Risk Management in Complex Construction Projects that Apply Renewable Energy Sources: A Case Study of the Realization Phase of the Energis Educational and Research Intelligent Building

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Abstract. Nowadays, one of the characteristic features of construction industry is an increased complexity of a growing number of projects. Almost each construction project is unique, has its project-specific purpose, its own project structural complexity, owner’s expectations, ground conditions unique to a certain location, and its own dynamics. Failure costs and costs resulting from unforeseen problems in complex construction projects are very high. Project complexity drivers pose many vulnerabilities to a successful completion of a number of projects. This paper discusses the process of effective risk management in complex construction projects in which renewable energy sources were used, on the example of the realization phase of the ENERGIS teaching-laboratory building, from the point of view of DORBUD S.A., its general contractor. This paper suggests a new approach to risk management for complex construction projects in which renewable energy sources were applied. The risk management process was divided into six stages: gathering information, identification of the top, critical project risks resulting from the project complexity, construction of the fault tree for each top, critical risks, logical analysis of the fault tree, quantitative risk assessment applying fuzzy logic and development of risk response strategy. A new methodology for the qualitative and quantitative risk assessment for top, critical risks in complex construction projects was developed. Risk assessment was carried out applying Fuzzy Fault Tree analysis on the example of one top critical risk. Application of the Fuzzy sets theory to the proposed model allowed to decrease uncertainty and eliminate problems with gaining the crisp values of the basic events probability, common during expert risk assessment with the objective to give the exact risk score of each unwanted event probability.

1. Introduction

Nowadays, one of the characteristic features of construction industry is an increased complexity of a growing number of projects. There are various dimensions, characterizing the project complexity: structural complexity, uncertainty, dynamics, pace and sociopolitical features [1]. In [2] the following definition of a project complexity was proposed "Project complexity is the property of a project which makes it difficult to understand, foresee and keep under control its overall behaviour, even when given reasonably complete information about the project system". Almost each construction project is unique, has its project-specific purpose, its own project structural complexity, owner’s expectations,
ground conditions unique to a certain location, and its own dynamics. Failure costs and costs resulting from unforeseen problems in complex construction projects are very high. Project complexity drivers pose many vulnerabilities to the successful completion of the projects. This paper discusses the process of an effective risk management in complex construction projects in which renewable energy sources were used, on the example of the realization phase of the ENERGIS teaching-laboratory building of Kielce University of Technology, from the point of view of DORBUD S.A., its general contractor. This paper suggests a new approach to risk management for complex construction projects in which renewable energy sources were applied. A new methodology for the qualitative and quantitative risk assessment for top, critical risks in complex construction projects was developed. Risk assessment was carried out applying Fuzzy Fault Tree analysis on the example of one top critical risk. Fuzzy sets theory was applied in the risk assessment to decrease uncertainty and eliminate problems with gaining the crisp values of the basic events probability, common during expert risk assessment with the objective to give the exact risk score of each unwanted event probability.

Risk assessment in engineering project was a subject of many works [3, 4, 5, 6, 7, 8, 9, 10, 11]. In [12], the benefits and various types of risks in “green building projects” connected with the market, industry, performance, as well as with legislative issues were described. Nowadays risk management in engineering project is more and more popular subject. In [13, 14, 15], various approaches to risk management process in engineering projects were described. In [16] the decision problem of identifying critical risks and selecting optimal risk mitigation strategies at the commencement stage in complex construction projects was described.

In the literature, no studies that describe risk management process in the realization phase of complex construction projects that apply renewable energy sources were found.

2. Characteristics of the project assumptions
Project assumption for Energis building (figure 1) was to design an energy-efficient building with classrooms for students and research laboratories, using various latest technologies to minimize energy consumption of the building. The building had to combine teaching and laboratory functions. The building consisted of 22 rooms, office spaces, laboratory facilities (renewable energy sources, intelligent systems in buildings, heat exchange and recovery, climate protection) and storage rooms. The building is an example of smart, energy-efficient sustainable building. The floor area of the building was 5 121.24 m². It had 4 floors above ground and 2 underground. The following renewable energy sources were designed in the building:

- solar collectors for hot water preparation,
- photovoltaic batteries for covering the electricity demand of some lighting circuits in corridors and staircases,
- heat recovery from the glass chamber,
- two heat pumps, which receive the heat thanks to the liquid flowing in sixteen vertical geothermal probes,
- hydrogeological wells, which take water from the Devonian formations and bring it back into the ground after reaching heat pumps.

To make the building more sustainable, the rainwater recycling system, which would be used to flush toilets, was designed. As an alternative energy source, heat pump installations with Variable Refrigerant Flow (VRF) was also designed. Heat recovery from the glass chamber was designed inside semi-circular southern glass façade. The air in the space between the semi-circular façade and flat glass should be heated thanks to solar energy. Then, the heated air should be drawn, and the heat accumulated.
3. The risk management process
The risk management process was divided into 6 stages: gathering information, identification of the top, critical risks resulting from the project complexity, construction of the fault tree for each top, critical risks, logical analysis of the fault tree, quantitative risk assessment applying fuzzy logic and development of risk response strategy.

Step 1: Gathering information
In order to identify the potential hazards in the analysed complex project, information about the problems encountered during realization phase of various complex projects was gathered. Identification of potential problems connected with the realization of complex projects was also supported by Polish and foreign literature review. Moreover, the project documentation was analysed in detail in order to familiarize with the assumptions and identify potential hazards.

Step 2: Identification of the top, critical risks related to the realization phase of ENERGIS building
Various risk identification techniques supported the process of the top, critical risks identification: risk assessment based on Brainstorming Session, risk checklists and Experience-Based Risk Assessment thanks to using experts’ experience in the construction industry, renewable energy and complex construction projects.

For the General Contractor, it is important to define the components of the overall realization phase project risks (formula 1). During the risk assessment of the realization phase of the complex project, it is essential for a General Contractor to take into consideration not only risks connected with construction itself (Rc), but also with design (Rd) and maintenance during the guarantee period (Rm) (formula 2). Such analysis should include the risks associated with design errors, as the general contractor duties also cover verifying the project documentation and errors or difficulties, which can occur during the realization phase and have a significant influence on the project success. Risks connected with the building maintenance during the warrantee period ought to be included in such analysis, as this risk result from the realization period and has a significant influence on the financial result of the investment.

\[
C = \{TC, TI, LES, GPHP, HWHP, PV1, SI, HPVRF, HRGC, RRS\} \\
V_{een} R_{GC}(c) = R_d(c) + R_r(c) + R_m(c)
\]

where: \(R_{GC}(c)\) – component risk, \(TC\) – typical construction, \(TI\) – typical installation, \(LES\) – low energy standard of the building, \(GPHP\) – geothermal probes with heat pumps, \(HWHP\) – hydrogeological wells with heat pumps, \(SI\) – solar installation, \(PV1\) – photovoltaic installation, \(RRS\) – rain water recycling system, \(HRGC\) – heat recovery from the glass chamber, \(HPVRF\) – heat pump with VRF system.
The risk associated with typical construction works and typical installations was described in many works [3, 10, 11, 14], so this paper focused on the analysis of the critical risks associated with the installation of renewable energy sources.

**Step 3: Construction of the fault tree for each top, critical risks**

A horizontal format of fault tree was chosen and the critical top event was located at the top of the page, the basic and underdeveloped events at the bottom. Basic and underdeveloped events were grouped into intermediate events. An underdeveloped event is such an event which is not further developed because it is of insufficient consequence or because information is unavailable [17]. In the example described in section 4 logic gates OR were used to connect the sequences of events. It was intended to develop the fault tree for such a level of detail, which would allow to identify the functional dependencies and the relationship between the identified unwanted events. Figure 2 shows the proposed FT for the example of top critical risk connected with geothermal heat probes for heat pumps.

**Step 4: Logical analysis of the fault tree (FT)**

The methodology of general FT studies was applied to carry out the logical analysis (qualitative) of the fault tree. The occurrence of any of the basic or underdeveloped events in the proposed FT is sufficient to cause the critical, top event occurrence.

**Step 5: Quantitative risk assessment applying fuzzy logic**

It is very difficult to calculate the top event probability of the project task using the classical probability theory, because the basic events in construction projects are not stationary and there is not enough historical data available to assess the crisp failure rates of the individual elements, which are imprecise, deficient and vague in practice. Experts assessing unwanted events probabilities often claimed that they were unable to give crisp values and preferred to use the linguistic terms, which are based on a more intuitive model, based on years of experience. The solution is applying the fuzzy sets, which allows a gradual transition between the linguistic terms used in spoken language [5]. In this paper, the linguistic terms were used to assess the probability of the individual basic events occurrence. A group of construction experts was asked to assign one linguistic term (very low, low, medium, high, very high) to each basic event. It was needed to construct a membership function of a trapezoidal shape for a group of experts that would adequately capture a given linguistic term. The group of experts was asked “which elements p (probability) have the degree μA(p) of membership in a fuzzy set A” [18]. The detailed description concerning how to create membership function for a group of experts was presented in previous author work [5].

From the membership function, it is possible to read the fuzzy probability of each of the basic and underdeveloped events for different values of the membership grade α with the step k.

The following formula can be used to calculate the probability of the top event occurrence [5]:

$$P_{TUE_{a, j, k}} = \left[ 1 - \left( 1 - \frac{P_{UE_{a, j, k}}}{100} \right) \cdot \left( 1 - \frac{P_{UE_{a, j, k}}}{100} \right) \cdot \ldots \cdot \left( 1 - \frac{P_{UE_{a, j, k}}}{100} \right) \right] \cdot 100\%$$  \hspace{1cm} (3)

where: $P_{TUE_{a, j, k}}$ – the fuzzy probability of the critical top event occurrence for the membership degree $a, j, k$, (%); $P_{UE_{a, j, k}}$ – the fuzzy probability of the basic or underdeveloped event $i$ occurrence for the membership degree $a, j, k$, (%); $a, j, k$ – $\text{j}-\text{th}$ membership degree to the set of fuzzy probabilities defining each linguistic value; $n$ – the number of basic or underdeveloped events connected with OR gates $j=0,1,2,\ldots,m-1$; $m$ – the number of the analysed membership grades; $k$ – the step of changes of the membership grades to the fuzzy set $k = \frac{1}{m-1}$. 

\[4\]
The formula (4) defines the fuzzy probability of the top event occurrence for the membership degree \( \alpha_{jk} \)[5]:

\[
P_{\text{uei}_{ajk}} = (P_{\text{uei}_{da_{ajk}}}, P_{\text{uei}_{da_{ajk}}})
\]  

(4)

where: \( P_{\text{uei}_{da_{ajk}}}, P_{\text{uei}_{da_{ajk}}} \) – the extreme (from the left and high side) values of the fuzzy probability of the basic or underdeveloped event \( u_{ei} \) occurrence, read from the trapezoidal membership function for the membership grade \( \alpha_{jk}, \) (%).

It was needed to read the extreme values of each event fuzzy probability from the membership function for values of \( \alpha \) with the step \( k \) between each \( \alpha \). The top event fuzzy probability was calculated by substituting various values of fuzzy probability to the formula (4) for various values of membership grades \( \alpha \). The calculations which were carried out allowed to develop the fuzzy probability distribution graph for the top event.

In order to choose the right value of top event probability from the fuzzy set it was needed to carry out the defuzzification process. It allows to define the crisp value of \( p \), which would represent the set in the most reliable way [19]. The Centroid Method was used in the defuzzification process.

The probability of the top event occurrence (defuzzified value) can be obtained from the formula (5), [5]:

\[
P_{\text{f}}^C = \frac{\sum_{j=0}^{m} P_{\text{uei}_{djk}} \cdot \alpha_{jk}}{\sum_{j=0}^{m} \alpha_{jk}} + \frac{\sum_{j=0}^{m} P_{\text{uei}_{ajk}} \cdot \alpha_{jk}}{\sum_{j=0}^{m} \alpha_{jk}}
\]

(5)

where: \( P_{\text{f}}^C \) - the top event probability of occurrence (the defuzzified value) (%); \( P_{\text{uei}_{djk}} \) - the extreme (from the left side) values of the top event for \( jk \)-th membership grade (%); \( P_{\text{uei}_{ajk}} \) - the extreme (from the right side) values of the top event for \( jk \)-th membership grade, (%); \( j=0,1,2,\ldots,m-1,m \) – the number of the analysed membership grades; \( k \) – the step of changes of the membership grades to the fuzzy set \( \alpha_{jk} \)-jk-th membership grade to the set of fuzzy probabilities of the top event occurrence.

**Step 6: Development of risk response strategy**

Four types of risk response should be considered:

- risk reduction – removing of one or more causes of risk, one or more consequences of the risks or removing both,
- risk retention – documenting the risk existence, preparing contingency plans,
- risk transfer – transferring risk to the party who will be willing to bear the risk,
- risk avoidance – stopping the project, choice of different solution.

**4. Example risk assessment for the critical risk “thermal probes installation for heat pumps”**

The earthworks were to be carried out in very different soil and water conditions. Water was identified at different levels and came primarily from filtration between various layers and lenses of sand and filtration through sandy clays. Three levels of water were identified:

- 1st - ground water,
- 2nd - water with low pressure in the sand layer under the clay, at the depth of 8 to 9 meters,
- 3rd - strained water table at a depth of 23-25 m, on the bottom of a clay layer.

Due to the fact that the layer of the silty clay in the plastic state, which separated the water-bearing compositions of the Devonian Pleistocene, was thin, it was not a solid insulation between the level 2...
and 3 of water. Levels 2 and 3 were therefore connected to each other, forming one Pleistocene-Devonian aquifer. It was needed to drill 16 holes for geothermal probes to the depth of 90 m below the surface. Holes were to be made in the protection zone of underground water. Drilling was to be carried out in quaternary non-rocky grounds as well as in concise rocks. The works were carried out in late summer and autumn. The risk assessment for thermal probes installation was carried out for two alternative drilling technologies:

- traditional drilling using drilling fluid based on bentonite (first alternative),
- hammer drill technology with compressed air for slurry transport and simultaneous casing (second alternative).

In traditional technology classic, multirotational drilling is applied using a drill rig with bentonite slurry transport system. It was assumed to use the three-teeth drill with a diameter of 143 mm in quaternary formation and non-rocky ground formation and the drill bit cutter bit S-T with a diameter of 134 mm in concise rocks. In the hammer drill technology with compressed air it was assumed to use the drill rig Casagrande C6 with ODEX system (drilling with simultaneous casing the hole). After drilling to the ceiling of limestone and dolomite it was assumed the use "barefoot" drilling technology applying the same tool (without casing). The last stage would be lowering the probe and pulling steel pipes.

The risk assessment was carried out according to the procedure describing in section 3. The top, critical event was defined as unsuccessful geothermal installation. In figure 2 a proposed FT for geothermal probes installation for heat pumps was presented. It was drawn for both technological alternatives.

![Fault Tree for geothermal probes installation for heat pumps](image)

**Figure 2.** The proposed Fault Tree for geothermal probes installation for heat pumps

Table 1 presents the identified basic and underdeveloped events for two alternative technologies with linguistic terms assessing their fuzzy probability of occurrence.
**Table 1. Basic and underdeveloped events for two alternative technologies with linguistic terms assessing their fuzzy probability of occurrence**

| Event symbol | Basic events for first alternative technology | Linguistic terms assessing unwanted events fuzzy probability of occurrence | Basic events for second alternative technology | Linguistic terms assessing unwanted events fuzzy probability of occurrence |
|--------------|-----------------------------------------------|--------------------------------------------------------------------------|-----------------------------------------------|--------------------------------------------------------------------------|
| ue1          | Design mistake                               | low                                                                       | Design mistake                               | low                                                                       |
| ue2          | Drilling fluid seepage                       | high                                                                     | N/A                                           | N/A                                                                       |
| ue3          | Blocking of the drilling progress (swelling of clays) | very low                                                                 | Blocking of the drilling progress (swelling of clays) | very low                                                                 |
| ue4          | Borehole collapse                            | very high                                                                 | Borehole collapse                            | medium                                                                    |
| ue5          | Problems with the drilling progress due to encountering different ground and water condition than anticipated | high                                                                       | Problems with the drilling progress connected with encountering different ground and water condition than anticipated | low                                                                       |
| ue6          | Problems with the drilling progress due to encountering man-made obstacles | high                                                                       | Problems with the drilling progress due to encountering man-made obstacles | low                                                                       |
| ue7          | The problem with installation e.g. leaky installation, improper length of drilling due to its dependence on the specific density of the drilling fluid used and the specific density of the pipe | very low                                                                  | The problem with installation e.g. leaky installation, improper length of drilling due to its dependence on the specific density of the pipe | very low                                                                  |
| ue8          | The problem with the supply and quality (low quality materials, delays in materials’ delivery) | low                                                                       | The problem with the supply and quality (low quality materials, delays in materials’ delivery) | low                                                                       |
| ue9          | Drill rig breakdown                          | low                                                                       | Drill rig breakdown                          | low                                                                       |
| ue10         | Breakdown of the drilling fluid system (preparation system or mud cleaning system) | low                                                                       | Compressor failure                          | low                                                                       |
| ue11         | Chipping of the drill bit due to material’s wear | low                                                                       | Hammer drill breakdown                      | low                                                                       |
| ue12         | Adverse weather conditions (frozen plant and equipment, pipe damage) | very low                                                                  | Adverse weather conditions (frozen plant and equipment, pipe damage) | very low                                                                  |
| ue13         | Contamination of groundwater, which is connected with the water from 2nd level | low                                                                       | Contamination of groundwater, which is connected with the water from 2nd level | low                                                                       |
| ue14         | Damage to the surrounding structures, damage to tree roots | very low                                                                  | Damage to the surrounding structures due to ground aeration, damage to tree roots | low                                                                       |
| ue15         | Accidents at the building site               | low                                                                       | Accidents at the building site              | low                                                                       |
The quantitative risk assessment applying fuzzy logic was carried out according to procedure in section 3, step 5. Figure 3 presents the trapezoidal membership function for the probability of the basic or underdeveloped events occurrence for geothermal probes installations for heat pumps according to the group of specialists.

![Trapezoidal membership function](image)

**Figure 3.** The trapezoidal membership function for the probability of the basic or underdeveloped events occurrence for geothermal probes installations for heat pumps according to the group of specialists.

The fuzzy probability for each basic and underdeveloped event occurrence was read from the membership function in figure 2 for various for various membership grades (for various $\alpha$ with step k=0.05). Figure 4 shows the distribution of fuzzy probability of the op event occurrence for hammer drill technology with compressed air and simultaneous casing (second alternative).

![Probability distribution](image)

**Figure 4.** The distribution of fuzzy probability of the op event occurrence for hammer drill technology with compressed air and simultaneous casing (2nd alternative)

The probability of the top event occurrence was calculated from the formula (5) and equals for the first alternative technology $P_{CT}=94.20\%$ and for the second alternative $P_{CT}=65.61\%$. The calculated
crisp risk level was compared with the project run applying hammer drill technology with compressed air and ODEX system. Large amounts of water came from the drill hole during the progress of hammer drilling with compressed air for cleaning the hole. The water was pumped back to the tank, so that the drill cuttings could sediment, and water could be discharged into drains. Karst phenomena in the form of caverns filled with sand and clay were encountered during "barefoot" drilling. In such cases, in order to prevent borehole collapse, the hammer was withdrawn from the drill hole and the hole was cased using ODEX technology. Risk assessment carried out by the General Contractor DORBUD S.A. enabled choosing a technology with lower risk, which allowed to successfully drill through unconsolidated formation (using ODEX system prevented risk of borehole collapse) as well as through rock formation (prevented problems with the drilling progress). U-shaped PE pipes were installed in a closed system. The geothermal probes were filled with water with anti-freezing agent. The geothermal probes were a source of heat for the two-pumps Vitocal 300-G BW129 (each with a capacity of 25 kW, COP coefficient of 4.83). Autonomous installation of 8 vertical probes was prepared for each of the pumps. Before starting the exploitation of vertical probes, the evaluation of the existing thermal properties of the soil was carried out using research Thermal Response Test. ZakładUsługStudziennych studnie.biz proved to be a reliable subcontractor, who considered the identified risk.

The risk response strategy was developed for the installation of geothermal probes for heat pumps. Many risk response actions were defined:

- risk reduction – e.g. analysis of the project documentation, looking for weaknesses and errors, carrying out regular and periodic inspections of equipment, the use of a suitable drilling tool, which allows to produce larger cuttings, the use of casing pipes, experimental verification of the length of drilling,
- risk transfer – e.g. risk transfer to insurance companies, risk transfer to the subcontractor,
- risk avoidance – e.g. changing the depth, structure and number of holes in adapting to the actual conditions encountered in soil and water,
- risk retention – e.g. preparing contingency plans.

5. Conclusions
The developed mathematical model for risk assessment in complex construction projects enables to carry out qualitative and quantitative risk assessment. Application of the Fuzzy sets theory to the proposed model allowed to decrease uncertainty and eliminate problems with gaining the crisp values of the basic events probability, common during expert risk assessment with the objective to give the exact risk score of each unwanted event probability. Using Fault Tree Analysis enabled to clearly show failure mechanisms and the way in which various events could lead to the top event occurrence. It is vital to assess the risk level for each top, critical risk, especially in complex construction project, as it is a key parameter when assessing the project feasibility and calculating the budget. Moreover, it is a starting point for introducing risk response strategy, which supports further risk reduction. In the presented case study carrying out risk assessment allowed to compare two alternative technologies in terms of risk and to choose a technology with lower risk. The described risk management proved to be useful, readable, and enabled easy interpretation of the results. It supported the choice of the proper technology, taking into consideration risk. It allowed to carry out the complex project successfully, allowing to avoid many serious economic and legal consequences and problems with carrying out works on the construction site.

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