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LCC ANALYSIS OF RAINWATER UTILIZATION SYSTEM IN MULTI-FAMILY RESIDENTIAL BUILDINGS

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Abstract: The paper deals with examination of financial profitability of the introduction of rainwater utilization system (RWUS) in multi-family residential buildings. The aim of the work was to build a simulation model of such system and make an LCC analysis of some options of rainwater utilization system. The proposed conception of a new method of selecting the most cost-effective option of RWUS includes: building of simulation model of such system, making the LCC analysis and using a scenario analysis for supporting decision making process with uncertainty. This new method has been applied to a dwelling house in Poland. The results obtained from the analysis demonstrate the unprofitability of the introduction of RWUS in multi-family residential buildings for the adopted location in Poland. The presented method can be used by individual designers and managers to decide on the selection of the most appropriate water supplying option for a specific location.

INTRODUCTION

Poland, despite its location in central part of Europe within the area of mesothermal climate zone, is a country with one of the most unfavorable hydrologic balances on the whole European continent. The annual average run-off of surface waters in lakes and rivers from the area of Poland amounted in the years 1951–2000 to 54 km^3, or about 62 km^3 with inflow from outside of the country boundaries taken into account. Expressed as a per capita figure this makes about 1600 m^3 per year. In other European countries, per capita surface water resources are almost three times as high and amount to 4600 m^3 per year as an average.

Poland's water resources are also characterized by a significant seasonal variance and the unevenness of territorial distribution. The most favorable situation exists in the mountainous regions in the southern part of the country (the Carpathian and Sudeten Mountains) and, in the north-east, in the Masuria Lake District area, while central regions of Poland and Silesia have the most unfavorable hydrologic balance.

Utilization of atmospheric precipitation as a lower-quality water source is rather rare in Poland. While rainwater collection systems can be found in single-family houses where they are used mainly for irrigation purposes, commercial and multi-family residential buildings are equipped with such facilities very sporadically.

As opposed to Poland, rainwater utilization systems (RWUS) are frequently used in other European countries in both small and large buildings. The literature of the subject includes studies on a possibility of using rainwater instead of municipal water in commercial buildings [5], university campuses [2], sport stadiums [15] and individual residential houses [6, 12], as well as studies concerning certain country regions [7, 8].

In on of the studies [13], financial results were presented concerning implementation of rainwater harvesting systems in small dwelling buildings and collection of rainwater from the ground in Namibia (Africa). In view or social and economic conditions, the analysis was focused on very simple rainwater utilization systems. Results of these analyses are especially favorable for systems with rainwater collection from roof surfaces. In the case of rainwater collection from land surface, economical analysis revealed necessity for search of additional financial support from national government in implementation of such systems. The problem of financial unprofitability of RWUS based on specific design solutions is not limited to African countries, but concerns also certain European countries, including Poland.

The capital investment return period depends on many factors, of which the most important are: municipal water price, number of system users, rainwater collection and utilization system design. It follows from data published in the literature that the investment outlay return period can range from 6 up to even 210 years [10] in the case of rainwater being used for external purposes only, or about 30 years if it is utilized in a building's internal systems. The results are confirmed by studies carried out by Brechbühl [3, 4] and the author [11].

Payback period as an investment's economical effectiveness indicator is an imperfect (static) tool as it does not take into account the money value evolution in time. For that reason, a definitely more favorable new investment economical analysis method consists in determination of the Life Cycle Cost (LCC).

The paper presents results of LCC analysis performed for RWUS applied in a newly designed multi-family dwelling house. According to the Life Cycle Cost methodology, the calculations were performed for the whole undertaking's existence cycle, taking into account both investment outlays and annual operation and maintenance costs. Calculations were performed for different capacities of rainwater storage tanks and for a building without such system. In the calculations, a newly developed RWUS simulation model [12] was used as well as meteorological data for the selected location.

PROBLEM FORMULATION

From the point of view of a newly designed building user, one of the most important factors affecting the decision on possible implementation of rainwater utilization system (RWUS) in such building consists in possibility of obtaining some annual saving in municipal water purchase cost.

The important questions that must be answered by a decision-maker are: (i) should a RWUS be applied and (ii) what should be the optimum capacity of tank used to collect rainwater. In fact, the bigger the tank, the higher investment outlay for construction of the system will be, but also annual volume of rainwater used and thus the amount of purchased municipal water will be reduced (resulting in actual savings in annual house maintenance costs). Taking also into account an increasing level of air pollution [14], in some cases RWUS should have the possibility of cleaning rainwater not only through mechanical filtration but also by the use of low-pressure membrane systems and disinfection.

As the subject of analysis was a newly constructed building, the LCC methodology was used as an analytic tool (analysis covering the whole undertaking's existence period taking into account both investment outlays and annual operation and maintenance costs). Calculations were performed for several variants corresponding to different rainwater tank capacities and for a variant without tank (the latter being the most frequently used in Poland).

A schematic diagram of the most important elements of rainwater utilization system in a multi-family building being the subject of the study is presented in Fig. 1.

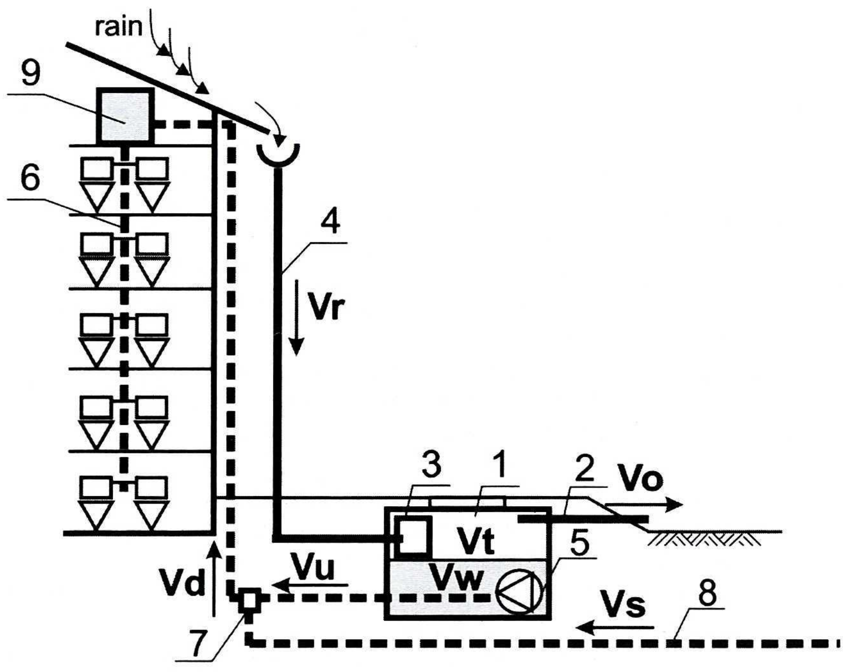

Fig. 1. A diagram of distribution of the most important elements of rainwater utilization system together with water flows

1 – tank, 2 – emergency overflow, 3 – filter, 4 – rainwater delivery from the roof, 5 – pump, 6 – water supply to receiving spots, 7 – control, 8 – emergency supply of tap water, 9 – auxiliary tank, *Vw* – water volume in storage tank, *Vr* – volume of rainwater inflow to storage tank, *Vo* – volume of rainwater discharge to sewage system, *Vd* – water demand for specific purpose, *Vu* – volume of rainwater outflow from storage tank to equipment using it, *Vs* – volume of tap water supplied to the system, *Vt* – capacity of the storage tank

MODEL SPECIFICATION

The RWUS simulation model was constructed in accordance with rules concerning decision-making-oriented mathematical modeling [9] and consists of two sub-models.

In the first RWUS simulation sub-model, the annual average rainwater volume VR_{av} utilized in a multi-family residential building is calculated on the grounds of meteorological data concerning precipitation. That is a static model with the averaging period of 24 hours. The result of application of that sub-model in the form of the auxiliary variable VR_{av} represents a base for further calculations aimed at determination of Life Cycle Cost (LCC) cost and carried out with the use of the second RWUS sub-model. The result of calculations performed in that sub-model consists, in turn, in an output LCC variable determined for each of the adopted investment variants and for the assumed investment realization period.

Assumptions

During the model realization, a number of assumptions were adopted, including the following important factors:

- the storage tank capacity is fixed, Vt = constant;
- the largest volume of rainwater accumulated in storage tank, Vr, equals the capacity of the storage tank, Vt;
- demand for water in the house is satisfied primarily by water accumulated in the storage tank, and only then by water from the water-supply system;
- any excess of rainwater, i.e. quantities exceeding the capacity of storage tank, Vt, is drained to sewage systems or to other rainwater-using equipment;
- demand for water depends on the number of inhabitants, average water requirements for specific purpose, as well as the time of the year, Vs = constant;
- the simulation model does not take into account the effect of wind direction and strength, as well as that of air temperature and humidity;
- the scale of rainwater flow depends on the type of roofing, the roof surface area, roof inclination and the type of precipitation (rain, snow, etc.);
- the capacity of the storage tank is higher than the daily demand for water by the respective sanitary system, $Vt > Vd$;
- the model does not take into account the phenomenon of snow sublimation;
- because of the small size of the systems, a time shift between the precipitation itself and the rainwater inflow to storage tank was not considered;
- the precipitation has a random character, and its quantity is the parameter that characterizes it in the developed simulation model;
- LCC analysis period of $T = 30$ years was adopted (service life of rainwater tank and water distribution piping);
- based on 10-year archival data, the annual average volume of rainwater used in sanitary system was calculated as well as the annual average of municipal water that must be purchased.

Decision variables – inputs of the model

The decision variables in the model are denoted as x_k – meaning implementation of a RWUS with storage tank with Vt_k volume ($k \in K$, $K = \{0, 1, 2, ..., m\}$, $m \in N$). Therefore, $m + 1$ investment variants are analyzed (m of them differing with tank volume Vt_k and a variant without tank – Vt_0).

Parameters of the model

The input parameters of the simulation model are as specified below:

- precipitation level over a time interval, p, mm;

- average demand for water for specific purpose in time interval per inhabitant, Vd, m^3/day (24hrs);
- number of inhabitants in the building, M, number of inhabitants;
- roof surface, F, m^2;
- average coefficient of rainwater flow from the roof surface area, Ψ, –;
- storage tank capacity, Vt_k, m^3;
- rainwater volume in the storage tank, Vw, m^3;
- level of storage tank filled with rainwater, h, m;
- volume of rainwater inflow in a time interval, Vr, m^3;
- volume of rainwater outflow from the tank through overflow in a time interval, Vo, m^3;
- purchase price for 1 m^3 of municipal water, Ctw, EUR;
- fee for discharge of 1 m^3 wastewater, Cs, EUR;
- purchase price for 1 kWh of electric power (according to household tariff), Ce, EUR;
- discount rate r for analyses in fixed and variable prices, –;
- capital investment for each of k RWUS variants (taking into account the cost of rainwater tank and additional system supplying water from the tank to all toilets in the building, and the cost of a simple mechanical cleaning rainwater system); INV_k, EUR.

Auxiliary variables of the model

In the analytic model of a decision situation it is also possible to define some auxiliary variables. Although their values are not important for the decision-maker, they facilitate the task of formulation of the model as a whole. This subsection contains auxiliary variables of both the first and the second model.

Auxiliary variables of the 1^st^ sub-model

The mode of functioning of the system according to its model is described by a series of conditions which determine the course of processes of rainwater inflow, their accumulation and outflow to sanitary systems and to sewage system.

- The process of rainwater filling and accumulation in the tank is defined by the following conditions:
  if $Vw_i + Vp_{i+1} > Vt$, then $Vk_{i+1} = Vt$, $i = 1, 2, \ldots, n$;
  if $Vw_i + Vp_{i+1} \leq Vt$, then $Vk_{i+1} = Vw_i + Vp_{i+1}$, $i = 1, 2, \ldots, n$.
- Rainwater drawing (consumption), from storage tank, by the sanitary system, is characterized by these two conditions:
  if $Va_i - Vd_i < 0$, then $Vw_i = 0$ and $Vu_i = Va_i$, $i = 1, 2, \ldots, n$;
  if $Va_i - Vd_i \geq 0$, then $Vw_i = Va_i - Vd_i$ and $Vu_i = Vd_i$, $i = 1, 2, \ldots, n$.
- Tap water consumption by sanitary systems is described by these conditions:
  if $Va_i > Vd_i$, then $Vs_i = 0$, $i = 1, 2, \ldots, n$;
  if $Va_i \leq Vd_i$, then $Vs_i = Vd_i - Va_i$, $i = 1, 2, \ldots, n$.
- The process of rainwater outflow (discharge) from storage tank to sewage system is defined by these conditions:
  if $Va_i + Vp_i \leq Vt$, then $Vo_i = 0$, $i = 1, 2, \ldots, n$;
  if $Va_i + Vp_i > Vt$, then $Vo_i = Vw_i + Vr_i - Vt$, $i = 1, 2, \ldots, n$.
  where:

Va_i – volume of rainwater kept in the tank prior to the water being drawn (consumption) by the system in the i^{-th} time interval, m^3;
Vd_i – volume of total water consumption for specific purpose in the i^{-th} time interval, m^3;
Vk_i – volume of rainwater kept in the tank at the end of the i^{-th} time interval, m^3;
Vo_i – volume of rainwater drained off the system to sewage system, or to 'infiltration' equipment, in the i^{-th} time interval, m^3;
Vp_i – volume of inflowing rainwater in the i^{-th} time interval, m^3;
Vr_i – volume of rainwater supplied to the tank in the i^{-th} time interval, m^3;
Vs_i – volume of tap water supplied to the system in the i^{-th} time interval, m^3;
Vw_i – volume of rainwater kept in the tank after water drawing (consumption) by the system in the i^{-th} time interval, m^3.

– The amount of municipal water consumed during a year, for k-th investment variant, Vtwk, m3:

$$Vtw_k = 365 \cdot Vd - VR_{yk} \tag{1}$$

where VR_{yk} – annual volume of rainwater used in RWUS for k^{-th} investment variant, m^3/year:

$$VR_{yk} = \sum_{j=1}^{365} Vu_{jk} \tag{2}$$

where Vu_{jk} – daily volume of rainwater outflow from the storage tank to the equipment for k^{-th} investment variant, m^3. Dependence of Vu_{jk} on the decision variable x_k cannot be given by means of an analytical formula but its value is recursively calculated in the framework of the first sub-model.

– Annual average of rainwater volume used in RWUS for k^{-th} investment variant, VR_{avk}, m^3/year:

$$VR_{avk} = \sum_{y=1}^{Tt} VR_{yk} / Tt \tag{3}$$

where Tt – period of the used meteorological data on precipitation, years.

Auxiliary variables of the 2nd sub-model

– Annual cost of operation of the system supplying water to toilets, OMC_k.

In the analysis, costs related to purchase of municipal water, discharge of wastewater and electric power supplying the pumps were taken into account. For k^{-th} investment variant, the cost will be calculated as follows:

$$OMC_k = Vtw_k \cdot Ctw + \left(Vtw_k + VR_{avk}\right) \cdot Cs + VR_{avk} \cdot Cp \tag{4}$$

where Cp – cost related to transport of 1 m^3 rainwater from the tank to users, EUR/m^3:

$$Cp = \frac{VR_{avk} \cdot \rho \cdot g \cdot \Delta h}{\eta \cdot 3.6 \cdot 10^6} \cdot Ce \tag{5}$$

where:

Ce – purchase price for 1 kWh of electric power according to tariff applicable to households, EUR/kWh.

g – acceleration of gravity, m/s^2;
Δh – average elevation of sanitary facilities with respect to minimum rainwater level in the tank, m;
η – efficiency of the motor-pump system, –;
ρ – water density, kg/m^3.

Outcome variable – output of the model

The Life Cycle Cost – LCC – is the total cost of a system over its entire lifespan (the investment cost of RWUS and discounted annual cost of using the RWUS during T years time). The LCC for k^{th} investment variant is:

$$LCC_k = INV_k + \left(\sum_{t=1}^{T} (1+r)^{-t} \right) \cdot OMC_k \tag{6}$$

Data used for the model

The simulation studies concerning operation of rainwater utilization system were carried out for a multi-family building with the following parameters:

– number of floors: 5;
– number of stairwells: 4;
– number of occupants: 200;
– average daily water consumption for flushing toilets: 35 dm^3.

Simulation calculations were carried out with the use of archival data concerning twenty-four hour precipitation for a period of 10 years observed in the town Rzeszów of located in south-eastern part of Poland. Average annual precipitation in the analyzed period amounted to 612 mm and was slightly lower than the average for the years 1890–1931, when precipitation was 642 mm, and for the period 1971–2000, when its average value was 629 mm.

Other parameters of the simulation model adopted for calculations:

– storage tank capacity (6 options): $Vt_0 = 0$ m^3, $Vt_1 = 5$ m^3, $Vt_2 = 10$ m^3, $Vt_3 = 15$ m^3, $Vt_4 = 20$ m^3, $Vt_5 = 30$ m^3;
– purchase price for 1 m^3 municipal water, $Ctw = 0.94$ EUR;
– price for discharging 1 m^3 of wastewater, $Cs = 0.83$ EUR;
– purchase price for 1 kWh of electric power (according to tariff for households), $Ce = 0.1159$ EUR;
– discount rate for analyses in fixed ($r = 0.05$) and variable prices ($r = 0.08$);
– capital investment for RWUS, INV_k: $INV_0 = 0$ EUR, $INV_1 = 8{,}080$ EUR, $INV_2 = 8{,}750$ EUR, $INV_3 = 9{,}500$ EUR, $INV_4 = 10{,}250$ EUR, $INV_5 = 11{,}700$ EUR;
– LCC analysis period, $T = 30$ years.

RESULTS OF SIMULATION

The LCC obtained for the analyzed investment is presented in Table 1.

The lowest LCC was obtained for the variant without RWUS. It should be, therefore, concluded that implementation of such system in a multi-family residential building is not justified economically for the adopted location in Poland. Lower operation costs related to the reduced use of tap water in buildings with RWUS within the 30-year period

Table 1. The LCC for the analyzed investment variants

Variant k [EUR]	Vt_k [m^3]	INV_k [EUR]	LCC_k [EUR]
0	0	0	46405
1	5	8080	50880
2	10	8750	50460
3	15	9500	50671
4	20	10250	51084
5	30	11700	52118

covered by the analysis do not compensate high investment outlays related to piping and tank cost.

COPING WITH UNCERTAINTY OF THE MODEL

The whole decision-making support process is aimed at provision of assistance to a decision-maker in taking the best possible decision on the grounds of data from the past, the present and those obtained from forecasts concerning their values in the future.

The preceding sections presented the creation process of the mathematical model of the RWUS-related decision problem and results of the performed simulation. Therefore, any decision taken on the grounds of that information will be a decision making use of data concerning both the past and the present.

Selection of a solution satisfying the decision-maker on the grounds of additional information, related to forecasted variations of selected model parameters in the future, will permit the decision-maker to take into account the risk related to possible changes and make a better decision.

In this paper, the scenario analysis [1] was applied in order to determine the effect of adopted set of model parameters representing the analyzed decision situation on the model's output variable values. In the scenario analysis it was assumed that in the future (the period adopted for the scenario analysis was 30 years) the following model parameters can be subject to changes:

- purchase price for 1 m^3 of municipal water Ctw,
- discharge fee for 1 m^3 of wastewater Cs.

Scenarios for changes in values of selected parameters of the mathematical model

In the performed analysis, the following scenarios concerning variations of selected mode parameters were taken into account: (i) the most probable scenario (obtained on the grounds of forecasting), (ii) optimistic scenario (assuming that both mode parameters will vary in a way favourable for the decision-maker – municipal water and wastewater discharge rates will increase slowly), (iii) pessimistic scenario (municipal water and wastewater prices will increase at a fast rate). Detailed values of the adopted parameters are presented in Figs. 2 and 3.

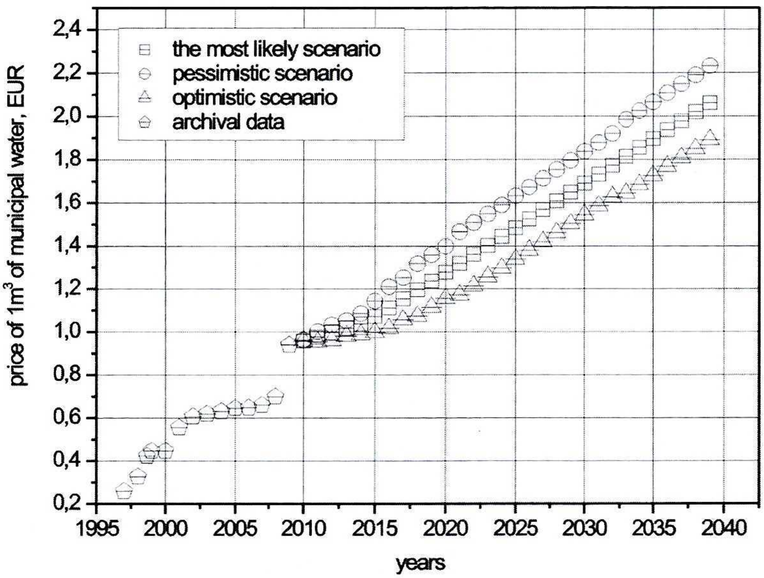

Fig. 2. Archival data from 1997–2009 and municipal water price forecast for the years 2010–2039

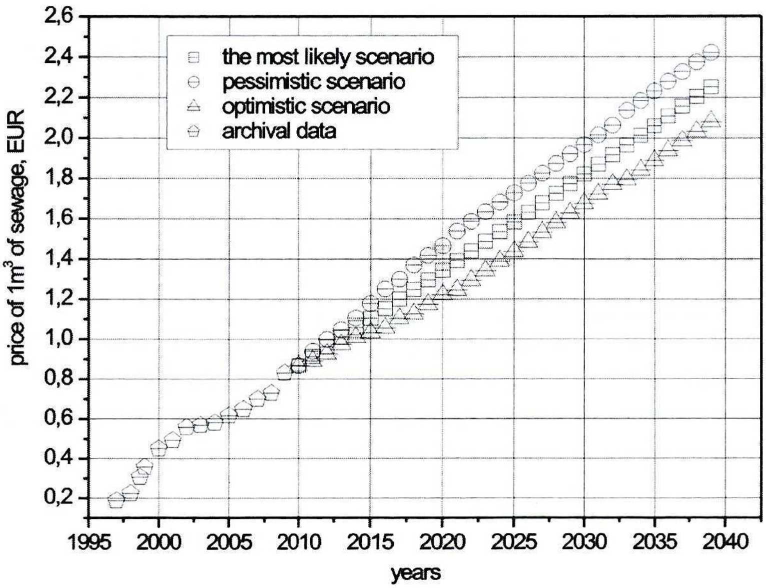

Fig. 3. Archival data from 1997–2009 and wastewater discharge fee forecast for the years 2010–2039

Results of scenario analysis

For each investment variant, a scenario analysis was performed corresponding to the three adopted water and wastewater price variation scenarios. The results of the analysis are presented in Fig. 4.

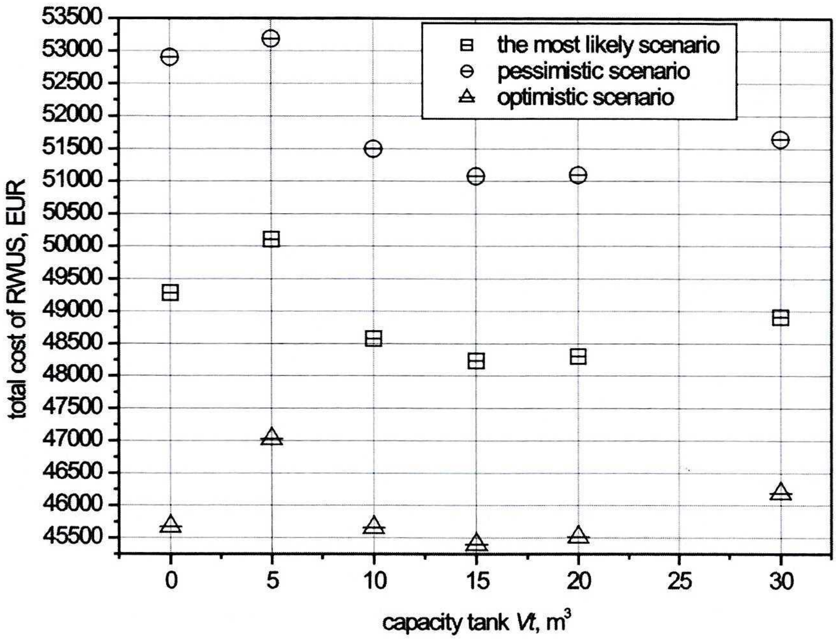

Fig. 4. *LCC* analysis results for adopted variation scenarios of selected model parameters

From among all forecasts, the lowest LCC was obtained for the variant without rainwater utilization system (zero rainwater tank capacity). It should be therefore concluded that, on the grounds of financial analysis carried out in variable prices, the implementation of RWUS for the analyzed multi-family residential house is not justified for the adopted location in Poland.

CONCLUSIONS

The paper presents results of the Life Cycle Cost (LCC) analysis for rainwater utilization systems in multi-family residential buildings. In the beginning, the decision problem was formulated; then a simulation model for operation of such system was presented. Calculations were carried out for a selected multi-family residential building and actual meteorological data on precipitation. The presentation also included results of scenario analysis supporting the decision-making process in uncertainty conditions.

The results obtained from analyses performed for both fixed and variable prices demonstrate explicitly the unprofitability of introduction of RWUS in multi-family residential buildings for the adopted location in Poland.

The performed analysis entitles us to formulate a number of general conclusions.

- The current municipal water prices and fees for wastewater discharge (compared to prices in Western Europe) significantly affect unprofitability of RWUS implementation for multi-family residential buildings.
- A significant increase of municipal water price and wastewater discharge fees adopted in the forecasted scenarios do not result in satisfactory increase of profitability of RWUS implementation in buildings of that type.

- Investment outlays incurred for implementation of RWUS in Western Europe and Poland are similar, while savings resulting from replacement of municipal water with rainwater are significantly lower in Poland.
- The use of RWUS in residential buildings in Poland is currently unprofitable, therefore, implementation of such systems must be based on other (non-financial) decision criteria.

The presented LCC method can be used by individual designers and managers to decide on selection of appropriate water supplying option for a specific location. The paper also sets a good example of the full modeling cycle, including model specification, analysis and dealing with uncertainty.

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ANALIZA LCC SYSTEMU ZAGOSPODAROWANIA WÓD DESZCZOWYCH W WIELORODZINNYCH BUDYNKACH MIESZKALNYCH

Artykuł dotyczy analizy rentowności finansowej systemu wykorzystania wody deszczowej (RWUS) w wielorodzinnych budynkach mieszkalnych. Celem pracy było zbudowanie modelu symulacyjnego oraz przeprowadzenie analizy LCC różnych wariantów systemu wykorzystania wody deszczowej. Zaproponowano sposób wyboru najbardziej opłacalnego wariantu systemu RWUS na podstawie analizy w pełnym cyklu istnienia przedsięwzięcia LCC i analizy scenariuszowej, która wspiera proces podejmowania decyzji w warunkach niepewności. Metoda ta została zastosowana dla istniejącego obiektu mieszkalnego. Otrzymane wyniki dla przypadku studyjnego wykazały niską opłacalność wprowadzenia systemu RWUS w wielorodzinnych budynkach mieszkalnych o podobnej charakterystyce w warunkach polskich. Przedstawiona metoda może być wykorzystywana przez projektantów przy podejmowaniu decyzji o wyborze najbardziej odpowiednich wariantów dostawy wody do budynków dla określonych celów.