

Comprehensive Risk Management in Passive Buildings Projects

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Abstract: Nowadays, we can observe a growing interest in passive buildings due to global climate change, environmental concerns, and growing energy costs. However, developing a passive building is associated with meeting many Passive House requirements, which results in their increased complexity as well as many challenges and risks which could threaten the successful completion of the project. Risk management is a key tool enabling meeting today's challenging passive house project's demands connected with quality, costs, deadlines, and legal issues. In this paper, a new model of risk management dedicated for passive buildings based is proposed, in which a novel Fuzzy Fault Tree integrated with risk response matrix was developed. We proposed 171 risk remediation strategies for all 16 recognized risks in passive buildings projects. We show how to apply the proposed model in practice on one passive building example. Thanks to applying the proposed risk management model an effective reduction of the risks of the basic event is enabled, leading to a significant reduction of the top event risk. The proposed model is useful for architects, installation designers, contractors, and owners who are willing to develop attainable and successful passive buildings projects that benefit all stakeholders.

Keywords: passive buildings; risk management; fault tree analysis; fuzzy logic



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1. Introduction

A passive house is a construction concept that has become a building standard characterized by true energy efficiency, user comfort, affordability, and care for ecology at the same time [1]. Passive houses generally use 80 to 90% less heating energy than typical new buildings, with a low increase of building cost of 5 to 10% compared to typical structures [2,3]. Since the first "Passive House" construction in 1991 in Darmstadt-Kranichstein [3], 5175 passive buildings have been built worldwide [4], and the passive house standard has gained many supporters, especially among designers, owners and contractors who value sustainable development and care for the natural environment. A growing interest in passive house construction and design is mainly caused by environmental concerns and growing energy costs [5]. The popularity of this standard also results from the care for the interior microclimate, user comfort, the building's life cycle, and contribution to active climate protection.

The European Green Deal's goals are to radically reduce greenhouse emissions by at least 55% by the year 2030, hopefully making Europe the first climate-neutral continent in the world by 2050 [6]. This goal is in line with the goal of the passive house standard, which focuses on minimizing the energy consumption and carbon footprint of the building, ensuring at the same time high comfort for building users and minimization of additional costs connected with building construction and operation [7]. Moreover, improving the buildings efficiency, considering indoor climate, local conditions, and cost-effectiveness are the key issues that are of interest to the European Union Energy Performance of Buildings Directive [8]. This directive encourages for the nearly Zero-Energy Buildings

(nZEB) approach, which is understood as a very high-energy performance building that requires nearly zero or very low amount of energy that should be acquired from renewable sources. The passive house standard is considered to be a key enabler for achieving the nZEB standard as it promotes the reduction of energy consumption and greenhouse gases emissions [9,10]. Thanks to integrating passive houses with renewable energy sources, it is possible to achieve low or zero carbon in a suitable way.

Passive buildings are recognized as highly energy-efficient buildings with a minimal ecological footprint [11,12]. This standard is universal as it is not tied to any type of architecture, construction or building type, and therefore the owner has the freedom to choose from many various solutions and technologies [7].

1.1. Principles of Passive Buildings

The principles of the Passive House standard were stated by the Passive House Institute (PHI) in [2]. The key assumptions of the standard are as follows:

- The compactness of the building and very good thermal insulation resulting in achieving low heat transfer coefficient values of all elements of the building envelope (typical U values 0.6–0.15 W/m²K),
- Minimisation of “thermal bridges”,
- High airtightness of the construction (airflow ≤0.6 air changes per hour at a pressure difference of 50 Pa),
- Effective mechanical ventilation with heat recovery (heat recovery efficiency above 80%),
- Southern orientation of windows, use of solar energy, and internal gains including shading issues to avoid overheating (the frequency of excessive temperatures exceeding 25 °C cannot exceed 10%),
- Energy-saving, certified passive windows (glazing and window frames): windows (glazing and frames) should have U coefficients below 0.80 W/(m²K), with g window coefficients having to be around 50%,
- Use of renewable energy sources,
- Use of energy-saving household appliances.

Fulfilling the above-mentioned requirements should allow a space heating demand of the building to be achieved not exceeding 15 kWh/m²year, or a peak load 10 W/m². In the case of climates for which active cooling is needed, approximately the same values are used for the cooling component. Conventional primary energy use of a passive building cannot be over 120 kWh/(m²·year). Though the passive house standard originates from Germany, it can be successfully used for buildings in various climate zones all over the world. In the case of different climate zones, the passive house conception is the same, but the features such as insulation thickness, windows parameters, and mechanical services should be adapted to the specificity of the climate zone. The inappropriate adaptation of those parameters can cause a serious risk and lead to not meeting the passive standard requirements. The subject of properly adjusting parameters for six climates was taken in [13]. The most important rules of Passive Houses planning were described in [2,3]. In [14], passive houses requirements in European and North American climates were compared. In [15], fundamental rules for the development of energy-efficient and energy-conscious buildings were presented. Traditional methods of energy conservation as well as energy efficiency methods followed by renewables, which are important for passive buildings were described.

The passive house standard popularity quickly increased in many countries on each continent [16]. In Germany, Austria and Norway the increasing share of newly built objects fulfilling this standard is especially high [11]. Nowadays, an increasing number of North American architects and engineers are interested in developing complicated buildings but reaching the passive house standard. Not only are single-family houses built with this standard, but also skyscrapers and non-residential buildings. High passive buildings, multi-family dwellings, and non-residential are more and more popular nowadays in North America. Examples may be a 26-story, 352-unit residential high rise in Cornell Tech campus

in New York (2017), a 3734 m² multi-family dwelling in New York (2020), a 12-story multi-family dwelling in New York (2019), and a 5100 m² multi-family dwelling in New York (2021) [4]. Many companies and institutions decide to build passive offices, sports halls, production halls, and concert halls, because their perception as supporters of the passive standard has a positive impact on their image as those minimizing energy consumption, caring for the environment, therefore making them reliable for their stakeholders.

1.2. Risk, Challenges and Troubleshooting Solutions in Passive Buildings Projects—Literature Review

It is important to notice that passive building design and construction are connected with meeting many requirements imposed by the passive housing standard, which is challenging for architects, installation designers, contractors, and owners. It increases the complexity of the project and results in many risks that could lead to the failure of achieving the project goal. Thirty risks connected with passive house design and construction were presented in the author's previous work [17]. It needs to be highlighted that in practical applications, there are many passive building projects that cause problems not only at the design but also at the construction stage, resulting in developing buildings that do not meet the passive house standard requirements and not provide user satisfaction. Problems resulting from architectural, installation designers' or contractors' errors result in the failure to achieve the assumed effect of the project, to meet the construction completion deadline, and to fit into the project budget, not to mention the disappointment of the users of the building. It often ends with many conflicts, misunderstandings, frictions, and claims between an investor, designer, and contractor.

Even a minor mistake could cause serious problems, threatening meeting passive house standard requirements or not acquiring user's satisfaction [18]. E. Jochem defined five factors that hinder the widespread implementation of the passive house standard: insufficient information among potential builders, inexperienced participants of the investment process, low energy prices (e.g., decrease of gas price), regulation issues, inexperienced trade people, and other competitive technologies on the market [19]. S. Piraccini and K. Fabbri also presented several problems concerning passive house design and construction: improper design and construction of shading appliances resulting in overheating in summer, insufficient supervision at the construction site and the formation of water vapor condensation inside the building [20]. In [21], several barriers in passive house expansion were discussed, including difficulties in using new techniques and technologies, lack of experience among designers and builders, applying cheaper materials and systems off-the-shelf, risk of overheating, difficulties in achieving airtightness as well as building site impacts.

In [22], attention was paid to improper design or construction of the building that could seriously influence the indoor air quality inside the building, creating risk to residents health and the condition of the building structures. Moreover, it also happens that unaware investors ask the designers to apply cheaper installation solutions, in particular ventilation, resulting in a negative impact on residents' health and the building structure [23]. In [24], the following potential problems which can appear during the operation of a passive building were presented: overheating, domestic water buffers contaminated with legionella, excessive noise, weak ventilation, complicated control systems and inflexible ventilation services.

In the case of modernization of existing buildings to the passive house standard, the influence of hydraulic balancing of heating installations should also be taken into account [25] and the possibilities to increase the energy efficiency of domestic hot water preparation systems in existing buildings [26], as well as differences between planned and energy savings achieved [27]. In [28], the air quality in decentralised ventilation systems was shown, which can be applied in retrofitting existing buildings to the passive house standard. It was found to be efficient in reducing air pollution. In [29], a risk and benefit assessment approach was proposed for solar photovoltaic and thermal systems in traditional and historic buildings. Risks and benefits were assessed in seven categories, including

technical compatibility, historical importance of the building, economic viability, energy issues, the quality of the indoor environment, the impact on the outside environment, practical aspects.

In [24,30–35], the problem of overheating in passive houses was stressed. In [34], it was found out that the overheating hours are often underestimated in the energy model because of overestimating design infiltration and ventilation rate. It was proposed to improve the airflow modeling thanks to coupling the thermal and airflow network models to carry out overheating analysis. In [35], a new, easy-to-apply tool allowing the assessment of the microclimate conditions in a passive building was presented, which points out the hours of inconvenience. Moreover, some alternative solutions which allow to obtain the desired microclimate conditions in a passive school were presented. The following solutions were proposed and investigated: strong mechanical ventilation at night in buildings with a structure of high thermal inertia, applying a system combining mechanical and natural ventilation, using intelligent ventilation control systems. In [36], the shortcomings of the shading calculation method for passive houses were discussed. It was suggested to use dynamic building simulation's shading algorithm combined with the current PHPP method based on monthly balance.

In [37], building orientation multiobjective genetic algorithms were proposed for green building optimization. This model used the following variables: aspect ratio, window type, window-to-wall ratio, wall type and its layers, roof type, and its layers to optimize the life cycle cost and life cycle environmental impact of the building. In the case of passive houses, several parameters should be added, such as mechanical systems, passive solar design strategy, and building shape. This model can be useful for passive houses, but it should be supported with multizone energy simulation software taking into account with daylighting.

In [38], the capabilities of 20 building energy performance simulation programs, which can be useful in passive buildings projects, were compared. In [39], it was stressed that applying the building energy model (BEM) with optimisation algorithms supports proper prediction and optimisation of building operation. In [40,41], it was proved that combining modelling and optimisation software such as EnergyPlus, MATLAB (version R2015a) is very helpful for designers in making decisions. In [39], a new approach for optimizing lightweight passive buildings was proposed, which combines evolutionary algorithms and life cycle cost. It can be a very useful tool to mitigate risk in passive houses design.

In [42], an optimization method for passive buildings design was proposed, which is a combination of redundancy analysis, gradient-boosted decision trees, and the nondominated sorting genetic algorithm. It takes into account energy savings, thermal comfort, and economic aspects of the design. This model is helpful for architects, as it shows the effects of adjusting various parameters on the building performance.

In [43], a new multiobjective optimization model for thermal comfort and energy consumption in a residential building was proposed. It uses TRNSYS simulations, multiobjective genetic algorithm, and an artificial neural network.

In the literature, some new and innovative solutions were presented that can be applied in passive buildings and contribute to risk reduction, and their better performance were presented. In [44], the thermal resistance characteristics of walls with multilayer reflective insulation were presented, which can be applied in a passive house project. Its application contributes to better thermal performance properties of the whole building, reducing heating and cooling costs. In [45], a mobile shading system with a phase-change heat store aiming to illuminate the rooms with natural light and reduce the unwanted overheating of the rooms was tested. A depletion in room overheating in the summer of 29.4% was reached. In [46], the operation and energy performance of a heat pump driven by a PV system for space heating of a house was analyzed. It was found that in Polish conditions, the primary energy consumption reduction is not remarkable. In [47], attention was paid to the application of sustainable materials in building construction, especially by using recyclable waste for manufacturing building materials, which is an interesting solution contributing to sustainable development also for passive buildings. In [48], a new

stochastic approach to forecast the energy demand and thermal comfort in office buildings taking into account materials and human-related Gaussian uncertainties was proposed. In [49], stochastic energy demand analyses with random input parameters were presented for the single-family house. The proposed approach is simple to apply and leads to the reduction of the computational cost of the buildings' energy demand calculations.

In the case of passive buildings, it is important to know the real influence of atmospheric factors on heat consumption and then forecast control of its supply. These issues were discussed in [50–52]. In [53] it was stressed that passive buildings require remarkably less energy for heating in comparison to standard ones, so the proper models of every “energy-consuming” building's components are crucial. As a result of comparing various models, it was found out that the discrepancy in energy need for heating obtained using accurate and simplified methods of internal heat gains determination was 30.1%. The subject of modelling heat and air transfer in ventilated partitions, which can also be applied in passive houses, was taken in [54]. A model of heat and air transfer in a naturally ventilated horizontal air cavity that might be under a flat roof or under a building as a crawl space was presented and verified.

In the years 2014 to 2019, there were many conferences, trainings concerning passive house standards organized in Ireland, UK, Italy, North America, Latvia and Lithuania. This contributed to increasing the awareness of investors, designers, and contractors regarding passive construction, gaining the necessary knowledge to develop real passive buildings. In the beginning, many materials products dedicated to passive house standards appeared on the German and Austrian markets, but few of them were available on international markets, and there was no training and service abroad.

In the literature, the authors did not find any comprehensive risk management model dedicated for passive buildings projects. In [55,56], it was proved that effective proactive risk management in low energy building construction projects that apply renewable energy sources resulted in successful project realization according to the planned schedule and budget. In [57–59], it was shown that effective proactive risk management in various complex construction projects supported effective project execution.

In practice, it can be seen that many investors, engineers, and contractors are not able to start the risk management process early in the passive building planning phase, because they do not have any comprehensive risk management model that could be a practical tool to effectively model and mitigate risks. It often ends in creating projects that do not provide user satisfaction and Passive House Institute requirements.

1.3. Contribution of the Proposed Approach

The aim of this work is to contribute to the first risk management model dedicated to passive building projects. It is a development of traditional risk analysis towards complex risk management in passive buildings design and construction, as this model uses a novel Fuzzy Fault Tree integrated with a risk response matrix. It is a dynamic risk management model based on proactive and holistic risk approaches, which when calculating risk, takes into account several factors: the unwanted event, probability of occurrence, its consequences, risk reduction for the chosen risk treatment strategies, and the experience of the project team in introducing the risk management strategy.

The main contributions to the body of knowledge of this work include:

- Identification of 16 basic events (BE) and underdeveloped events (UE) in passive buildings projects with factors determining risk level,
- Identification of the top event (TE),
- Development of a fault tree integrated with risk management matrix,
- Decreasing the uncertainty, imprecision, and the problems connected with getting the crisp values of the BEs/UEs probability of occurrence from the experts assessing them thanks to using fuzzy sets theory in the proposed model,
- Taking into account the specificity and dynamics of risk in passive buildings projects and its dependence on several parameters: the unwanted event, probability of occur-

rence, its consequences, risk reduction for the chosen risk treatment strategies, the experience of the project team in introducing the risk management strategy,

- Proposing 171 risk remediation strategies for passive buildings projects with risk reduction coefficients proposed for each action.

The outline of this paper is as follows. Section 2 presents the proposed approach to risk management, including risk identification, risk analysis, risk evaluation, risk treatment, risk registers, risk monitoring, and financing. Section 3 presents an example of the application of the proposed model. Discussion of the results is presented in Section 4. Section 5 summarizes the paper.

2. The Proposed Approach

To justify the need to work on a risk management model dedicated to passive buildings, the author carried out a survey of 16 enterprises specializing in passive buildings design and construction in Europe, the USA, and Australia. The survey was based on rich companies' experience from 748 passive buildings projects. The responding companies were asked if they see the need to develop a risk management model dedicated to passive buildings projects. A proportion of 93.75% of the surveyed companies answered that it is needed.

Risk management in a passive building project can be defined as a process for identifying, analyzing, and responding to risks at every stage of the project execution aimed at achieving the acceptable risk level, often thanks to introducing risk treatment. In the proposed approach, the risk management process in passive buildings projects includes five steps: risk assessment, risk treatment, risk registers, risk monitoring, and review, as well as risk financing, which will be described in detail in the following subsections (Figure 1).

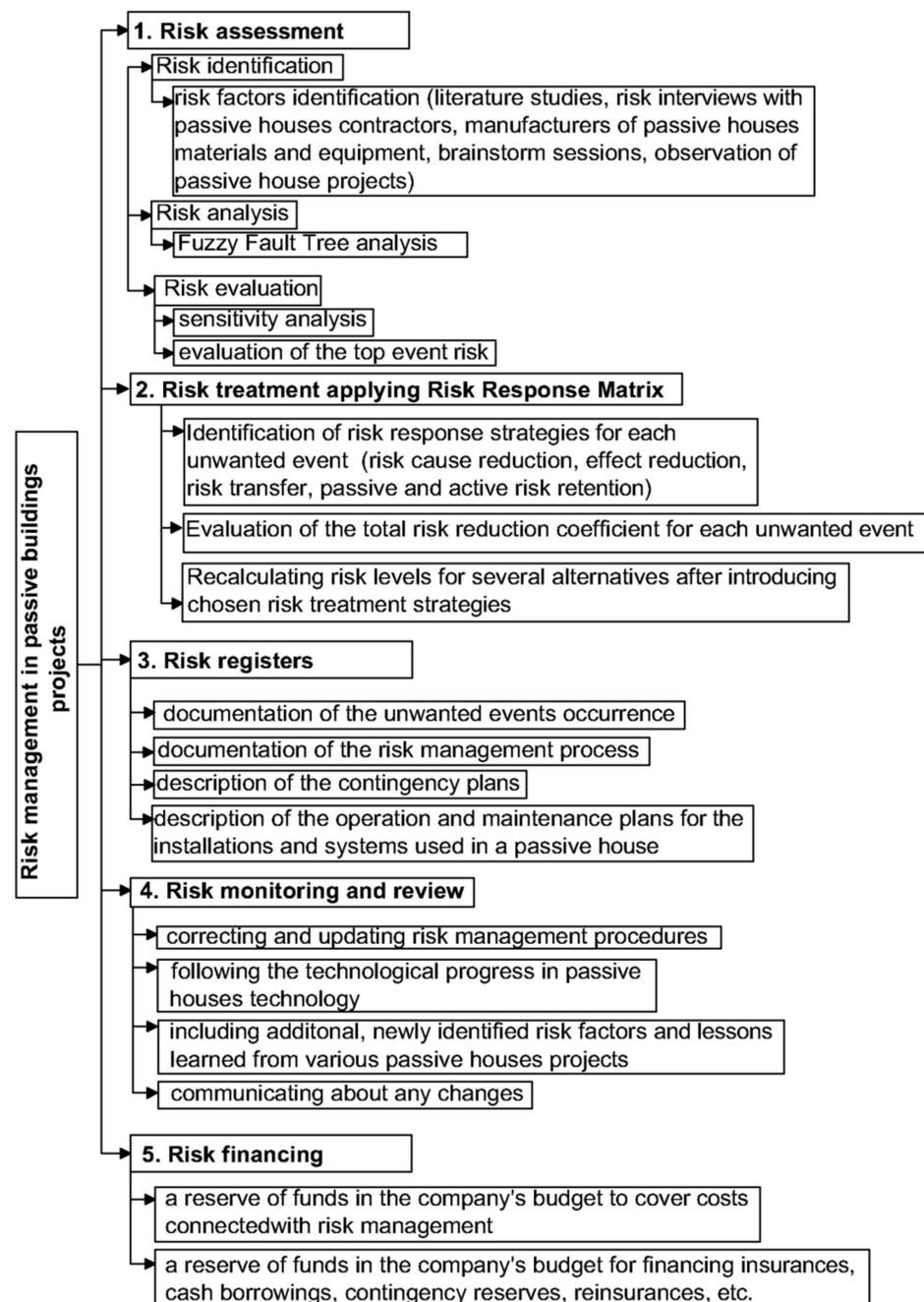


Figure 1. The proposed methodology of risk management in passive buildings projects.

2.1. Risk Assessment

2.1.1. Risk Identification

The first substep in the risk assessment stage is called risk identification. The applied methodology of risk identification included carrying out a literature study, scenario analysis, risk interviews with manufacturers of systems, and building materials dedicated for passive construction, passive buildings, architects, constructors, and contractors, as well as the own experience of one of the authors as Certified Passive House Consultant coming from observations of passive buildings development and operation. In the author's previous work [17], 30 risks in passive house projects were identified and assigned into four categories: problems with architectural and construction design, installation design, and difficulties at the building site. The identified risk factors will not be mentioned in this paper due to their length.

2.1.2. Risk Analysis

Risk analysis, which is the second substep of the risk assessment, was carried out using a novel Fuzzy Fault Tree (FFT) connected to the risk response matrix (RRM). Figure 2 presents the proposed hybrid FFT and RRM dedicated for passive building projects. A horizontal format of FFT was used, so the TE “the unsuccessful passive building project” was put on the left of the page; the four identified intermediate events to the right were furthermore divided into basic events marked with circles or underdeveloped events marked with rhombus. The TE was understood as an unsuccessful passive building project, not meeting the project objectives, exceeding the project budget or the failure to comply with the work schedule, or not meeting the passive house quality standards. In the author’s previous work [17], the FMEA technique was used to qualitatively analyze 30 failure modes in passive buildings projects, identify their causes, consequences, and the possibilities of detection. On this basis, four intermediate events and 16 BEs or UEs in the FFT were defined and presented in Table 1.

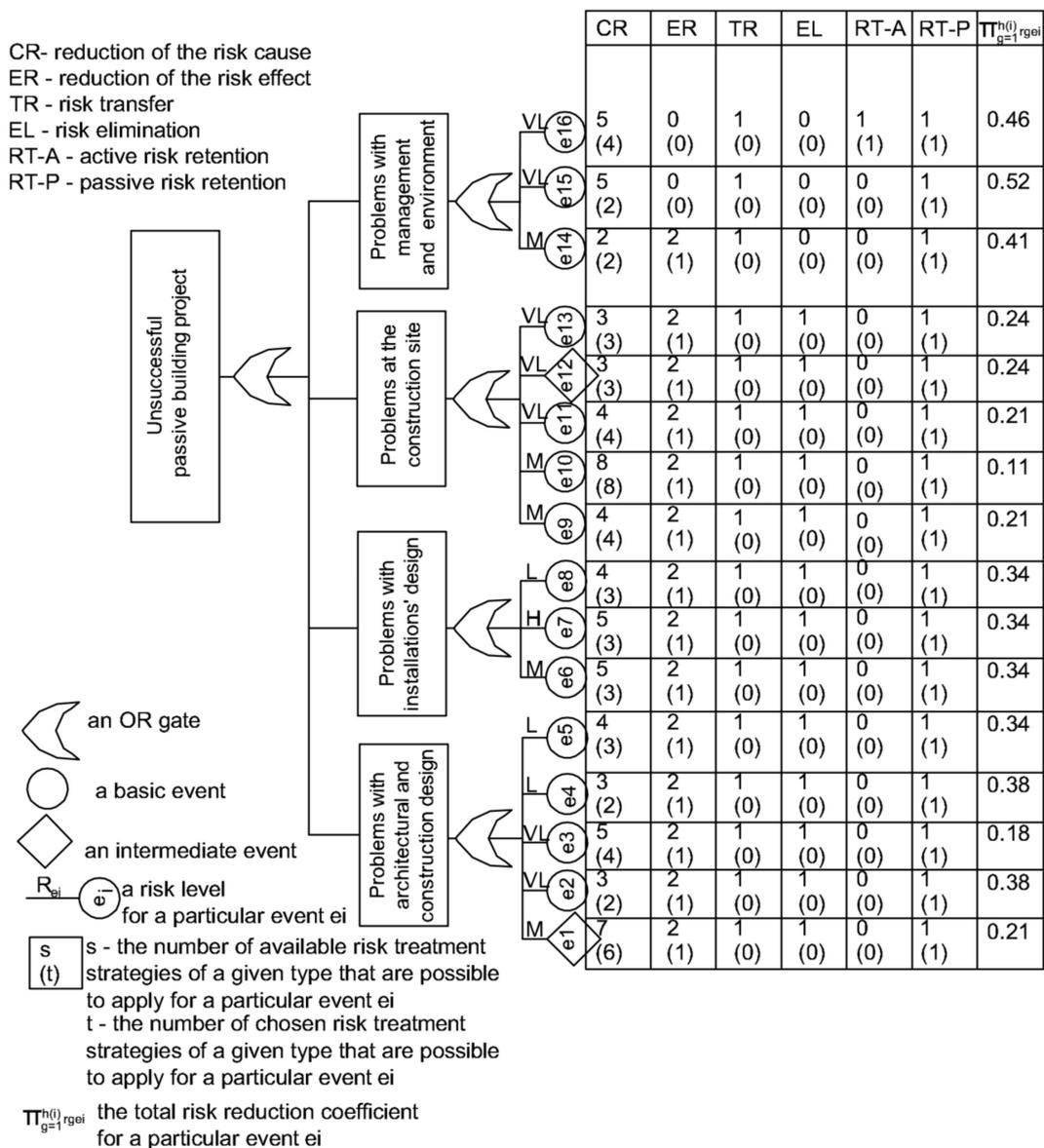


Figure 2. Proposed hybrid Fuzzy Fault Tree and Risk Response Matrix for risk management in passive buildings projects (on the example of Polish project).

Table 1. Identified basic and underdeveloped events.

Symbol	Event Name
e1	Taking erroneous assumptions
e2	Leakages in the building's envelope due to the inappropriate location of the installations
e3	Leakages in the building's envelope due to recommending improper materials or systems in the design
e4	Leakages through gaps in the building's envelope due to omitting critical points in the design
e5	Designing a building with undesirable structural thermal bridges
e6	Mistakes in the design of noise protection of the ventilation installation
e7	Mistakes in the installations' design
e8	Incorrectly designed insulation of the installations
e9	Selecting the improper window installation technique or mistakes in windows' and doors assembly process
e10	Leakages in the building's envelope caused by the improper assembly
e11	Lack of quality control of the embedded materials
e12	Inappropriate interpretation of correct drawings and details received from the designer
e13	Conscious assembly inconsistent with the project
e14	Problems with inter-branch coordination and information for the building's user
e15	Incorrect cost calculations
e16	Unfavorable external conditions (weather, legal)

Table 2 presents the definitions of the risks covered by each unwanted event.

Table 2. The definitions of risks covered by each unwanted event.

Symbol	Risk Description
e1	Making wrong assumptions (improper climate zone, improper methodology of carrying out calculations, incorrect modeling of individual thermal bridges, improper parameters of doors and windows, incorrect location of doors and windows, choosing low-quality materials, complicated building shape leading to not meeting a form factor requirement A/V, inadequate placement of the building on the plot, improper orientation of rooms, inappropriately planned room layout or sunlight control)
e2	Designing unnecessary breakthroughs through the building's envelope, lack of the installation layer in the case of the frame building structure
e3	Selection of materials that do not provide airtightness of the building envelope, such as: wood wool and softwood fiber building boards, unplastered masonry wall structure, hard foam polystyrene boards, perforated foils, tongue and groove system, designing application of short-life joints, such as wrapping adhesive tape, seals made of silicone, polyurethane assembly foam
e4	Leakages in the building's envelope due to omitting sensitive points in the design (e.g., lack of detailed production drawings and clues for the contractor such as: plastering required on internal walls to bottom of the wall, air seals needed at the roof and wall interface, plastering required under the installations in front of the wall, sealed strip near the windows needed, tightening electrical sockets needed)
e5	Thermal bridges at the connections between the roof and external walls and the balcony with the ceiling, inadequate insulation of basement walls, crowns (including the ceiling above the basement) and lintels, thermal bridges at connection of the garage with the building's wall, connection of the balcony slab with the building structure; thermal bridges in the roller shutter box insulation, thermal bridges at joints in the roof structure; thermal bridges at the rims at the gable wall
e6	Lack of silencers or their improper placement, designing long pipe sections while the shortest should be preferred, lack of noise protection with flexible connectors at the air handling unit, lack of silencers between rooms or in front of the air handling unit

Table 2. Cont.

Symbol	Risk Description
e7	Incorrectly selected filter in front of the air handling unit or the filter missing; revision missing, no inspection of the intake vent, improperly designed protection of the plate heat exchanger against freezing (if the exchanger is chosen to be applied in the design), selection of a low-quality air handling unit (minimum efficiency required of 75%, electrical efficiency max. 0.45 Wh/m ³ , no planned condensate drain for the sewage system for the ventilation unit, no use of a double siphon, or a ball siphon (when a typical siphon dries out unpleasant odors arise), frost protection of heat or electric heater missing (if they are applied); mistakes in calculating the minimum required air changes, improper specification of supply and exhaust zones; flow holes under the door missing; air intake protection without protection against rain and snow, incorrect coupling of the Building Management System with the building installations arranging no fire protection (lack of fire dampers, smoke dampers) in buildings where it is required, designing a fireplace with too much power without encapsulating it with a storage mass (risk of overheating the room), insufficient renewable energy sources to ensure thermal comfort of the building users; when choosing a fireplace a failure to take into account the risk of negative pressure in the building resulting from a leaky chimney system, which sucks flue gases into the room with a clogged filter; not including in the design documentation about the need to reprogram the air handling unit to use a fireplace; lack of the designed vacuum sensor in the case of a fireplace design; no designed carbon monoxide sensor in the case of a fireplace design; in the case of multi-family housing no main emergency fire switch provided in the design; in the case of single-family houses no smoke detector provided in the design at the place of air intake with an emergency switch ventilation system; no fire dampers with thermal release mechanism (if required); no designed protection against cold smoke (e.g., no smoke detector in the supply and exhaust duct or a sensor installed in the ceiling of the room)
e8	Improperly designed insulation of ventilation and heating pipes, domestic hot water and circulation pipes in the building: vapor barrier missing, incorrectly arranged heating pipes' insulation outside the building's thermal coating, locating the recuperator without considering conditions for insulation in the warm zone and cold zone, unsolved thermal bridges at pipe connections with fittings,
e9	"Warm installation method" not used, windows installed behind the insulation layer (in the wall), improperly fixing of the jamb surface without using a primer, insulating tapes missing, a vapor barrier film missing; too few anchors, improper intervals when spacing anchors; metal elements (anchors, mounting rails, support blocks) with unreliable isolation
e10	Execution errors apart from errors in the installation of window and door, gaps in the mortar, sticking sealing tapes to uncleaned, dusty or wet surfaces, breakage of the vapor barrier caused by improper sealing of punctures in the airtight layer of the building, leaky electrical sockets, no plastering of the walls under the installations, no sealing with swelling or gypsum mortar the breakages in the airtight layer of the building caused by the installation pipes, no sealing of the sewage system penetrations in the floor on the ground, not plastering the walls at the foot, inaccurate plastering, wrong order of execution of works (e.g., placing connecting foil after fixing the roof structure above the attic wall is incorrect), tapes glued on an unprimed wall structure, too dry or wet concrete,
e11	Lack of careful quality control of the covered elements, e.g., the method of installing windows; improper location of the vapor barrier, no quality control of the laying of thermal insulation boards (gaps or no laying of the boards "staggered"), no control of the accuracy of plastering internal surfaces (e.g., unplastered frames, plaster not led to the foot of the wall), no control of the order of execution of works (e.g., no laying of the foil) connecting before installing the roof structure over the attic wall)
e12	Incorrect interpretation of properly prepared drawings in the project caused by the contractor's lack of knowledge
e13	Conscious execution inconsistent with the design in order to simplify the work and speed up the execution of works
e14	Lack of knowledge of the architect of the basic principles of the installation to be used in the building, uncoordinated routes of installation affecting the technique and possibilities of installation, lack of coordination of works between the contractor of construction works and the contractor of installation works, resulting in the need to disassemble the installed elements or breaking the airtight coating of the building, failure to carry out identification collisions in a cross-industry project
e15	Incorrect cost calculation (underestimation or overestimation), failure to take into account some important costs in the costing (material costs, execution costs, certification costs, costs of several tightness tests during the works), not including costs in the so-called risk pool, errors in the take-off of works
e16	Unfavorable weather conditions preventing further progress of works, inability to commence or continue works due to the lack of permits or legal conditions, problems resulting from claims related to nuisance noise emissions and the destruction of existing elements of ground and underground infrastructure

Table 3 presents the most important factors determining the risk level for each unwanted event in passive building investments.

Table 3. The most important factors determining the risk level for each unwanted event in passive building investments.

Symbol	Factors Determining Risk Level
e1–e9	<ul style="list-style-type: none"> - the number of years of experience of the designer in designing passive buildings of a specific type taking into account their specificity (e.g., skyscrapers, single-family buildings, multi-family buildings, public utility buildings, sports halls, museums, office buildings) - designer's knowledge in the field of passive construction, knowledge of the use of specialized computer programs enabling the performance of specialized calculations necessary for the design of buildings of this standard - the degree of complexity of the project - type of construction adopted - investor's pressure - the designer's attachment to a specific material manufacturer and the willingness to promote it - contractor's pressure (contractors' reluctance to install windows in the insulation layer due to the greater complexity of the work) - the number and type of computer simulations are planned to be carried out and the degree of designer's knowledge of the specialist software and experience with computer modeling - whether the building certification is declared (then the risk is reduced)
e10, e11, e12, e13	<ul style="list-style-type: none"> - the number of years of experience of the contractor in designing passive buildings with of a specific type taking into account their specificity (e.g., skyscrapers, single-family buildings, multi-family buildings, public utility buildings, sports halls, museums, office buildings) - contractor's knowledge in the field of passive construction - number of airtightness tests to be carried out - the degree of complexity of the project - whether the building certification has been declared (then the risk decreases) - the contractor's attachment to a specific system manufacturer and the willingness to promote it - knowledge, experience and qualifications of the employed air tightness specialist - ease of installation and time of assembly
e14	<ul style="list-style-type: none"> - architect's knowledge about the basic principles of operation of the installations intended for use in the passive building, - the method of coordinating the routes of installation, affecting the technique and possibilities of installation, - the degree of coordination of works between the contractor of construction works and the contractor of installation works, resulting in a pessimistic scenario in the necessity to dismantle the installed elements or break the tightness of the building envelope, - whether it is planned to identify a collision in an interbranch project (standard, assembly, hard collisions involving the overlapping of the geometry of two model elements, soft, 4D related to the work schedule) - whether the building certification is declared (then the risk is reduced)

An underdeveloped event is defined as an event that has not been not further developed either because it is of its subevents' minor consequences or because of a lack of available information [60]. The events covering human error (e.g., a contractor's mistake) are often underdeveloped because they result from many various factors. and it is not needed to examine them in further detail. Expanding a fault tree to too high level of detail may result in getting great probabilities and rising the uncertainty of the fault tree analysis.

The level of detail to which the FFT was extended is vital as it decides about the significance of the final result. In this work, the proposed FFT was developed to the mechanisms necessary for the identification of the functional dependencies between events, which allows the consistency and readability of the analysis to be maintained. In the proposed FFT structure containing only OR gates, the occurrence of any of the 16 basic or underdeveloped events is sufficient to cause the TE occurrence. Figure 2 presents the proposed hybrid FFT combined with RRM dedicated for risk assessment and management in passive buildings projects. It is shown on the example of one project to make it more practical and clear.

The authors' intention was to select the methods that would allow for developing a dynamic risk management tool, enabling not only to assess the risk connected with basic events and TE occurrence, but also to check the impact of risk remediation strategies on the basic event risk and TE risk. The combination of FTA with RMM makes it possible

to achieve this goal. FTA enables carrying out both qualitative and quantitative risk analysis. The most important advantages of FTA include its high readability, clear visual representation of the failure structure, and clear presentation of the logical relationship between the TE and all basic events which lead to its occurrence [61,62]. Moreover, using FTA, it is possible to assess the impact of a single failure and combined failures on the whole passive building investment.

Due to the quite simple structure of the proposed FFT, containing only OR gates and the fact that the same events do not occur on separate FFT branches, it was possible to apply the methodology of general tree studies to its qualitative analysis. The proposed approach is not based on the conventional approach of solving Fault Trees using probability theory. In the case of a passive house project, the historical data needed to determine the probability distribution for basic events in passive buildings projects is not available. Therefore, the crisp failure rates for basic events in passive buildings projects cannot be obtained. That is why using the conventional approach to solving FT in the case of passive buildings could lead to gaining misleading information in risk analysis or increasing the uncertainty of the analysis. It should be stressed that the basic events in passive buildings projects are dynamic, as they depend on human factors and changing environmental conditions. In this work, it was decided to solve the problem of gaining probability distributions for unwanted events in passive buildings projects by using fuzzy sets theory. It enables to lower the lack of precision and uncertainty, as well as eliminate the problems with getting the crisp values of the probability of the basic event in passive houses projects.

The fuzzy sets have an advantage over the crisp sets because they enable the gradual assessment of the membership of the elements in a set, which is reflected by a membership function taking values in the real unit interval $[0,1]$ [63], e.g., the statement “the element “b” is a member of a set B” can be true to some degree called membership degree. It allowed for a gradual transition between the linguistic terms.

In the literature, there are some examples of successful application of Fuzzy sets theory in risk assessment and management in various building construction projects, e.g., [57,58,64–67].

The theory of possibility was introduced by L.A. Zadeh and allowed making decisions based on inaccurate and incomplete information that appears in the statements of the language we use (e.g., low temperature, high temperature). In everyday life, we deal with a blur of concepts used in expressing information in a shortened form. Therefore, in everyday communication, we use the possibility theory, the basis of which is fuzzy sets theory. However, the basis of the theory of probability is the theory of measure. In the statistical approach, the probability density function should be known, and the precise determination of the characteristics determines the obtaining of better results.

Often the trapezoidal membership function is used to analyze safety problems where a more detailed description is required to obtain a more accurate solution. In the proposed approach to the risk assessment model, the groups of experts in passive houses are familiarized with the analyzed project and the risk management model. Then, they evaluate the probability of basic events occurrence using the following linguistic values: very low (VL), low (L), medium (M), high (H), and very high (VH). Separate trapezoidal membership functions should be developed for each group of experts to show how they understand certain linguistic values (e.g., they are 100% sure that the low probability is between 4 and 6%, 50% sure that it is between 3% and 7%). The methodology of developing the membership function was described in the author’s previous work [68]. Particular attention should be paid to the appropriate selection of experts. They should have many years of experience in passive buildings of a particular size and type (e.g., single-family buildings, public utility buildings, multi-family buildings, skyscrapers, and office buildings).

It should be noted that the group of specialists evaluated the probability of BEs occurrence supposing taking no additional risk mitigation actions.

Equation (1) presents the way of calculating the risk of the BE or UE occurrence for the membership degree α_{jk} from both sides (left and right):

$$\widetilde{R_{eia\alpha_{jk}}} = \left(\widetilde{P_{eia\alpha_{jk}}} \cdot C_{ei} \cdot \prod_{z \in Z} w_{ei}^z \cdot x_{ei}^z, \widetilde{P_{eid\alpha_{jk}}} \cdot C_{ei} \cdot \prod_{z \in Z} w_{ei}^z \cdot x_{ei}^z \right) \quad (1)$$

where:

$\widetilde{P_{ei\alpha_{jk}}}$ —fuzzy probability of the BE or UE e_i occurrence, which is taken from the trapezoidal membership function for the membership grade α_{jk} from both sides $\left(\widetilde{P_{eia\alpha_{jk}}}, \widetilde{P_{eid\alpha_{jk}}} \right)$
 α_{jk} —the degree of membership to fuzzy probabilities set describing each linguistic value,

$j = 0, 1, 2, \dots, m - 1$

m —analyzed membership grades number,

k —the membership grades' step of change, $k = \frac{1}{m-1}$

C_{ei} —the factor depicting the consequences of the BE or UE,

w_{ei}^z —the total risk reduction factor for the selected risk management actions of a given type for unwanted event e_i , $w_{ei}^z \neq 0$, which will be clarified in Section 2.2.

x_{ei}^z — z -th—the experience factor for a given risk treatment action.

Z —the set containing all kinds of risk response strategies, described by Equation (2):

$$Z = \{CR, ER, EL, TR, RT - P, RT - A\} \quad (2)$$

where: CR—risk cause reduction, ER—risk effect reduction, EL—risk elimination, TR—risk transfer, RT-P—passive risk retention, RT-A—active risk retention

After substituting $\left(\widetilde{P_{eia\alpha_{jk}}}, \widetilde{P_{eid\alpha_{jk}}} \right)$ to the Equation (1), the risk of BE or UE occurrence will be calculated from the left side $\widetilde{R_{eia\alpha_{jk}}}$ and right side $\widetilde{R_{eid\alpha_{jk}}}$.

The occurrence of any BE or UE can result in a TE occurrence. That is why all BEs and UEs are equally important in terms of their consequences. Therefore, the factor reflecting the consequences of unwanted event occurrence $C_{ei} = 1$ for all the identified BEs or UEs. The risk connected with BEs or UEs occurrence should be firstly assessed without considering introducing any additional risk treatment strategies (or using only a passive risk acceptance strategy). It means that the total risk reduction factor from Formula (1) is equal 1 ($\prod_{z \in Z} w_{ei}^z = 1$), so no additional risk reduction is received and the experience factor for a particular risk response strategy is not taken into account ($x_{ei}^z = 1$).

The individual experience of the architect, installation's designer, contractors, and consultants in introducing risk treatment strategies can be taken into account in this model thanks to introducing the individual experience factor " x_{ei}^z ", which takes values from the range $\langle 1, 1.2 \rangle$, where 1 means that the passive building project team is experienced in introducing a particular risk management strategy and 1.2 means that the crew is not experienced in it. The individual experience factor values may be chosen by experts who assess the individual experience of the team engaged in the passive building projects project.

Fuzzy risk of the TE from the left and right side $\widetilde{R_{t\alpha_{a_{jk}}}}, \widetilde{R_{t\alpha_{d_{jk}}}}$ should be obtained for values of the membership grade α from Equation (3) by putting fuzzy risks $\left(\widetilde{P_{eia\alpha_{jk}}}$ and $\widetilde{P_{eid\alpha_{jk}}}$, which were earlier obtained from Equation (1).

$$\widetilde{R_{t\alpha_{jk}}} = \left(\left[1 - \prod_{i=1}^n \left(1 - \frac{\widetilde{P_{eia\alpha_{jk}}}}{100} \right) \right] \cdot 100\%, \left[1 - \prod_{i=1}^n \left(1 - \frac{\widetilde{P_{eid\alpha_{jk}}}}{100} \right) \right] \cdot 100\% \right) \quad (3)$$

where: $\widetilde{R_{t\alpha_{jk}}}$ —the fuzzy risk of the TE calculated for the membership degree α_{jk} , (%).

Thanks to carrying out the defuzzification process, it is possible to select the proper crisp value of the TE risk from the fuzzy set. TE risk after defuzzification (the crisp risk) can be obtained from Equation (4) using the Center of Area Method:

$$R_t^{COA} = 0.5 \cdot \left(\frac{\sum_{j=0}^m \widetilde{R}_{ta\alpha_{jk}} \cdot \alpha_{jk}}{\sum_{j=0}^m \alpha_{jk}} + \frac{\sum_{j=0}^m \widetilde{R}_{td\alpha_{jk}} \cdot \alpha_{jk}}{\sum_{j=0}^m \alpha_{jk}} \right) \quad (4)$$

where: R_t^{COA} —the defuzzified risk of the TE occurrence) (%),

$\widetilde{R}_{ta\alpha_{jk}}$ —the extreme values of the risk of the TE occurrence for jk -th membership graderead from the left side (%), $\widetilde{R}_{td\alpha_{jk}}$ —the extreme values of the risk of the TE occurrence for jk -th membership grade read from the right side (%).

2.1.3. Risk Evaluation

Risk evaluation aims to determine if an analyzed passive house project entails an acceptable or unacceptable risk level. Risk evaluation should be based on the results of the risk assessment (namely, the TE risk expressed in percent obtained assuming taking no additional risk treatment strategies, $\prod_{z \in Z} w_{xi}^z = 1$) and the findings of the sensitivity analysis. Acceptable and unacceptable risk borderlines of BE/UE and TE should be set individually by each investor for the analyzed passive building project, taking into account the project specificity together with technical, legal and economic conditions.

Sensitivity analysis enables the identification of the critical risk factors in passive building projects, which should be subject to particularly careful risk management. It is advised to carry out risk analysis once again by taking into account introducing the most recommended risk response strategies to assess the impact of the chosen risk mitigation actions on the entire system. In this work, a Fuzzy Weighted Index (FWI) was used to carry out the sensitivity analysis. It enables to measure the share of each of the BEs/UEs which can cause the TE occurrence. The fuzzy weighted indicator FWI for the BE or UE e_i can be calculated by the formula:

$$FWI_{ei} (R_t^{COA}, R_{ti}^{COA}) = R_t^{COA} - R_{ti}^{COA} \quad (5)$$

where:

R_t^{COA} —the risk of the TE occurrence taking into account the BE or UE e_i , (%),
 R_{ti}^{COA} —the risk of the TE occurrence obtained without considering the BE or UE e_i (%).

The BE or UE with the highest value of FWI are considered critical and should be a subject of particular attention when choosing adequate risk treatment strategies for them.

2.2. Risk Treatment

Risk treatment is the process of choosing and applying a variety of measures aiming to lower or modify risk. It plays a key role in the risk management process. In the proposed risk management methodology dedicated to passive buildings, four types of risk treatment are taken into account: risk cause or effect reduction, risk elimination, risk transfer, as well as passive and active risk retention. Table 4 presents the characteristics of various risk treatment strategies.

Table 4. The characteristics of various risk treatment strategies.

Risk Management Strategy	Approach	Description
Risk reduction	Holistic	Removing causes of risk, consequences of the risks, or reducing both of them
Risk elimination	Holistic	Taking actions intended to exclude risk (e.g., stopping the investment, choosing another project solution)
Passive Risk retention	Fatalistic	Accepting the risk's consequences, documenting the risk appearance
Active risk retention	Fatalistic	Accepting the risk's consequences, recording the risk existence combined with preparing rescue plans
Risk transfer	Fatalistic	Sharing or carrying out by someone other than an owner consequences of risk

Thanks to combing the FFT with the risk response matrix, it is easy to check for each unwanted event, what kinds of risk response strategies are accessible, and how many actions (s) of every type can be used for a particular unwanted e_i . Moreover, the hybrid FFT and RRM enables the assignment of the number of selected risk management strategies (t) of a given type (CR, ER, EL, TR, RT-P, RT-A) to a certain BE or UE. A complex indicator describing the possibility to lower the BE or UE risk level $\prod_{z \in Z} w_{ei}^z$ is calculated in the last column of the RMM. Thanks to combing FFT with RMM a holistic view of all undesirable events were presented, which revealed dependencies between the events and the possibilities of risk treatment for each event. It is also suggested to prepare individual sheets of a hybrid FFT and RMM and examine a few alternatives of risk response strategies to select the most relevant one.

All identified risk response strategies for BEs and UEs are shown in Table 5. Risk reduction values for them proposed by the authors based on risk interviews with manufacturers of systems, building materials and software dedicated for passive construction, passive buildings architects, constructors and contractors, as well as the own experience of one of the authors as Certified Passive House Consultant coming from observations of passive buildings development and operation. For example, a risk reduction factor of 0.6 is understood as obtaining a risk reduction by 40%, which is equivalent to a residual risk remaining at 60% of the base risk value. Risk response strategies were divided according to the holistic or fatalistic approach. It is suggested to specify for each chosen risk treatment action in which stage of the passive building realization process it should be implemented and define who is responsible for its implementation. It should be noted that some risk response actions presented in Table 5 have already been singly applied in good passive buildings investments. However, it should be stressed that their selective implementation without basing on a complete dedication to passive building project risk management strategy is insufficient and can result in overlooking other significant risk treatment strategies, which meaningfully affect the passive house investment risk level.

Table 5. Risk treatment possibilities for passive building projects.

Symbol	Risk Treatment	r_{gei}
CR(e1–e8)a	Choosing a certified passive house designer or consultant by Passivhaus Institute	0.60
CR(e1–e8)b	Using the double-checking rule by a certified passive house consultant or designer recognized by Passivhaus Institute	0.70
CR(e1–e8)c	Checking the project by a specialist in the field of passive buildings other than certified	0.90
CR(e1)d	Using the designer's checklist regarding the orientation of rooms (places prone to overheating such as the kitchen—from the south, living rooms—from the south, bedrooms, children's rooms, and study rooms—from the east, west, or north)	0.90
CR(e1)e	Checking the form factor of the building (surface to volume requirement for a passive house $A/V \leq 0.7 \text{ 1/m}$), inspecting if obtuse angles were selected	0.90

Table 5. Cont.

Symbol	Risk Treatment	r _{gei}
CR(e1)f	Applying recognized software dedicated for passive buildings ^a (e.g., PHPP [69], EnergyPlus [70], DesignBuilder [71], TRNSYS [72], MATLAB [73] and optimization algorithms, e.g., [37,39,41–43])	0.70–0.85
CR(e1)g	Conducting an on-site visit	0.80
ER(e1–e14)a	Contractual penalties (psychological effect)	0.90
ER(e1–e14)b	Warranty deposit as a means of securing the owner against detecting any irregularities in the project, which can be detected during the airtightness test and examination with a thermal imaging camera	0.80
EL(e1–e13)a	Choosing a different construction type (less problematic from the point of view of passive building design or execution)	0.80
TR(e1–e16)a	Risk transfer on the insurance company (risk policy)	0.90
CR(e2)d	Checking if the installations are designed in an installation layer of the building (only for skeletal constructions)	0.80
CR(e3)d	Checking if the materials recommended by a designer are certified and dedicated for applications in passive buildings (e.g., are awarded with Passive House Institute Component Certification)	0.60
CR(e3)e	Selection of proven material suppliers with references from similar passive buildings constructions	0.80
CR(e5)d	Use of the designer’s checklist for structural thermal bridges	0.90
CR(e6)d	Using a checklist: checking silencers were designed (e.g., in front of the air handling unit or between rooms), checking the correctness of location of silencers, checking if the shortest pipe sections were designed, checking if noise protection using flexible connectors was designed at the air handling unit	0.90
CR(e7)d	Using a checklist to find mistakes in the design, such as an incorrect specification of supply and exhaust zones; mistakes in calculating the minimum required air exchange, flow holes under the door missing; lack of revision, lack or inadequate filter in front of the air handling unit, improperly designed air intake protection against rain and snow, lack of frost protection of heat exchanger or electric heater (if applied), fire and smoke dampers missing in objects where they were obligatory	0.90
CR(e7)e	Application of computer aided design, simulation and optimization of installations with the use of recognized software, e.g., PHPP [69], EnergyPlus [70], DesignBuilder [71], TRNSYS [72], MATLAB [73], PVSYST [74], PVSOL [75], PVGIS [76] and optimization algorithms, e.g., [37,39,41–43] ^a	0.70–0.85
CR(e8)d	Using a checklist to identify mistakes that could occur on the building site: unreasonably long sections of circulation pipes, insufficient insulation thickness of domestic hot water and circulation pipes, not taking into account the recuperator’s location (guidelines for insulation vary for the cold and warm zone), vapor barrier missing, incorrectly designed heating pipes’ insulation outside the building’s thermal coating, unsolved thermal bridges at pipe connections to fittings	0.90
CR(e9–e13)a	Selection of a certified contractor with experience and references from similar projects (Certified Passive House Builder)	0.70
CR(e9–e13)b	Carrying out specialist passive construction training on the construction site	0.70
CR(e9–e13)c	Specialist supervision and consulting on the construction site, employing an air-tightness specialist to supervise and inspect the design and building site	0.60
CR(e9)d	Using the checklist to identify mistakes which would be likely to occur: positioning the window behind thermal insulation line; using not enough anchors or placing them at the wrong intervals; lack of isolation of anchors, mounting rails, and support blocks; improper preparation of the jamb surface without using a primer, failure to apply a vapor barrier film; failure to apply insulating tapes	0.90

Table 5. Cont.

Symbol	Risk Treatment	r _{gei}
CR(e10)d	Taking regular temperature and humidity readings on the building site, as a number of seals, tapes and membranes do not seal effectively in high humidity if the atmospheric relative humidity is above 80%.	0.90
CR(e10)e	Consultations with the sealing products' manufacturers to get information about the proper way of their applications and conditions	0.90
CR(e10)f	Use of advanced weather forecasts and anemometers on the day of testing to confirm that weather conditions are suitable for testing in advance of issuing a final test confirmation	0.90
CR(e10)g	Use of designer's checklist: Using a checklist to make sure that the system flanges, cuff seals, and careful wrapping of installation passages through partitions were introduced	0.90
CR(e10)h	Leakages identification during the three air pressure tests (when the air barrier is complete, but any services and/or appliances have not been fitted; when services have been installed, but fixtures and fittings such as shower trays, baths, kitchen units have not been put in place when all works have been completed). Applying thermal imaging to identify thermal bridges and leaks (the moving air cools down the surfaces that are very well visible in infrared photos). Leakages identification thanks to smoke puffers and pencils application for determining draughts at specific locations. Using a low flow thermal anemometer after locating the leak to visualize its size. Carrying out remedial sealing works.	0.70–0.90
CR(e11)d	Preparation of photographic documentation of the covered elements	0.90
ER(e1–14)b	Contractual penalties (psychological effect)	0.90
CR(e14)a	Using Building Information Modeling (BIM) software to find out inconsistencies and collisions in the inter-branch design, as well as in the passive building's operation and maintenance	0.65
CR(e14)b	Carrying out mandatory consultations of the design with a competent contractor with many years of experience in passive houses constructions	0.70
CR(e15)a	Applying Building Information Modeling (BIM) software for accurate bills of quantities and detailed costing	0.65
CR(e15)b	Choosing the right type of contract ^b	0.80
CR(e15)c	Risk-sharing between the investor, contractor, designer and consultant	0.70
CR(e15)d	Partnering	0.60
CR(e15)i	Using Alternative Project Delivery Methods (APDM), e.g., construction manager at risk (CMAR) ^c	0.70–0.90
CR(e16)a	Preparation of photographic documentation of the existing infrastructure elements	0.90
CR(e16)b	Carrying out works not in the bird-breeding season (in the case of the construction of tall buildings and their location near areas with special environmental values)	0.90
CR(e16)c	Obtaining the required permits prior to the commencement of works	0.80
CR(e16)d	Checking precise weather forecasts and warnings of the national weather services	0.80
CR(e16)e	Early preparation of equipment and protection of equipment against weather conditions	0.80
RT-P(e1–e16)a	Documentation of the risk existence	1.00
RT-A(e16)a	Contingency Plans—An inclement weather evacuation plan	1.00

^a More information about the software used in building energy simulations can be found in [38]. ^b Some practical guidelines can be found in [77]. ^c Some practical guidelines can be found in [78].

3. Example of Application

The application of the proposed model will be shown on one example. Table 6 shows the analyzed passive building characteristics.

Table 6. The passive building characteristics.

Parameter	Description
Building type	A single-family building
Usable area	175.16 m ²
Foundation structure	A single reinforced concrete foundation slab, thermally insulated with 20–35 cm Styrodur, $U \leq 0.14 \text{ W}/(\text{m}^2\text{K})$
Wall structure	Large size prefabricated polygon reinforced concrete elements of thickness 15 cm, insulated with Styrofoam of thickness 25 cm, covered with external silicate plaster, $U \leq 0.1 \text{ W}/(\text{m}^2\text{K})$
Roof and gable walls structure	Gable roof with a slope of 45°, wooden frame construction, insulation made of mineral wool (30 cm thick), $U \leq 0.1 \text{ W}/(\text{m}^2\text{K})$
Doors and windows	Wooden, airtight balcony windows and doors, $U \leq 0.80 \text{ W}/(\text{m}^2\text{K})$, $g = 50\%$, thermal bridged free assembly
Shading	Automatic shading blinds in all windows
Installations	Hot water installation, sanitary installation, mechanical supply-exhaust ventilation with recuperation with a set of max. airstream 330 m ³ /h, active summer throttle, electric heater, hybrid PVT cells placed on the southern roof' sside, a fireplace with a water jacket, floor heating, a wind turbine with a vertical axis of nominal power 2 kW, ground heat storage tank, a high-temperature vacuum collector, a heat accumulator with a capacity of 700 dm ³ , a water–water heat exchanger

No certified passive house designer was planned to be selected for the design of the passive building. However, it was planned to check the design by a passive construction specialist (not certified by the Passive House Institute, PHI). The building was not planned to be certified by PHI. It was planned to carry out the airtightness tests only once. The general contractor that was planned to be chosen has no previous experience in constructing passive buildings.

It was planned to design heating water as a system consisting of a high-temperature vacuum collector, a fireplace with a water jacket, a heat accumulator with a capacity of 700 dm³, and a water–water heat exchanger. A combination of several heat sources were designed: a seasonal ground heat accumulator, a fireplace with a water jacket, and electric heaters. Seasonal ground heat accumulator was assumed to store the heat obtained by flat solar collectors. The heat accumulator was designed in the form of vertical ground probes, approximately 5-m long, located under the building. In periods when the amount of heat supplied from the ground heat accumulator and solar collectors will be insufficient, it was designed to activate a fireplace with a water jacket. The heat from the fireplace was assumed to be collected by the water jacket and directed to the buffer tank. Due to the fact that the building is equipped with mechanical ventilation, air for combustion is supplied through a ventilation duct led outside the building. Hybrid solar PVT installation was designed to obtain simultaneous electricity to power consumers and devices in the house, and thermal energy to heat water and ground heat exchanger. The installation included 31 hybrid solar collectors of 300W and one vacuum collector, which was installed on the roof and facade of the building. The project lacked information on how to operate, set up, and maintain the installation systems.

The linguistic terms used for assessing the fuzzy probability of the identified BEs and UEs occurrence were gained from the group of experts in passive houses, supposing no additional risk remediation actions were taken. The membership function for the BEs or UEs probability of occurrence was presented in Figure 3. The linguistic values estimating the probability of occurrence of BEs or UEs were presented in Figure 2 on the tree branches close to the events' symbols.

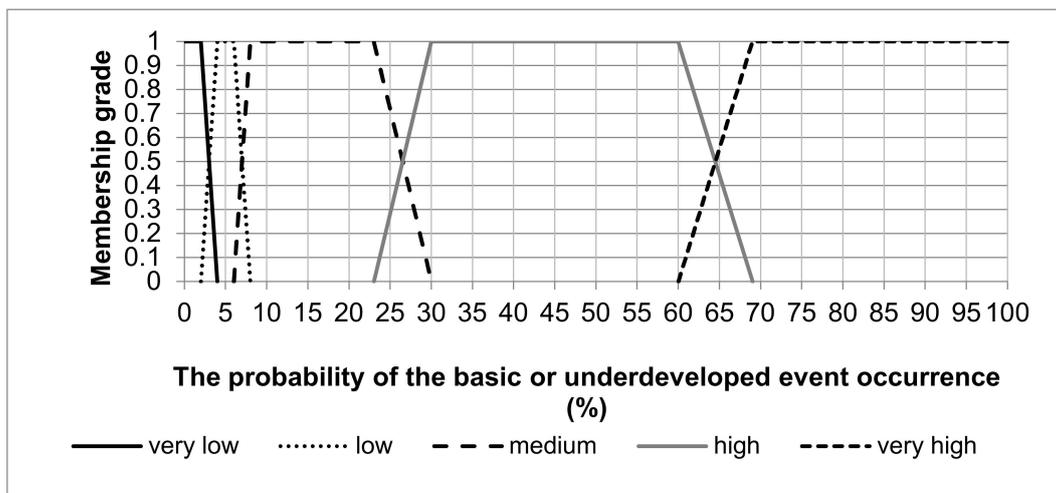


Figure 3. Membership function for the probability of the BE/UEs occurrence probability for the analyzed passive building project.

For the analyzed passive building project, the authors compared two alternatives of risk response strategies. The first alternative assumes taking no additional risk treatment strategies. The second alternative assumes that the most relevant risk response strategies would be chosen. The chosen risk remediation strategies for each alternative are presented in Table 7.

Table 7. Analyzed alternatives of the risk treatment strategies for the passive building project.

Alternative	The Chosen Risk Remediation Strategies
Alternative 1	RT-P(e1–16)a
Alternative 2	CR(e1)a,b,d,e,f,g, ER(e1–e14)a, CR(e2)a,b, CR(e3)a,b,d,e, CR(e4)a,b, CR(e5)a,b,d, CR(e6)a,b,d, CR(e7)a,b,d, CR(e8)a,b,d, CR(e9)a,b,c,d, CR(e10)a,b,c,d,e,f,g,h, CR(e11)a,b,c,d, CR(e12)a,b,c, CR(e3)a,b,c, CR(e14)a,b, CR(e15)a,b, RT-P(e1–16)a, CR(e16)a,c,d,e, RT-A(e16)a

The fuzzy risks connected with BEs or UEs occurrence for Alternative 1 are shown in Table 8. They were obtained from formula (1), with an assumption that no additional risk remediation strategies would be introduced ($\prod_{z \in Z} w_{ei}^z = 1$), and taking unwanted events consequences $C_{ei} = 1$. BEs/UEs probabilities were read from the left and right side of the membership function in Figure 3 for various membership grades α with the step $k = 0.05$.

To estimate the contribution of each of BE or UE to the TE occurrence and to find out the critical events for the analyzed project, a sensitivity analysis was carried out. From Equation (5), the values of fuzzy weighted index (FWI) were obtained for all BEs and UEs. They were presented in Table 9. It was found out that the critical event, which particularly should be subject to risk treatment was e7 with $FWI_{e7} = 13.53\%$.

The last column in Figure 2 presents the total values of the risk reduction coefficients $\prod_{z \in Z} w_{ei}^z$ for Alternative 2 for all the identified events in the analyzed passive building project. The fuzzy risks of BEs or UEs occurrence for Alternative 2 were obtained from Formula (1), taking into account the unwanted events' probability of occurrence assessed by the experts, their consequences $C_{ei} = 1$, the risk reduction coefficients for the chosen risk treatment strategies and assuming that the consultant, architect, designer and contractor have experience in introducing risk remediation strategies ($x_{ei}^z = 1$).

The risk reduction for the TE that could be reached after introducing risk treatment strategies from Alternative 2 is clearly illustrated in Figure 4, which shows the distribution of the fuzzy risk of the TE occurrence for the two analyzed alternatives. The individual TE risk values for successive degrees of membership were calculated from Equation (3).

Table 8. The fuzzy risks connected with the BEs or UEs occurrence for the analyzed passive building project for various values of the membership grade for Alternative 1.

The Membership Grade (α_{jk})	The Fuzzy Risk of the Basic Event Occurrence (%)							
	e2, e3, e11–e13, e15, e16		e4, e5, e8		e1, e6, e9, e10, e14		e7	
	$\widetilde{P_{ei_a\alpha_{jk}}}$	$\widetilde{P_{ei_d\alpha_{jk}}}$	$\widetilde{P_{ei_a\alpha_{jk}}}$	$\widetilde{P_{ei_d\alpha_{jk}}}$	$\widetilde{P_{ei_a\alpha_{jk}}}$	$\widetilde{P_{ei_d\alpha_{jk}}}$	$\widetilde{P_{ei_a\alpha_{jk}}}$	$\widetilde{P_{ei_d\alpha_{jk}}}$
0.00	0.00	4.00	2.00	8.00	6.00	30.00	23.00	69.00
0.05	0.00	3.90	2.10	7.90	6.10	29.65	23.35	68.55
0.10	0.00	3.80	2.20	7.80	6.20	29.30	23.70	68.10
0.15	0.00	3.70	2.30	7.70	6.30	28.95	24.05	67.65
0.20	0.00	3.60	2.40	7.60	6.40	28.60	24.40	67.20
0.25	0.00	3.50	2.50	7.50	6.50	28.25	24.75	66.75
0.30	0.00	3.40	2.60	7.40	6.60	27.90	25.10	66.30
0.35	0.00	3.30	2.70	7.30	6.70	27.55	25.45	65.85
0.40	0.00	3.20	2.80	7.20	6.80	27.20	25.80	65.40
0.45	0.00	3.10	2.90	7.10	6.90	26.85	26.15	64.95
0.50	0.00	3.00	3.00	7.00	7.00	26.50	26.50	64.50
0.55	0.00	2.90	3.10	6.90	7.10	26.15	26.85	64.05
0.60	0.00	2.80	3.20	6.80	7.20	25.80	27.20	63.60
0.65	0.00	2.70	3.30	6.70	7.30	25.45	27.55	63.15
0.70	0.00	2.60	3.40	6.60	7.40	25.10	27.90	62.70
0.75	0.00	2.50	3.50	6.50	7.50	24.75	28.25	62.25
0.80	0.00	2.40	3.60	6.40	7.60	24.40	28.60	61.80
0.85	0.00	2.30	3.70	6.30	7.70	24.05	28.95	61.35
0.90	0.00	2.20	3.80	6.20	7.80	23.70	29.30	60.90
0.95	0.00	2.10	3.90	6.10	7.90	23.35	29.65	60.45
1.00	0.00	2.00	4.00	6.00	8.00	23.00	30.00	60.00

Table 9. Fuzzy weighted Index values for BEs and UEs calculated for Alternative 1.

Alternative 1	
Event	RWW(R_t^{COA}, R_{ii}^{COA}). (%)
e2, e3, e11–e13, e15, e16	0.01
e4, e5, e8	0.98
e1, e6, e9, e10, e14	2.76
e7	13.53

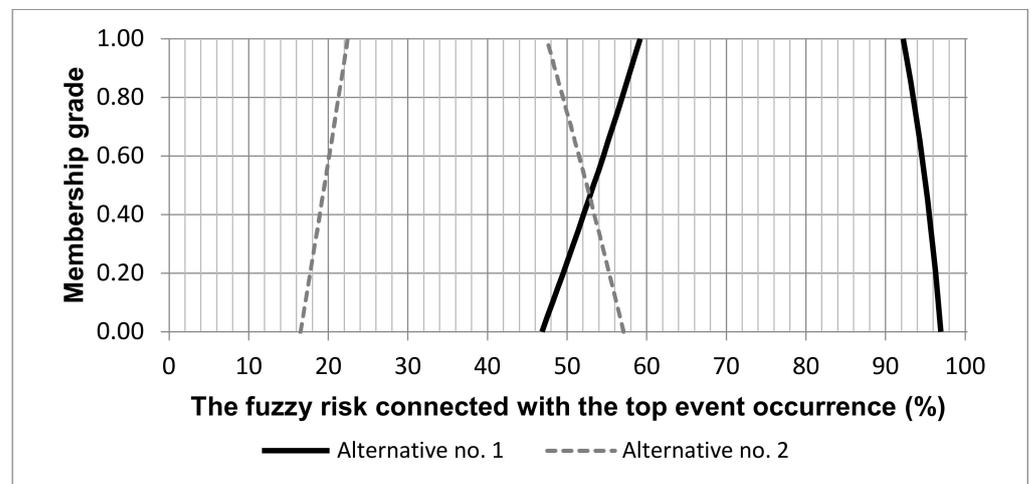


Figure 4. Distribution of the fuzzy risk of the TE occurrence for the analyzed passive building project for two configurations of risk management strategies.

From Equation (4), the crisp risk of the TE occurrence in the analyzed project was obtained. The TE risk for Alternative 1 was 74.74%, and for Alternative 2 was 35.59%. Thanks to applying the proposed risk treatment strategies, it was possible to reach a risk reduction of 39.15%.

4. Discussion of the Results

It is vital to confirm the risk management process results by comparing the obtained BEs and UEs risks and TE risk level with the passive building project execution. Due to the lack of approval of the first version of the design by a consultant specializing in passive buildings, the design was revised, which resulted in a slight delay in the deadline for building acceptance (event e14 occurred). The photovoltaic system based on hybrid PVT modules was in practice, able to meet the needs of the household in terms of electricity production, as envisaged in the project. The installed wind turbine was able to provide the electricity necessary for the operation of the building without residents with small surpluses. The design and construction documentation for the ground energy storage did not include selection calculations regarding the flow resistance of individual spiral probes to ensure the optimal flow velocity and reduce losses. It was also not known at what depth the probes were mounted temperature sensors. The designed 5-m long probes turned out to be too short of ensuring thermal comfort in the building. The introduced high limit temperature for loading the tank from hybrid collectors resulted in irregular (or complete lack of) loading of the buffer tank throughout the year. According to the design assumptions, in winter, the heat from the ground under the building should supply the underfloor heating with a temperature of 25 °C. However, such an assumption made it impossible to maintain the thermal comfort of individual rooms in winter. Such a small temperature difference between the air temperature in the rooms and the supply temperature resulted in an imbalance of the temperature gradient of the heat exchange between the media, causing the extension of the time to obtain thermal comfort in individual rooms. Moreover, in practice, when lighting the fireplace, it was necessary to unseal the entire system by tilting the window. The air intake dedicated to the fireplace did not make it possible to light the fireplace in practice. It means that the event e7 occurred. The user also reported that the ventilation system was too loud (e6). The air handling unit has not been reprogrammed in all rooms for the use of a fireplace.

A noticeable convergence was observed between the identified critical events and undesirable events that really appeared during the passive building project in the case when not all suggested risk response actions were implemented. Thus, the correct operation of the proposed risk management model was confirmed.

It is believed that if a risk reduction was carried out as proposed in Alternative 2 (the most recommended option), the passive house project would be more successful, as the risk of critical events would be significantly reduced. According to the calculations carried out, the proposed approach would allow to reduce the risk connected with e7 by 66%, e1 by 79%, e6 by 66%, e9 by 79%, e10 by 89% and e14 by 59%. In the presented passive building project, introducing the risk management model would allow reducing the basic events risk from 48% up to 89% ($\prod_{z \in Z} w_{ei}^z = 0.52$ up to $\prod_{z \in Z} w_{ei}^z = 0.11$). It would result in a reduction of the TE risk by 39.64% in the case of a full implementation of the suggested risk mitigation strategy for the analyzed passive building investment.

Similar assumptions in the risk management model were applied in another study of the author for Horizontal Directional Drilling technology, except the individual experience factor for a particular risk response strategy, which was not taken into account in the previous model. Therefore, the proposed approach becomes a universal model for risk management, which could be adjusted to various areas of environmental engineering and building construction projects by: investigating the specificity of the project and technology, identifying basic events specific for the analyzed problem identifying factors determining the risk level, defining the TE, determining the fault tree structure by examining the failure mechanisms, identifying risk treatment strategies, defining the values of risk reduc-

tion factors, and developing risk management matrix dedicated for a particular problem or technology.

5. Conclusions

In this work, the first comprehensive risk management model dedicated to passive buildings projects was proposed. It covers not only risk assessment but also risk treatment. It is important to stress that it covers not only one specific risk, but the most important risks that are specific for passive houses projects, which were covered by the 16 proposed unwanted events. The proposed risk management model is helpful for architects, installation designers, contractors, and owners who are willing to develop successful quality and attainable passive building projects for the benefit of all parties involved.

Thanks to combing fault tree analysis with fuzzy sets theory and Risk Reduction Matrix, the risk of unwanted events e_i and TE risk occurrence can be assessed and effectively reduced. The proposed approach covers five steps, with each stage consists of several important sub-steps; all are needed and should not be omitted. Risk assessment and modeling was carried out taking the following important factors into account: the unwanted event probability of occurrence, its consequences, risk reduction for the chosen risk treatment strategies, and the experience of the project team in introducing the risk management strategy. Applying fuzzy logic by introducing linguistic values (very low, low, etc.) and developing a membership function describing them individually for each group of passive buildings experts enabled to increase the precision and solve the difficulties in getting the crisp values of the basic events probability from the experts.

Thanks to applying fault tree analysis, it is possible to better understand the failure mechanisms in passive buildings design and construction, as the dependencies between unwanted events are clearly illustrated in the fault tree structure. Sensitivity analysis enabled the identification of the critical risk factors in the passive building projects, which should be subject to particularly careful risk management. The proposed Risk Management Matrix with identified 171 risk remediation strategies clearly shows the possibilities of risk treatment of a given type for each event and the possibility to lower the risk level for a given unwanted event expressed with a value of comprehensive indicator $\prod_{z \in Z} w_{ei}^z$. It enables selecting the most desirable combination of risk response strategies from the several options considered. Using this model increases the likelihood of achieving sufficient quality of passive house projects and is an efficient tool to meet the contemporary challenges of passive buildings. Various values of risk reduction can be obtained for the particular analyzed unwanted event e_i , depending on the selected combination of the presented 171 risk treatment options.

The most important contributions to the body of knowledge of this work are: identification and definition of 14 BEs and 2 UEs with factors determining their risk level; identification of the top event; development of an original fault tree structure integrated with the risk management matrix; decreasing the uncertainty, and the problems with getting the crisp values of the BEs and UEs probability from the experts, thanks to employing fuzzy sets theory; taking into account the specificity and dynamics of risk in passive buildings projects and its dependence on several parameters: the unwanted event probability of occurrence, its consequences, risk reduction for the chosen risk treatment strategies, the experience of the project team in introducing the risk management strategy; proposing 171 risk remediation strategies for passive buildings projects with risk reduction coefficients values proposed for each action. Summing up, this model can be applied in practice for risk management in subsequent passive house projects.

It is vital to emphasize that risk analysis follows up risk management and their combination, as shown in the proposed approach is desirable. However, it should be stressed that it is not possible to obtain a 100% guarantee of the project's success, even with the use of the most advanced risk management models. It is due to a residual risk that persists after introducing the most relevant risk response strategies. It should be stressed

that applying the proposed model enables to diminish the predictable problems in passive building projects.

The main limitation of the presented model is the need to employ passive building specialists who assess risk during the risk assessment phase. Moreover, it is sometimes problematic to gather proper experts with suitable experience in passive building projects of a particular type and size. Therefore, the direction of future research could be a work on a novel model, in which the participation of experts will not be necessary thanks to the use of artificial intelligence.

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