technologies are incorporated to achieve this goal, have been given less attention. Accordingly, the present research studies how such projects can be successfully managed.

The *Net Zero Energy (NZE) Building* concept that has recently gained significant international attention [6]. It can be described as a grid-connected building that generates the same amount of energy that it uses over a year [7]. The NZE concept is based on the idea of an energy-producing, low-energy building that interacts with the energy infrastructure. This interaction gives the possibility to purchase energy from the grid, to feed excess renewable energy back to it, and thus to offset the previous and/or future energy use from the grid [6].

In *NZE settlements* the concept is taken to a district level. This is expected to bring advantages on a number of levels:

- The ability to utilize more efficient settlement-level technologies for energy generation;
- The ability to reduce energy consumption through settlement-level energy management systems;
- Reduced costs due to the economies of scale;
- Reduced energy consumption due to an improved micro-climate that can be attained through an optimal design of the settlements.

This study was carried out in the framework of ZERO-PLUS – a project for the development and implementation of a comprehensive, cost-effective system for NZE settlements in a series of case studies across the European Union (EU). The goal of this project is to provide the market with an innovative, yet readily implementable system for NZE residential neighborhoods that will significantly reduce their costs. Therefore, in addition to the fulfillment of the NZE energy requirements, a primary objective of the project is to develop a system whose investment costs will be at least 16% lower than current costs. The project is carried out by a consortium that includes universities, project owners, technology providers and organizations, who closely collaborate in all the project's phases.

The project poses a number of unique challenges:

- It involves the application of several innovative technologies, such as technologies for the generation of energy from renewable sources (e.g. building integrated wind energy and PV systems, and concentrated PV systems); technologies for improved building insulation; technologies for the reduction of energy consumption (e.g. thermo-solar HVAC systems and Building Energy Management Systems); and technologies for energy management at a settlement scale (e.g. a distribution network combining MV and LV with micro grid capabilities). Some of these technologies have not been previously implemented in construction projects.
- It has very ambitious goals in terms of energy performance and cost savings.
- It requires the coordination between a number of stakeholders, with very different backgrounds and incentives, who are located in different countries and have not previously collaborated.
- It involves an iterative design process that requires frequent changes and adjustments.

In order to successfully cope with these challenges, a set of control and optimization tools were developed and implemented in the project. These tools supported the incorporation of the highly innovative energy technologies in the design of the NZE settlements. They allowed the project team to handle frequent design changes, to successfully manage the risk of cost overruns, and to synchronize the work of the different stakeholders.

2 Control and Optimization Tools

The project included the development and implementation of three tools:

1. A cost control tool tracks each technology's initial costs during the design phase, so that any cost overrun can be easily recognized and treated.
2. A change management tool allows the project's designers to identify, examine and discuss the implications of every proposed change in the design before the change is executed, and prevent deviations from the project's cost and energy performance requirements.
3. A third tool supports a life cycle cost analysis of the technologies implemented in the project and an identification of their optimal configuration.

2.1 Methodology

In response to a tight schedule and the uncertainty regarding the users' exact requirements, an Evolutionary Prototyping methodology was adopted to develop the tools [1]. In the Prototyping approach an initial model (prototype) of the system is developed in order to demonstrate the functional abilities of the system. The goal is to receive feedback from the customer in order to decrease the uncertainty of the requirements and to increase the chances to successful product. The Prototyping approach is suitable for longer projects and less complicated systems. In the Evolutionary Prototyping approach the prototype is developed in order to be improved and eventually become the final product. Each iteration begins with the collection of requirements, development, evaluation and feedback. This loop continues until the final product is developed. The advantages of this approach are:

- Initial modelling is possible in the early stages of development
- It enables better understanding of the customers' requirements
- It allows an early detection of problems
- It supports the practical exploration of ideas

Using this methodology, all the tools were developed in the Google Spreadsheets platform. The use of this platform allows collaborative and simultaneous work, and automatic online data collection.

Each case study in the project is different and adjusted to the local climate, regulations and market. Therefore, the tools had to include four adjusted modules, one for each case study. As part of the methodology the initial prototypes of the tools included only one module, of one of the case studies. The feedback and comments received were used to adjust the module, while the rest of the modules, for the remaining case studies, were created based on the revised initial module. During the project the tools were revised multiple times according to the comments and feedbacks received from the users, but the main structure and workflow was maintained.

2.2 Cost control tool

Cost overruns are common in the construction industry, and have been observed in projects in many different countries (e.g. [3-5]). Construction costs tend to be systematically underestimated [2]. In a project in which many of the technologies are innovative, and have not been previously implemented, the risk of cost overruns is likely to be even higher. Since the reduction of costs is one of the main goals of the ZERO-PLUS project, it is essential to support an effective cost control process. To this end, a dedicated tool was developed and implemented to analyze the expected costs at each stage of the project.

Four types of costs were taken into consideration for the cost analysis:

- Initial costs - Costs at the start of the project: Acquisition, Supply and On-site Construction.
- Operational costs - Costs that are incurred during normal operation.
- Maintenance costs - Costs due to maintenance tasks – either scheduled or due to failures.
- End of life costs - Costs that appear at the technology's end of life.

The data described in Table 1 was collected to perform the analysis.

Table 1. Required input for LCC analysis and optimization

Data category	Field
General project data	Project lifetime (years)
	Interest rate (%)
	Electric energy cost (€/kWh)
	Net area size (m^2)
General technology data	Technology name
	Technology description
	Number of units
	Technology's life time (years)
Energy performance	Annual energy reduction (kWh/year)
	Annual energy production (kWh/year)
Initial costs	Initial cost of the matching technology in the reference case (€/unit)
	Initial Cost (€)
Operational costs	Annual cost of energy needs for the operation of the technology (€/year)
Maintenance costs	Annual maintenance cost (e.g. manpower, spare parts, upgrade costs) (€/year)
End of life costs	End of life cost (e.g. decommission cost, recycling cost, etc.)

Due to uncertainty regarding the costs of the technologies in the different life cycle phases, the three following values were requested for each inputted data: lower bound, most likely value, upper bound. The calculations were provided accordingly. After all the required data is completed, the tool calculates the cost's Present Value in Euros for 50 years (the assumed life cycle of the system). The results are presented in tabular and graphic forms for each component and for all components combined (Figure 1).

The tool was consistently used by the design teams, the coordinator and the project owners to identify cost overruns during the design phase. The tool's output provided insights on the project's cost performance, and the design of the case studies was reviewed to determine if overruns occurred. To date, all the projects are fulfilling the required cost reduction. However, this a tentative result since the project is only at the beginning of the construction phase.

All values' units are euro/50 years	Initial costs	Operational costs	Maintenance costs	End of life costs	**Life Cycle Cost**
Lower bound	110066	845	19864	175	130951
Most Likely	206851	931	36418	581	244782
Upper bound	436361	1064	425978	1940	865343

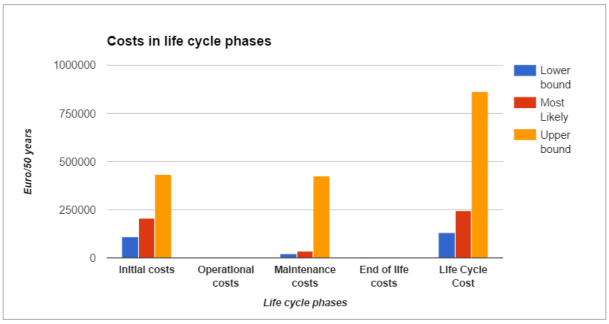

Figure 1: Cost analysis results

2.3 Change management tool

The ZERO-PLUS system design includes a number of different technologies, from different suppliers. It is expected to involve numerous changes, which, if not properly managed, may result in deviations from project goals. The change management process supports the identification and evaluation of the implications of every proposed change before it is implemented, in order to prevent such deviations. The implementation of changes will be monitored to ensure that their implications were correctly identified when the changes were requested.

The guiding principles of the change management process are

1. To allow the change initiator to have a clear view of the proposed change propagations between both physical components and functional requirements
2. To provide the change initiator with an easy, intuitive platform to manage the change and to progress with change execution

The change management process is implemented through the change management tool through the following procedure:

1. Fill in a Change Report Form.
2. Check the current cost and energy performance of the technology as provided by the cost control tool.
3. Answer questions regarding the expected implications of the change.
4. Check the impact of the proposed change on the project's Key Performance Indicators.
5. Check the impact of the proposed change for other technologies, as identified in a Technology Connections Table.
6. Add any other technologies that are expected to be affected by the proposed change and were not identified in step 5.
7. Receive a copy of the report to your email.
8. Share the Change Report with the partners responsible for the affected Key Performance Indicators (KPIs) and technologies.

The user will be able to coordinate and discuss the change with the partners responsible for the affected KPIs and technologies, and update the information on the identified implications of the proposed change based on those discussions. Once all affected sides are informed and have made the required configurations, the change is to be either approved or rejected.

The change management tool will support the teams in the implementation of changes during the construction phase of the project, which hasn't started yet. Therefore, results for the performance of this tool aren't available yet.

2.4 Life cycle cost optimization tool

A review of the currently available Life Cycle Cost (LCC) analysis and optimization tools was performed prior to development of the tool described here. A variety of tools were identified, but the clear majority of them could only perform an optimization for one building at a time, and for one project at a time. They would therefore have required a significant amount of customization for the Zero-Plus project. The tool that was developed in this research differs from the existing tools in the ability to optimize the design of a cluster of buildings, in different projects, and to compare the different results obtained.

After the cost analysis was completed, an optimization of the system's design according to its LCC was performed through the LCC optimization tool. The optimization's objective is to identify the configuration which will minimize the value of the target function, and yet fulfill 3 of the project's main objectives:

1. 16% initial cost reduction compared with the reference case.
2. Regulated energy consumption of less than 20 kWh/m2 per year.
3. Energy production from renewable energy sources of at least 50kWh/m^2 per year.

The target function is sum of the life cycle costs of Zero-Plus technologies minus the cost of the energy saved/produced by those technologies. The presence of the cost of the saved/produced energy in the target function is necessary to ensure that the optimal configuration will include technologies that are not only cheap, but also producing or saving more energy than the others:

$$Min\ LCC = \sum_{i=1}^{m}(u\_lcc_i - e_i) * X_i + \sum_{i=m+1}^{n}(u\_lcc_i * X_i - e_{i\_insulation}) \quad (1)$$

m – The number of relevant technologies, excluding the insulation.

n – The number of the technologies that were included in the LCC analysis.

u_lcc_i – The LCC of the technology as estimated in the LCC analysis stage (€/unit/50 years).

e_i – Present Value of 50 years' cost of energy produced/saved by one technology unit (€/unit/50 years).

$e_{i\_insulation}$ – Present Value of 50 years' cost of energy saved by the insulation (according to its thickness in mm) for 50 years (€/unit).

X_i - The size of the technology (number of units/thickness in mm).

A number of constraints were defined, to reflect the project's main objectives. Those constraints were then adjusted according to the specific attributes of each case study:

1. To represent the objective of reducing initial costs, the following constraint was used:

$$\frac{TCRZ - \sum_{i=1}^{n}(ic_i * X_i - cb_i) - \sum_{i=1}^{m} zp_i}{TCRZ} \geq 0.16 \quad (2)$$

$TCRZ$ – Total initial cost of the reference building (€/m2).

ic_i – Technology's initial cost per unit (€/m2/unit). Only the technologies that were included in the LCC analysis.

cb_i – Initial cost of the matching technology in the conventional building (€/m2).

n – The number of the technologies that were included in the LCC analysis.

zp_i – Initial cost of the technologies that were not included in the LCC analysis (€/m2).

m – The number of the technologies that weren't included in the LCC analysis.

2. To represent the objective of achieving net regulated energy consumption of less than 20 kWh/m^2 per year, the following constraint was used:

$$B - P - \sum_{i=1}^{m}(s_i + p_i) * (X_i - y_i) - \sum_{i=m+1}^{n}(s_i\_total\_after\_opt - s_i\_total\_before\_opt) \leq 20 \quad (3)$$

B – Settlement's annual energy consumption in the original design (kWh/m2/year).

P – Settlement's annual energy production in the original design (kWh/m2/year).

y_i – Technology's size (number of units/thickness in mm) in the original design.

s_i – Annual energy reduction contributed by the technology (excluding production) (kWh/m2/unit/year).

p_i – Annual energy production contributed by the technology (kWh/m2/unit/year).

$s_i\_total\_after\_opt$ - Annual energy reduction contributed by the insulation according to the optimized thickness (excluding production) (kWh/m2/year).

$s_i\_total\_before\_opt$ - Annual energy reduction contributed by the insulation according to the original thickness (excluding production) (kWh/m2/year).

The design teams used dedicated software to perform energy simulations, and provide data about the expected energy consumption in buildings with various levels of insulation and human activities.

3. To represent the objective of achieving an energy production from renewable energy sources of at least 50kWh/m2 per year, the following constraint was used:

$$P + \sum_{i=1}^{n} p_i * (X_i - y_i) \geq 50 \quad (4)$$

P – Settlement's annual energy production in the original design (kWh/m2/year).

p_i – Annual energy production contributed by the technology (kWh/m2/unit/year).

The target function's value was reduced by 5%-8% in three out of four case studies by implementing the described optimization process through the tool. These results are prior to actual implementation of technologies, and are therefore still tentative.

3 Conclusions

The ZERO-PLUS project is representative of projects which pose particular challenges due to the need to incorporate innovative technologies. These challenges were met by developing specific tools in order to support the design and management of the project. Cost control and optimization tools were successfully implemented in the project and used by the project partners. The change management tool is currently being tested by the partners following its adjustment according to their comments. This provided a validation of the appropriateness of the Evolutionary Prototyping methodology that had been adopted to develop the tools. This methodology required relatively few resources, while allowing a quick response to be given to evolving user requirements, and the adjustment and expansion of the tools according to those requirements.

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References

[1] R.A. Carter, Anton, A.I., Dagnino, A., & Williams L. Evolving beyond requirements creep: a risk-based evolutionary prototyping model, In *Proceedings. of the 5th IEEE Intl. Symposium on Requirements Engineering*, pages. 94-101, 2001.

[2] Flyvbjerg, B., Holm, M. S., & Buhl, S. Underestimating costs in public works, error or lie? *American Planning Association Journal*, 68(3), 279–295, 2002.

[3] Frimpong, Y., Oluwoye, J., & Crawford, L. Causes of delay and cost overruns in construction of groundwater projects in a developing countries; Ghana as a case study. *International Journal of Project Management*, 21(5): 321–326, 2003.

[4] Kaming, P. F., Olomolaiye, P. O., Holt, G. D., & Harris, F. C. (1997). Factors influencing construction time and cost overruns on high-rise projects in Indonesia. *Construction Management and Economics*, 15: 83–94, 2011.

[5] Mansfield, N., Ugwu, O., & Doran, T. Causes of delay and cost overruns in Nigerian construction projects. *International Journal of Project Management*, 12(4): 254–260, 1994.

[6] Marszal, A. J., & Heiselberg, P. Life cycle cost analysis of a multi-storey residential net zero energy building in Denmark. *Energy*, 36(9): 5600-5609,

2011.

[7] Salom, J., Widén, J., Candanedo, J., Sartori, I., Voss, K., & Marszal, A. Understanding net zero energy buildings: evaluation of load matching and grid interaction indicators. In *Proceedings of building simulation*, pages 2514-2521, 2011.