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Passive Buildings—Big Opportunities or Big Risks? Quantitative Risk Assessment for Passive Buildings Projects

Maria Krechowicz [1,*] and Adam Krechowicz [2]

[1] Faculty of Management and Computer Modelling, Kielce University of Technology, 25-314 Kielce, Poland
[2] Faculty of Electrical Engineering Automatic Control and Computer Science, Kielce University of Technology, 25-314 Kielce, Poland; a.krechowicz@tu.kielce.pl
* Correspondence: mkrechowicz@tu.kielce.pl

Abstract: The building sector contributes significantly to global final energy consumption and energy-related CO_2 emissions. The demand for sustainable and energy-efficient passive buildings with a minimal ecological footprint has increased due to the global energy crisis, climate change, and environmental concerns. This need can be met by constructing passive buildings. However, to develop a building that is truly passive, it is required to meet many passive house conditions, negligible for typical buildings, which increase the project complexity and pose challenges and risks threatening its successful completion. The aim of this work is to present the findings from a quantitative risk analysis in passive construction based on the results of expert surveys that were carried out using a Computer-Assisted Web Interview. Feedback from expert surveys covering the experience of 748 passive buildings projects from seven countries (Poland, Germany, Great Britain, the United States, Australia, Spain, and Austria) allowed us to access the frequency of occurrence, severity, detectability, and Risk Priority Numbers of the 32 risk factors identified in passive buildings projects. Those risk factors were identified based on literature research, risk interviews, scenario analysis, brainstorm sessions with passive buildings specialists, and our own observations of passive buildings projects. This study revealed that incorrect costing was the most frequent issue; complicated, non-compact building shapes with an unfavorable area-to-volume ratio had the highest severity of effects; the wrong interpretation of correctly prepared drawings and details obtained from the designer had the lowest detectability; and incorrect costing had the highest Risk Priority Number. In addition, this study allowed us to identify a narrow group of critical risk factors that are the most significant (have the highest RPN) and to which special attention should be paid in the risk-management process.

Keywords: passive house; energy efficiency; risk assessment; risk management; sustainable building; energy consumption

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1. Introduction

The global energy crisis, which began in 2021 with rapid economic rebound after the pandemic, deepened in 2022 due to the Russian invasion of Ukraine and the related increased prices of natural gas, electricity, and oil [1]. To make matters worse, global energy consumption is still increasing, causing adverse effects on the world, such as global warming, climate change, and civilization diseases caused by smog. According to the recent Global Status Report for Buildings and Construction, in 2020, the building sector contributed to 36% of global final energy consumption and 37% of energy-related CO_2 emissions [2]. It confirms the need to develop sustainable buildings with minimal energy demand. That is why improving the energy efficiency of buildings, taking into account the indoor climate, local conditions, and cost effectiveness, were stressed as vital issues in the European Union Energy Directive, amending the one on the energy performance of buildings and on energy efficiency [3]. This document is an incentive to introduce the nearly Zero Energy Buildings (nZEB) approach, defined as a very high energy performance building that requires nearly zero or a very low amount of energy that should be acquired from renewable sources. Furthermore, the European Union's response to increasing greenhouse gas emissions was the introduction of the European Green Deal, which aims to significantly reduce greenhouse emissions by at least 55% by 2030, with the goal of making Europe the first climate-neutral continent in the world by 2050 [4].

The above-mentioned goal is consistent with the objective of the passive house (PH) standard, which emphasizes the minimization of energy consumption and the carbon footprint of the building, without losing high comfort for residents [5]. Passive buildings allow for a reduction in heating energy consumption by 80–90% with a certain increase in building cost compared to typical buildings [6,7]. To sum up, the passive house standard is considered a key enabler in achieving the goals of the European Green Deal and the goals of the Directive of the European Union on building energy performance as it allows for reducing energy consumption and greenhouse gas emissions [8,9]. A house built with the PH standard combined with renewable energy sources can easily reach low or zero carbon in a suitable way.

However, the high complexity of PH projects and the multitude of conditions that must be met for the building to actually be passive make it necessary to pay attention to a number of aspects that are not as important in traditional design and construction. Even a minor mistake could lead to serious problems threatening the achievement of the standard requirements of the passive house [10]. In fact, there are a number of problematic buildings that were assumed to be passive but did not meet the standard requirements of the passive house. It should be noted that meeting the requirements of the PH standard during the design and realization stage is often a challenge for architects, installation designers, contractors, and owners. It leads to many risks that could result in failure to meet the project goal, leading to disappointment from the owner, legal claims, conflicts, and misunderstandings between the owner, the designer, and the contractor. The state of knowledge about risks and problems in passive construction is presented in Section 2.2. A significant research gap was found on quantitative risk assessments in passive house projects. The literature lacks works showing how often individual, significant problems in passive buildings projects occur in design and realization practice, how severe their effects are, and how the possibilities of detecting them are expressed in a quantitative way. Although each construction is slightly different and can be considered individually, such information from the statistical analysis of many passive house projects is crucial for investors, architects, installation designers, and constructors, as it indicates critical points to which special attention should be paid during the preparation and execution of the investment. This is especially valuable in the case of a preliminary risk assessment and projects with a modest budget, where the funds to carry out an individual project risk assessment were not included in the budget. This prompted the authors to discuss this topic in this work.

The aim of this work is to present the results of a quantitative risk analysis in passive construction based on the results of expert surveys. This allows us to focus not only on opportunities related to passive buildings but also on risk factors in passive building projects and to indicate which of them are the most frequent in passive building projects, associated with the greatest severity of effects, with the lowest detectability, and with the highest risk (Risk Priority Number).

2. Literature Review

2.1. Requirements and Benefits Connected with Passive Buildings

The first passive house was built in 1991 in Darmstadt-Kranichstein [7], while 5295 passive houses have been registered so far according to the Passivhaus Buildings database [11]. Looking at the floor area built to a PH standard from 2018 to now, it has been 774,806 m^2. Due to its numerous advantages, the passive building standard quickly gained popularity in many countries on all continents [12], but the largest share of passive buildings can be seen in Germany, Austria, and Norway [13].

The Passive House Institute (PHI) defined the criteria of the passive house standard for central Europe in [6]. The PHI also defined the key assumptions of the passive house standard, supporting the fulfillment of the criteria mentioned above [6,7]. They are summarized in Figure 1.

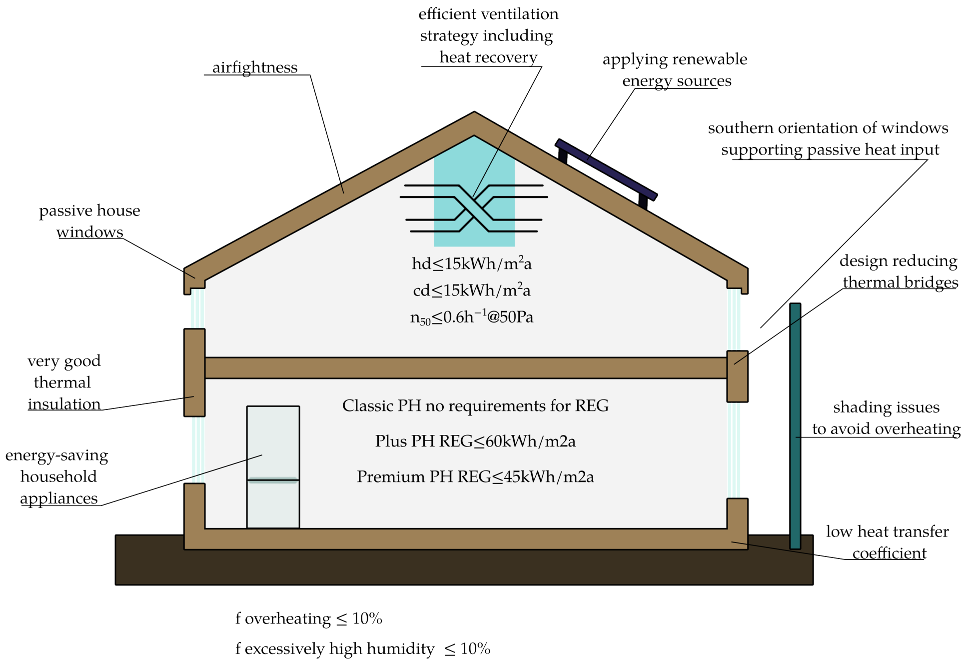

Figure 1. Criteria and assumptions of the passive house standard (where hd—heating demand; cd—cooling and dehumidification demand; n50—pressurization test result with a pressure difference of 50 Pa; REG—renewable energy generation with reference to project building footprint; f overheating—the frequency of overheating (excessive temperatures exceeding 25 °C) ≤ 10%; f excessively high humidity—the frequency of excessively high humidity (absolute indoor air humidity levels above 12 g/kg).

Originally, the PH standard was developed in Germany for its conditions. Still, it has been successfully applied to objects in different climate zones in various countries, since, generally, the passive house framework is the same. However, there are a number of factors that need to be adapted to the specificity of the climate zone. They include the window parameters, insulation thickness, and mechanical services. It should be stressed that the incorrect adaptation of those features can lead to many problems, resulting finally in not meeting the passive standard requirements. In [14], the authors used a hygro-thermal dynamic simulation to show that PHs can be successfully realized in six climatic zones of the world. It was also presented how to correctly adjust parameters for various climates. In addition to this, in [15], PH features for European and North American climates were compared.

The characteristic features of a passive house construction concept are real energy efficiency, user comfort, affordability, and care for the environment [16]. Real energy efficiency is understood as confirmed energy efficiency, checked and tested during the development and exploitation of the building, and not only the belief that the guidelines for passive construction were followed. Passive buildings are characterized by a lower heating energy consumption than typical buildings (reduction in heating energy consumption by 80–90%) with a higher initial cost of building development compared to typical buildings [6,7]. Furthermore, comparing a passive house to a low-energy building, it brings many more benefits as a well-designed and constructed passive building provides a higher comfort level for its occupants [17]. In [18], the authors analyzed the energy, environmental, and ecology effects of integrating passive strategies into buildings. It was found that depending on the combination of passive techniques applied, it can provide energy savings ranging from 6.7 to 66.2%, a reduction in the life cycle cost ranging from 12 to 52%, and payback periods of 0.5 to 84 years. In [17], the results of the comparison of five houses with passive and net-zero technologies with a traditional house were presented. The study revealed that the basic model containing renewable energy sources had a more significant impact on the cumulative cost benefit in not only economic but also social and environmental terms. In [19], a life cycle assessment of a few low-energy and passive buildings situated in Northern Ireland was carried out. The results indicate that the application of the passive house standard may contribute significantly to lowering the environmental impact on average by 30% (and up to 50%) compared to low-energy buildings in all categories, besides abiotic depletion. Furthermore, it was found that the passive house with the highest share of electricity demand received the highest reduction in global warming potential in all the analyzed cases.

The PH standard allows one to develop highly energy-efficient buildings with a minimal ecological footprint [13,20]. Other features of this approach are its universality, lack of attachment to any type of building type, architecture, or construction or building type, giving the owner the freedom of choice from many various materials, technologies, and solutions [5]. The concept of a PH is dedicated not only to single-family homes and residential buildings but also to skyscrapers and non-residential buildings, such as office buildings and schools. It can be observed that more and more conscious owners, engineers, and architects in North America, Europe, and China decided to design and build passive buildings. Large buildings with a large floor area are becoming more and more popular nowadays. Examples of such projects from recent years include an apartment house of 10,739 m^2 in Spain (2021), city block in New York of 5100 m^2 (2022), multifamily dwelling in Spain of 5736 m^2 (2022), and apartment house in China of 5430 m^2 (2022) [11]. Many conferences and trainings presenting the essence of the passive standard took place in the years 2014 to 2019 in the UK, Ireland, North America, Italy, Latvia, and Lithuania. They allowed us to gain and deepen our knowledge of owners, architects, constructors, and installation designers in the field of passive construction, which is essential to develop truly passive buildings. In addition to this, today on the market, a great variety of high-quality materials and systems are available dedicated to passive buildings, which are certified by the PHI.

To sum up, the presented literature review revealed the most important benefits of a properly designed and developed passive building. The energy efficiency of passive buildings translates into the high sustainability of the building, a lower carbon footprint, a lower impact of the building on the environment, a better LCA result, and lower energy bills. The comfort of the user of the passive house is achieved by ensuring thermal comfort, a lack of humidity, and a reduction in the risk of allergy due to an effective ventilation system. Moreover, using high-quality materials and systems certified by the PH Institute ensures the high durability of the building. Besides this, developing passive buildings enables the achievement of EU energy policy goals connected with the European Green Deal. In addition, passive buildings are affordable as their higher initial cost results in a lower cost during their design life due to lower energy consumption and a carbon footprint compared to traditional buildings [21]. Last but not least, the concept of a passive building is based on building physics, so it cannot fail, and meeting the heating, cooling, and primary energy demand of a building is checked in computer programs (e.g., the Passive House Planning Package (PHPP) dedicated to PHs) before its realization phase.

2.2. Problems with Reaching Passiveness and User Satisfaction in PH Projects and Troubleshooting Solutions

S. Piraccini and K. Fabbri listed some unwanted issues concerning the PH design and construction stages: mistakes in the design and construction of shading appliances leading to overheating during the summer, lack of proper supervision at the construction site, and the generation of condensation of water vapor inside the object [22]. In [23], the user experience of 500 passive buildings was analyzed in terms of health risks. The following problems were identified: overheating, noise from installations, legionella contamination of domestic water buffers, insufficient ventilation volumes, complicated control mechanisms, and inflexible ventilation services. In addition, recommendations were given on how to make indoor PH climate systems more user-friendly. Many authors have taken the problem of PH overheating, among others [23–30]. In [29], the subject of modeling and analyzing overheating risks in passive houses was taken. The authors discussed the problem of underestimating overheating hours in energy modeling, which is caused by overestimating the design infiltration and ventilation rate. A recommendation was given to couple the thermal and airflow network models when conducting an overheating analysis. In [24], efforts were made to choose the best natural ventilation and shading systems to reduce the risk of overheating during the hot period in a passive house located in Spain. In [30], the authors proposed a model to assess microclimate conditions in a passive building, which shows the hours of inconvenience. Besides this, some recommendations supporting the attainment of the desired microclimate conditions dedicated to passive schools were given (the application of intelligent ventilation control systems, strong mechanical ventilation at night in buildings with a high thermal inertia structure, and using combined mechanical and natural ventilation). The issue of calculating shading for passive houses was taken up in [31]. The application of the dynamic building simulation shading algorithm with the PHPP method based on the monthly balance was recommended.

A. Pitts gave several inhibitory factors that prevent passive house expansion: problems with the application of new techniques and technologies, inexperienced designers and builders, using cheap materials and systems off-the-shelf, risk of overheating, problems with the meeting of airtightness requirements, as well as impacts on the building site [32]. In [33], the problem of choosing the cheapest installation solutions (e.g., ventilation) by inexperienced designers or unaware owners was taken. In [34], it was found that the designer or constructor's mistakes can severely impact the indoor air quality of the building, the health of the residents, and the structure of the building. Moreover, in [35], the subjects of factors that threaten widespread dissemination of the PH standard were taken. It was found that misinformation among potential builders, a lack of experienced participants in the investment process, low energy prices, regulation matters, a lack of trade people with experience, and other competitive technologies on the market are important to consider. However, in the authors' opinion, a factor associated with a low energy price is not current and should not be taken into account nowadays, in the face of an increase in energy prices caused, among others, by the conflict in Ukraine.

In [36], attention was paid to the hydraulic balance of the heating installations in buildings modernized to the passive house standard, and in [37], to increasing the energy efficiency of the domestic hot water preparation systems. In [38–40], it was found that decentralized ventilation is efficient in reducing air pollution in existing buildings modernized to the PH standard. It was found to be efficient in reducing air pollution. Besides this, for passive houses, it is worth considering the real impact of atmospheric conditions on heat consumption and then predicting the control of heat supply, as shown in [41–43]. In the previous work of the author, thirty risk factors related to passive building design and construction were identified, and a qualitative Failure Mode and Effect Analysis was applied to identify the causes, consequences, and detection possibilities of PH problems [44]. In another author's previous work [45], a new expert risk-management model for PHs based on the Fuzzy Fault Tree and risk-management matrix was presented, and 171 risk-management strategies were listed. Table 1 presents some interesting troubleshooting and mitigation solutions for passive buildings that have been described in the literature so far.

Table 1. Troubleshooting and mitigation solutions dedicated for passive buildings.

Reference	Troubleshooting and Mitigation Solutions
[46]	Green and passive building optimization of the life cycle cost and life cycle environmental impact using building orientation multiobjective genetic algorithms with the following variables: mechanical systems, building shape, passive solar design strategy, aspect ratio, window type, wall and roof type and their layers, and window-to-wall ratio
[47]	Presentation of the possibilities of 20 building energy performance simulation programs, which are able to support the PH design
[48]	Presentation of how to optimize lightweight passive buildings using building exploitation evolutionary algorithms and life cycle cost
[49,50]	Proposal of using optimization software such as EnergyPlus and MATLAB to support designers when making decisions concerning PHs
[51]	Proposal of the optimization method considering energy savings, thermal comfort, and economic aspects for the PH design, which combines Gradient Boosted Decision Trees, a redundancy analysis, and a non-dominated sorting genetic algorithm.
[52]	Proposal of a multiobjective optimization model for thermal comfort and energy consumption in a residential building applying multiobjective genetic algorithm TRNSYS simulations and Artificial Neural Network
[53]	Presentation of the performance of a mobile shading system with a Phase-Change Heat Store to lighten the rooms with natural light and lower the overheating of the rooms (a 29.4% decrease in room overheating in the summer was observed)
[29]	Discussion about the problem of underestimating the hours of overheating during the development of the energy model of PHs because of overstating design ventilation and infiltration rate in the design. Proposition to coupling the thermal and airflow network models when carrying out overheating analysis
[45]	A total of 171 risk-management strategies for problems with PHs were given (for problems with architectural and construction design, problems with installation design, problems on the construction site, and problems with management and environment)
[44]	Identification of detection possibilities for 30 problems in PHs
[54,55]	Presentation of risk assessment models for complex and innovative low-energy building construction projects with renewable energy sources

In summary, the literature reports a number of problems in passive building projects and provides some interesting troubleshooting solutions. Although a complete model of comprehensive risk management based on project evaluation by an expert has already been described in the literature in [45], the literature lacks information on the frequency of occurrence of risk factors, the severity of their effects, or the quantified possibility of their detection. This information with its subsequent analysis and development of a model based on statistical data would be very useful for assessing the risk of low-budget passive building projects where it is not possible to employ external experts for risk assessment. Moreover, it would be useful for a preliminary risk analysis of all passive building projects. Taking into account the identified research gap in the area of quantitative risk analysis in passive building projects, the following research questions were formulated:

RQ1: Which risk factors are the most frequent in passive building projects?
RQ2: Which risk factors are associated with the greatest severity of effects?
RQ3: Which risk factors have the lowest detectability?
RQ4: Which risk factors are associated with the highest risk (Risk Priority Number)?

Answering these research questions will fill the identified research gap on quantitative risk assessments in passive houses projects.

3. Research Methodology

The proposed approach covers five steps and is presented in Figure 2. In the proposed approach, survey research, a Failure Mode and Effect Analysis (FMEA), and a Pareto–Lorenz analysis were used. The selection of methods was guided by the simplicity of their application and the possibility of future risk assessment without the involvement of experts.

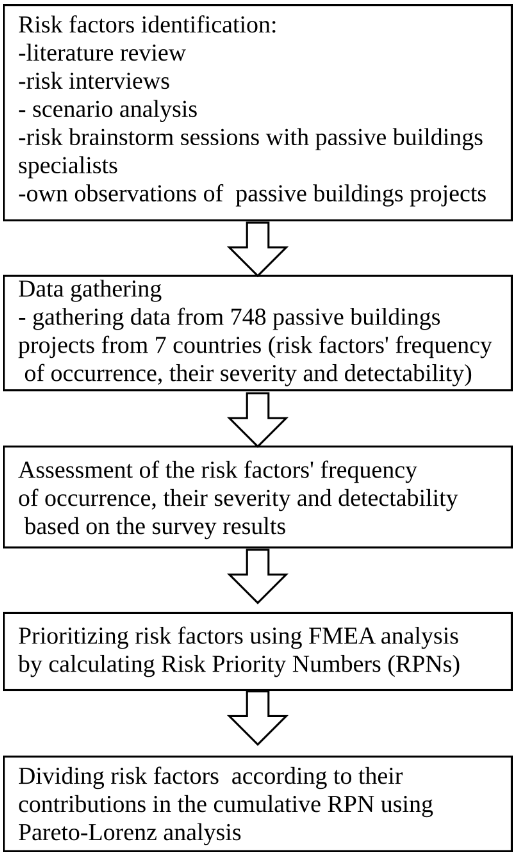

Figure 2. The proposed approach for quantitative risk assessment in passive buildings projects.

3.1. Risk Factors Identification in Passive Buildings Projects

Risk identification was carried out based on a literature review, analysis of failure scenarios, risk interviews, brainstorming sessions with passive building designers and contractors, and the author's own experience as a European Certified Passive House Consultant. The methodology applied to carry out our literature review consisted of several steps, which are described below:

1. Keywords definition, search scope, and database selection. In order to reach relevant results, it was decided to use various combinations of keywords. The following keywords were selected: {problem/risk/risk management/risk assessment/risk mitigation/troubleshooting} {in/with} {passive building/passive construction/passive house}. Scopus and Google Scholar databases were selected. Publishers included in Scopus are reviewed and chosen by an independent Content Selection and Advisory Board [56] in order to be indexed, ensuring high-quality research, while Google Scholar is known for providing wide and deep results. The default search scope was used for the Google Scholar database, and it was not possible to modify it.
2. Defining search filtering criteria. Journal articles, reviews, book chapters, and books written in English were considered.
3. Search.
4. Manual screening. It was needed to manually remove mismatched publications that were out of scope as automatic selection cannot fully replace human intelligence.
5. Analysis of publications. Publications were analyzed in terms of the described identified problems, challenges, and risks in passive construction.

Section 2.2 summarizes the most important findings from the literature research. It should be stressed that many contractors, architects, and installation designers are afraid that sharing problems that occurred during the development or operation of the passive house project could be bad publicity for the company. This belief often overrides the desire to share a lesson learned. Therefore, it was decided not only to rely on the literature analysis when identifying risk factors but also to use risk interviews, a scenario analysis, brainstorm sessions with specialists in passive buildings, and our own observations of passive buildings projects.

Risk interviews were carried out to identify risk factors; therefore, this was a qualitative study. They were conducted during passive construction fairs and meetings, during which PH designers or consultants certified by the Passive House Institute (7 experts) and representatives of the academic community dealing with the issues of energy-efficient buildings (3 experts) were interviewed. All of them have higher education. They came from Poland, Germany, and the United States. The age factor of the participants was not considered as important, whereas the documented experience of the participants in passive building projects was crucial. Someone may be many years old and have no experience in passive buildings projects. During the risk interviews, the purpose of the interview was given: the identification of risk factors in passive building projects. The following questions were asked: Have you encountered any problems with the design, implementation, or operation of passive buildings in your career? What are these problems? From what did they result? What mistakes were made? Could they have been avoided? If so, in what way? The results of the risk interviews were used to identify risk factors. The information obtained was documented in the form of a table containing the problem encountered, its causes, and risk-mitigation strategies. The collected risk factors were evaluated by the authors in terms of their usefulness to develop a list of risk factors.

Brainstorming sessions occurred with 12 specialists in the area of passive buildings (4 academics from Poland, Germany, and the USA and 8 Polish and German practitioners engaged in passive buildings design, development, or installations with at least 5 years of work experience in the passive building sector). During the brainstorming session, the following problems were posed: What are the risk factors associated with faulty architectural and construction design of passive buildings? What are the risk factors connected with faulty installation design in passive buildings? What are the risk factors associated with faulty workmanship on the building site of a passive building? What are the risk factors connected with the environment and management of passive buildings? Based on their many years of experience and the number of passive buildings projects in which they participated, they gave various responses to the stated questions, and the session leader (author) documented their responses. In several cases, they provided the same risk factor, formulating it in different words. The collected risk factors were evaluated by the authors in terms of their usefulness to develop a list of risk factors.

Several failure scenarios for passive buildings were developed based on the analysis of unsuccessful passive buildings projects gathered from PH experts and practitioners on the development of passive buildings. According to the authors, the best way to obtain information is to obtain it from the source, i.e., from specialists who actually work with passive buildings; otherwise, it is useless. The specialists involved in the scenario analysis did not consent to the publication of the results of the failure scenario analysis. Failure scenarios were considered for various problems with the selection of installations that should ensure the thermal comfort of the building users, implementation problems during building construction, operational problems related to the failure to provide instructions to building users on how to properly operate and maintain the installations, problems with interbranch coordination, and incorrect cost calculations. The causes and consequences of each failure scenario were analyzed.

Developing a list of 32 risk factors was a creative work based on multiple sources described in this work. Risk factors identified thanks to the literature review, risk interviews, scenario analysis, brainstorm sessions with passive buildings specialists, and our own observations of passive buildings projects were divided into four categories: faulty architectural and construction design, faulty installation design, faulty workmanship on the building site, and problems with the environment (natural and economic) and management. All the gathered risk factors were included in the final version of the questionnaire used to carry out expert surveys. In the case of more extensive risk factors, such as F14 (leakages in the airtight building's envelope caused by bypassing critical points in the design), it was compiled from many causes—critical points, such as no plaster under the sanitary/ventilation/electrical installation in front of the wall, no sealed strip near the windows, no plaster on internal walls reaching the bottom of the wall, no plaster on the air seals at the roof/wall interface, and leaky electrical sockets. In the case of F13 (leakages in the airtight layer of the building due to designing or applying improper materials), it was also compiled from risk sub-factors reported during the risk-identification stage, such as choosing non-air-tight materials, e.g., softwood fiber building boards, hard foam polystyrene boards, wood wool, polyurethane assembly foam, an unplastered masonry wall structure, perforated foils, wrapping adhesive tape, a tongue and groove system, and silicone seals. In the case of F24 (leakages in the airtight building envelope caused by improper assembly), it was compiled from risk sub-factors reported during the risk-identification stage, such as using sticking sealing tapes on dirty or wet surfaces, deficiencies in the mortar, improper sealing, deficiencies in plastering under installations, untight electrical sockets, and the improper order of works causing leakages. In the case of F17 (design errors in installations in the building), it was compiled from many risk sub-factors revealed during the risk-identification stage, i.e., concerning the filter selection; missing inspection of the intake vent; a too-low-efficiency air-handling unit; mistakes in the sewage system for the ventilation unit design; improper frost protection of the plate heat exchanger; improperly selected minimum required air changes; improper air intake protection; incorrectly selected renewable energy sources; and problems related to fireplaces—overheating, negative pressure, the necessity of reprogramming the air-handling unit to use a fireplace, and a vacuum sensor and carbon monoxide sensor missing.

The identified risk factors are as follows:

Faulty architectural and construction design

F1 Improper choice of the climate zone
F2 Improper design of the rooms' layout
F3 Incorrect design of the shading elements
F4 Complicated, not compact building shape with an unfavorable area-to-volume ratio
F5 Inappropriate situation of the passive building on the plot
F6 Choosing an improper methodology of calculating the energy balance and energy demand of the building
F7 Wrong user input taken into calculations concerning the building characteristics
F8 Selecting inadequate windows, doors, and glazing parameters
F9 Choosing an improper window situation
F10 Choosing low-quality materials
F11 Improper choice of materials to be used at the construction-planning stage
F12 Leakages in the airtight building envelope caused by the improper location of the installations
F13 Leakages in the airtight layer of the building due to designing or applying improper materials
F14 Leakages in the airtight building's envelope caused by bypassing critical points in the design (such as no plaster under the sanitary/ventilation/electrical installation in front of the wall, no sealed strip near the windows, no plaster on internal walls reaching the bottom of the wall, no plaster on the air seals at the roof/wall interface, and leaky electrical sockets)
F15 Structural thermal bridges

Faulty installation design

F16 Design errors in noise protection of the ventilation installation

F17 Design errors in installations in the building
F18 Design errors in the insulation of ventilation and heating pipes in the building
F19 Design errors in the insulation of domestic hot water and circulation pipes in the building
F20 Lack of or incorrectly designed fire protection
F21 Instructions on how to correctly operate and maintain the ventilation system missing

Faulty workmanship at the building site

F22 Incorrect window-installation technique chosen
F23 Mistakes in windows' and doors' assembly processes
F24 Leakages in the airtight building envelope caused by improper assembly
F25 Incorrect insulation layer assembly
F26 Lack of quality control of covered or concealed materials and works
F27 Wrong interpretation of correctly prepared drawings and details obtained from the designer
F28 Deliberate assembly inconsistent with the design

Problems with environment (natural and economic) and management

F29 Unfavorable weather conditions hindering the progress of works
F30 Interbranch coordination missing
F31 Incorrect costing
F32 Exceeding the assumed investment schedule

3.2. Data Gathering

Before the actual survey, the pilot survey was conducted from February to March 2021 to check the correctness of the used survey procedure and to validate the research tool, i.e., to check whether all questions are clear and whether the survey does not contain any answers that respondents would like to give. Similarly as in other works [57,58], they were intended only to validate the research tool, not to obtain any numerical results. Ten people with higher education in construction, with many years of experience working in sustainable, passive, and energy-efficient buildings and the installation sector, participated in the pilot survey. They came from Poland and Germany. The substantive contribution of participants and their experience was crucial because only specialists in passive buildings projects with experience could detect imperfections in the questionnaire. After conducting the pilot survey, it was decided to add a control question. It allowed for verifying the truthfulness of the respondents. The control question was consistent with another question but expressed in a different form. A control question "Adverse weather conditions" was used to verify the respondents answers to "Unfavorable weather conditions hindering the progress of works". In this study, to carry out our actual expert surveys, we used the Computer-Assisted Web Interview (CAWI) data collection technique. Experts in the area of passive buildings received an email inquiry to complete the survey questionnaire. This made it possible to conduct the survey in many different countries around the world, at a convenient time for the respondents and without direct contact with the respondents due to the threat of the COVID-19 virus. A deliberate sampling method was selected and the sample included 282 experts in the field of passive construction, selected on the basis of the knowledge and experience of the authors from the database of certified designers or advisors of the Passive House Institute. Feedback was received from 16 respondents from 7 countries whose experience was based on 748 passive buildings projects. The actual survey was carried out from April to July 2021. It should be noticed that the low return on surveys related to risks and problems in passive house construction is typical for surveys concerning risks. It was highlighted in other works on risk, for example, [59,60]. Many contractors, architects, and installation designers are afraid to share problems that occurred during their career as it could be bad publicity for the company. However, despite the low return rate, the surveys obtained in this study are based on the extensive experience of experts who participated in a total of 748 passive building projects. The collection of data on the frequency of occurrence of risk factors from such a large number of buildings is very valuable.

The results of the actual survey conducted by the authors are based on many years of experience of architectural companies, installation designers, contractors, as well as owners and persons who certify passive buildings from various countries around the world (Poland, Germany, Great Britain, the United States, Australia, Spain, and Austria), who in total participated in the construction of 748 passive buildings. Such a number of analyzed projects allowed us to obtain a relatively large international sample that constitutively gave a credible picture of the problems that occur in passive buildings projects. Table 2 summarizes the number of PH projects analyzed from each country. The frequency of occurrence of individual problems, their effects, and the possibility of detection were analyzed. The frequency of occurrence, severity of effects, and detectability of the 32 risk factors listed in Section 3.1 were examined in the survey.

Table 2. The number of analyzed passive house projects from each country.

Country	The Number of Considered Passive Buildings
Poland	86
Germany	533
Great Britain	60
The USA	10
Australia	1
Austria	53
Spain	5
Total	748

In the buildings on which the experience of the respondents in the actual survey was based, various material and structural solutions for external walls were used: a brick or concrete wall insulated with a light wet method (64%), a wall with a wooden frame structure with thermal insulation filling (28%), a wall with a light steel structure with insulation (1%), and a wall made of wooden logs (6%), a wall made of elements based on expanded clay (1%). Figure 3 shows the structure of the respondents in terms of experience in passive buildings projects. Respondents could select multiple options, e.g., some respondents were both passive house designers and building physicists or architects and passive house contractors, so their sum exceeds the number of surveyed entities.

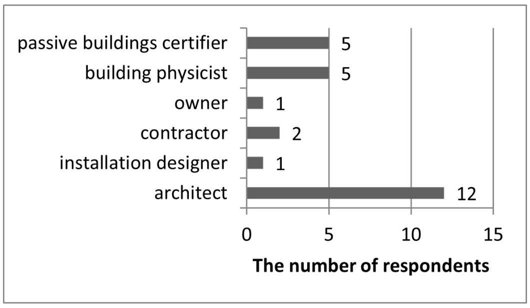

Figure 3. Structure of respondents in terms of experience in passive buildings projects.

3.3. Assessment of Risk Factors Frequency, Severity, and Detectability Based on the Survey Results

The use of the survey was dictated by the desire to obtain a statistical picture of the problems that occur in the design and realization of passive buildings. Thanks to conducting the research using an online survey, it was possible to carry out the research in different countries of the world and avoid being tied to one country and its specificity. Thanks to the survey conducted by the author, it was possible to assess the frequency of occurrence of problems in passive buildings projects, their severity of effects, and their detectability.

The frequency of occurrence of risk factors was calculated based on the results of surveys as a weighted average, taking into account the number of passive building realizations, on which the experience of the individual respondents was based (748). It was presented in Formula (1). The severity of the effects and the ability to detect individual problems were calculated as arithmetic means, considering the number of respondents (16), reflecting their expert knowledge and experience (Formulas (2) and (3)):

$$\overline{O} = \frac{\sum_{i=0}^{N} b_i O_i}{\sum_{i=0}^{N} b_i} \quad (1)$$

$$\overline{S} = \frac{\sum_{i=0}^{N} S_i}{N} \quad (2)$$

$$\overline{D} = \frac{\sum_{i=0}^{N} D_i}{N} \quad (3)$$

- O_i—the frequency of occurrence from the i-th respondent for the analyzed risk factor;
- S_i—the severity of effects from the i-th respondent for the analyzed risk factor;
- D_i—the possibilities of detection from the i-th respondent for the analyzed risk factor;
- N—the number of respondents;
- b_i—the number of passive buildings projects on which the i-th respondent's experience was based.

3.4. Prioritizing Risk Factors Using FMEA

For the execution of a quantitative risk assessment, the FMEA was selected as it allows for the definition, identification, and elimination of risks or failures. This technique allows one to obtain a ranking order among the risk factors analyzed [61] that is based on Risk Priority Numbers (RPNs). The RPN is a product of the frequency of the occurrence of an individual risk factor (O), its severity (S), and its detectability (D). It is a source of valuable information necessary to make decisions in the risk-management process [62]. If the calculated RPN value for a certain risk is higher than others, it is associated with higher risk, and more attention should be paid to its proper management [58,63]. A Pareto–Lorenz analysis is considered one of the most popular traditional quality-management tools, which aims to contribute to improving various processes and increase the level of quality of the product [64]. The Pareto principle was proposed by Joseph Juran in 1941, who observed that 80% of quality problems are caused by 20% of the causes [65]. This observation means that most causes contribute to minor effects, and therefore one should not focus too much on this group as it is not effective.

Table 3 presents the proposed FMEA scales for the frequency of occurrence, severity of effects, and detectability of risk factors in passive building projects. They benefited from traditional FMEA scales, a scale that describes the frequency of defects developed by Ford Motor Company (1988), and specialized FMEA scales for civil engineering projects [66]. The descriptions of these scales have been adjusted to the specificity of passive buildings projects. The occurrence scale describes the frequency of the occurrence of the risk factor. For example, an occurrence assessed as 1 means that a risk factor is nearly impossible to occur, while an occurrence assessed as 10 means an extremely high frequency of the occurrence of the risk factor. The severity of effects scale describes the influence of the risk factor on the goals of the PH project (cost, schedule, quality, legal, health, and safety issues). For example, severity assessed as 1 means that there is no effect on the PH project goal, while severity assessed as 10 means a disastrous influence on the PH project goals. Detectability describes the possibilities of detecting risk factors. For example, detectability assessed as 1 means that the project team control will almost certainly detect a potential cause of the risk factor (so detection is almost certain), while detectability assessed as 10 means that the project team is unable to detect a potential cause of the risk factor (so detection is absolutely uncertain). Risk factor detection is understood as activities aimed at the early detection of a problem (so it can be classified as a risk-cause-reduction strategy). This does not include actions aimed at stopping a failure that has already occurred (e.g., risk effect reduction, risk transfer, and risk elimination), as such actions cannot be classified as risk detection.

Table 3. FMEA scale for occurrence for passive building projects.

Frequency of Occurrence Scale	Severity Scale	Detection Scale	Rank
Extremely high	Hazardous	Absolute uncertainty	10
Very high	Serious	Very remote	9
Repeated failures	Extreme	Remote	8
High	Major	Very low	7
Moderately high	Significant	Low	6
Moderate	Moderate	Moderate	5
Relatively low	Low	Moderately high	4
Low	Minor	High	3
Remote	Very minor	Very high	2
Nearly impossible	None	Almost certain	1

3.5. Identifying a Narrow Group of Risk Factors That Contribute the Most to the Cumulative RPN Using Pareto–Lorenz Analysis

Pareto–Lorenz analysis is considered one of the most popular traditional quality-management tools, which aims to contribute to making improvements in various processes and increasing the quality level of the product [64]. The Pareto principle was proposed by Joseph Juran in 1941, who observed that 80% of quality problems are caused by 20% of the causes [65]. This observation means that most causes contribute to minor effects; therefore, one should not focus too much on this group, as it is not effective.

A Pareto–Lorenz analysis includes the following steps: (1) problem identification (unsuccessful passive building in terms of quality, budget, schedule, and project objectives), (2) data gathering, (3) risk identification, (4) ordering the risks in decreasing order according to the RPN, (5) drawing a bar chart for these values (a Pareto chart), (6) calculating the cumulative value of the RPN+ for each risk, (7) drawing a line chart for them (a Lorenz curve), and (8) analyzing the diagram. It can be noticed that the Pareto–Lorenz analysis is based on some of the results from the FMEA and partially overlaps with the FMEA (the RPN values and prioritization). However, the authors believe that it is worth describing the whole procedure of carrying out the Pareto–Lorenz analysis as it allows for replication of the research. The proportion of 80/20 or 70/30 does not always occur in the Pareto–Lorenz analysis, and the fact that it is different does not mean that there is a mistake in the analysis [67]. In this work, it was decided to use the Pareto–Lorenz analysis to identify a narrow group of risk factors that contribute the most to the cumulative RPN.

4. Results and Discussion

Table 4 shows the results of the assessment of risk factors in passive buildings projects (the frequency of occurrence, severity of effects, detectability, Risk Priority Number, and priority). The frequency of occurrence of risk factors was calculated based on the results of surveys as a weighted average, taking into account the number of passive building realizations, on which the experience of the individual respondents was based. The severity of the effects and the ability to detect individual problems were calculated as arithmetic means. The respondents assessed the frequency of occurrence (O), severity of the effects (S), and ability to detect individual problems (D) using a ten-point scale presented in Table 3. The Risk Priority Number (RPN) was calculated as the product of the frequency of the risk factor (O), severity of the effects (S), and detectability (D).

A Pareto–Lorenz analysis was performed to classify the risk factors in passive buildings projects according to their contribution to the cumulative priority risk number. Figure 4 shows the Pareto–Lorenz diagram for various problems in passive housing. Based on the results of the analysis, individual problems can be assigned to groups A, B, or C. Group A includes risk factors, the elimination of which is key to reducing risk in passive buildings projects. Group B contains secondary-importance risk factors. Group C includes the risk factors whose elimination results in the least risk reduction in passive buildings projects. In the analyzed case, there is a clear difference between the risk factor groups (A, B, and C), taking into account the criterion of the number of risk factors and the criterion of the effect value expressed as the cumulative Risk Priority Number (RPN+). The Pareto–Lorenz curve obtained as a result of the analysis is flatter than the standard Pareto–Lorenz curve in the initial phase.

Table 4. The results of the assessment of risk factors in passive buildings projects.

Symbol	Description	Frequency (O)	Severity (S)	Detectability (D)	RPN	Priority
F1	Improper choice of climate zone	3.45	6.40	3.60	79.58	31
F2	Improper design of the rooms' layout	6.54	6.27	4.00	164.01	28
F3	Incorrect design of shading elements	6.96	8.13	4.13	233.18	21
F4	Complicated, not compact building shape with an unfavorable area-to-volume ratio	8.29	8.50	3.13	220.10	23
F5	Inappropriate situation of the passive building on the plot	5.20	6.29	3.87	126.36	29
F6	Choosing improper methodology of calculating energy balance and energy demand of the building	8.19	8.13	4.63	307.85	11
F7	Wrong user input taken into calculations concerning the building characteristics	7.00	6.50	5.63	256.04	16
F8	Selecting inadequate windows, doors, and glazing parameters	8.39	7.63	5.25	335.66	7
F9	Choosing improper windows situation	5.36	7.50	4.75	190.98	27
F10	Choosing low-quality materials	5.63	7.25	6.13	250.05	17
F11	Improper choice of materials to be used at the construction-planning stage	8.09	7.07	5.20	297.12	13
F12	Leakages in the airtight building envelope caused by improper location of the installations	7.45	8.25	6.40	393.45	2
F13	Leakages in the airtight layer of the building due to designing or applying improper materials	5.86	7.73	6.67	302.00	12
F14	Leakages in the airtight building's envelope caused by bypassing critical points in the design (such as no plaster under the sanitary/ventilation/electrical installation in front of the wall, no sealed strip near the windows, no plaster on internal walls reaching the bottom of the wall, no plaster the air seals at the roof/wall interface, and leaky electrical sockets)	5.28	7.47	6.13	241.88	19
F15	Structural thermal bridges	7.29	7.38	6.00	322.53	10
F16	Design errors in noise protection of the ventilation installation	5.69	6.80	5.47	211.40	24
F17	Design errors in installations in the building	6.85	6.93	5.86	278.15	14
F18	Design errors in insulation of ventilation and heating pipes in the building	8.54	6.53	6.00	334.75	8
F19	Design errors in insulation of domestic hot water and circulation pipes in the building	8.37	6.27	6.53	342.49	5
F20	Lack of or incorrectly designed fire protection	2.38	6.46	7.08	108.92	30
F21	Instructions on how to correctly operate and maintain the ventilation system missing	6.30	7.07	5.47	243.51	18
F22	Incorrect windows installation technique chosen	5.79	6.27	5.47	198.37	26
F23	Mistakes in windows' and doors' assembly processes	5.74	6.86	6.00	236.35	20
F24	Leakages in the airtight building envelope caused by improper assembly	7.78	7.87	5.47	334.68	9
F25	Incorrect insulation layer assembly	6.80	6.80	5.60	258.84	15
F26	Lack of quality control of covered or concealed materials and works	7.43	7.00	6.92	360.15	4
F27	Wrong interpretation of correctly prepared drawings and details obtained from the designer	6.25	7.33	7.38	338.50	6
F28	Deliberate assembly inconsistent with the design	4.52	6.92	6.46	202.37	25
F29	Unfavorable weather conditions hindering the progress of works	3.00	5.00	5.14	77.14	32
F30	Interbranch coordination missing	8.88	6.92	6.00	369.03	3
F31	Incorrect costing	9.02	8.15	5.57	409.98	1
F32	Exceeding the assumed investment schedule	5.99	6.62	5.67	224.71	22

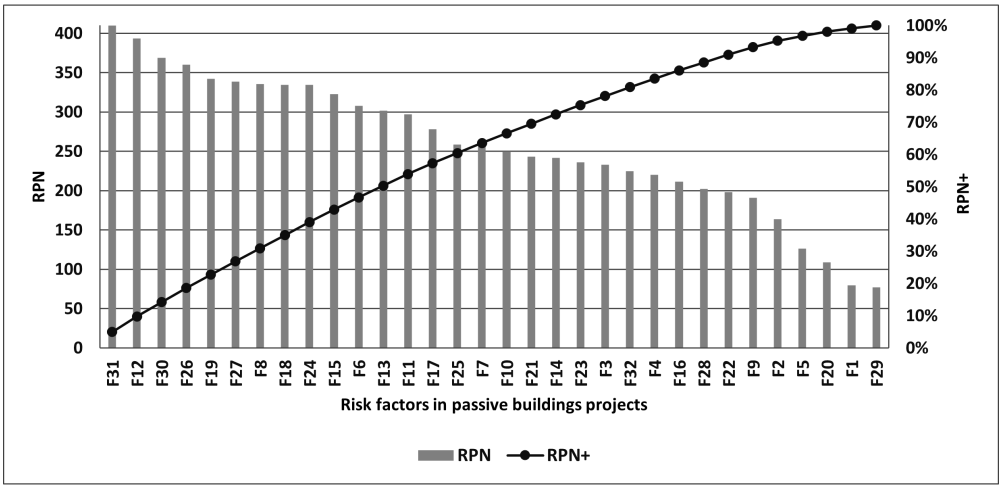

Figure 4. Pareto–Lorenz curve for the types of risk factors analyzed in passive building projects.

By performing a Pareto–Lorenz analysis for the number of risk factors, it can be seen that

- In total, 31% of risk factors generate 43% of effects (RPN+);
- Another 19% of risk factors generate 21% of effects (RPN+);
- The remaining 50% of the risk factors generate 36% of the effects (RPN+).

However, when performing a Pareto–Lorenz analysis in terms of the value of the effects of risk factors (RPN+), it can be seen that

- In total, 56% of risk factors generate up to 70% of effects (RPN+);
- Another 25% of risk factors generate 21% of effects (RPN+);
- The remaining 19% of the risk factors generate 9% of the effects (RPN+).

Table 5 illustrates the division of risk factors into groups A, B, and C according to the criterion of the number of risk factors and value of the effects of risk factors (RPN+).

In the analyzed case, there is a clear difference in the groups of causes (A, B, and C) taking into account the criterion of the number of causes and the criterion of the effect value. The obtained curve is flatter in the initial phase than the standard Pareto–Lorenz curve resulting from the 20–80 or 30–70 relationship. It is caused by a difference in the risk factors assigned to group A based on the criterion of the number of risk factors and the criterion value of the effects of risk factors (RPN+). That means that, in the analyzed case, 70% of effects (RPN+) are not caused by 30% of the risk factors (as it is in a typical Pareto–Lorenz principle), but 56% of the risk factors generate up to 70% of the effects (RPN+). The fact that, in our case, we received a different proportion than 30–70 does not mean that there is a mistake in the analysis, as was noticed in [61,63,67]. It just means that in the case of passive buildings projects, the problem of risk is more complex, and more risk factors cause significant effects. It also indicates the need to analyze more risk factors with more care. That is why, in our work, we look at risk factors from different perspectives, not only at those with the highest RPN but also at those with the highest frequency of occurrence, the most severe effects, and those that are the most difficult to detect.

Due to the fact that the main purpose of the analysis is to identify the most important types of risk factors, the effect value criterion (RPN+) should not be taken uncritically. In the analyzed case, the criterion of the number of types of problems would be more interesting.

It is important to stress that risk factors with a relatively low RPN but high frequency of occurrence, severity of effects, or low detectability should not be neglected in the risk-management process. Figures 5–7 show the risk factors in passive buildings projects with the highest frequency of occurrence, the highest severity of effects, and the lowest probability of detection of the problem, which should be subject to particularly careful risk management. Therefore, Figures 5–7 provide answers to the research questions (RQ1, RQ2, and RQ3) stated in this work.

Table 5. The division of risk factors into groups A, B, and C according to the criterion of the number of risk factors and value of the effects of risk factors (RPN+).

Symbol	Opis	RPN+	Pareto–Lorenz Analysis According to Criterion of Number of Risk Factors	Pareto–Lorenz Analysis According to Criterion of Value of Risk Factors
F31	Incorrect costing	5%	A	A
F12	Leakages in the airtight building envelope caused by improper location of the installations	10%	A	A
F30	Interbranch coordination missing	14%	A	A
F26	Lack of quality control of covered or concealed materials and works	19%	A	A
F19	Design errors in insulation of domestic hot water and circulation pipes in the building	23%	A	A
F27	Wrong interpretation of correctly prepared drawings and details obtained from the designer	27%	A	A
F8	Selecting inadequate windows, doors, and glazing parameters	31%	A	A
F18	Design errors in insulation of ventilation and heating pipes in the building	35%	A	A
F24	Leakages in the airtight building envelope caused by improper assembly	39%	A	A
F15	Structural thermal bridges	43%	A	A
F6	Choosing improper methodology of calculating energy balance and energy demand of the building	47%	B	A
F13	Leakages in the airtight layer of the building due to designing or applying improper materials	50%	B	A
F11	Improper choice of materials to be used at the construction-planning stage	54%	B	A
F17	Design errors in installations in the building	57%	B	A
F25	Incorrect insulation layer assembly	60%	B	A
F7	Wrong user input taken into calculations concerning the building characteristics	64%	B	A
F10	Choosing low-quality materials	67%	C	A
F21	Instructions on how to correctly operate and maintain the ventilation system missing	70%	C	A
F14	Leakages in the airtight building's envelope caused by bypassing critical points in the design (such as no plaster under the sanitary/ventilation/electrical installation in front of the wall, no sealed strip near the windows, no plaster on internal walls reaching the bottom of the wall, no plaster the air seals at the roof/wall interface, and leaky electrical sockets)	72%	C	B
F23	Mistakes in windows' and doors' assembly processes	75%	C	B
F3	Incorrect design of shading elements	78%	C	B
F32	Exceeding the assumed investment schedule	81%	C	B
F4	Complicated, not compact building shape with an unfavorable area-to-volume ratio	84%	C	B
F16	Design errors in noise protection of the ventilation installation	86%	C	B
F28	Deliberate assembly inconsistent with the design	89%	C	B
F22	Incorrect windows installation technique chosen	91%	C	B
F9	Choosing improper windows situation	93%	C	C
F2	Improper design of the rooms' layout	95%	C	C
F5	Inappropriate situation of the passive building on the plot	97%	C	C
F20	Lack of or incorrectly designed fire protection	98%	C	C
F1	Improper choice of climate zone	99%	C	C
F29	Unfavorable weather conditions hindering the progress of works	100%	C	C

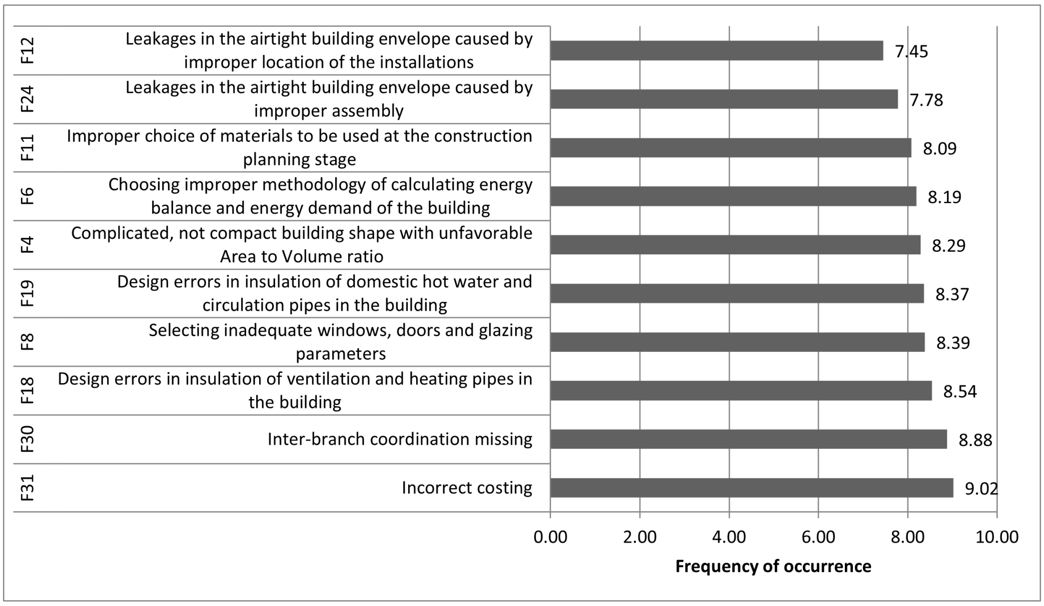

Figure 5. Risk factors in passive buildings projects with the highest frequency of occurrence.

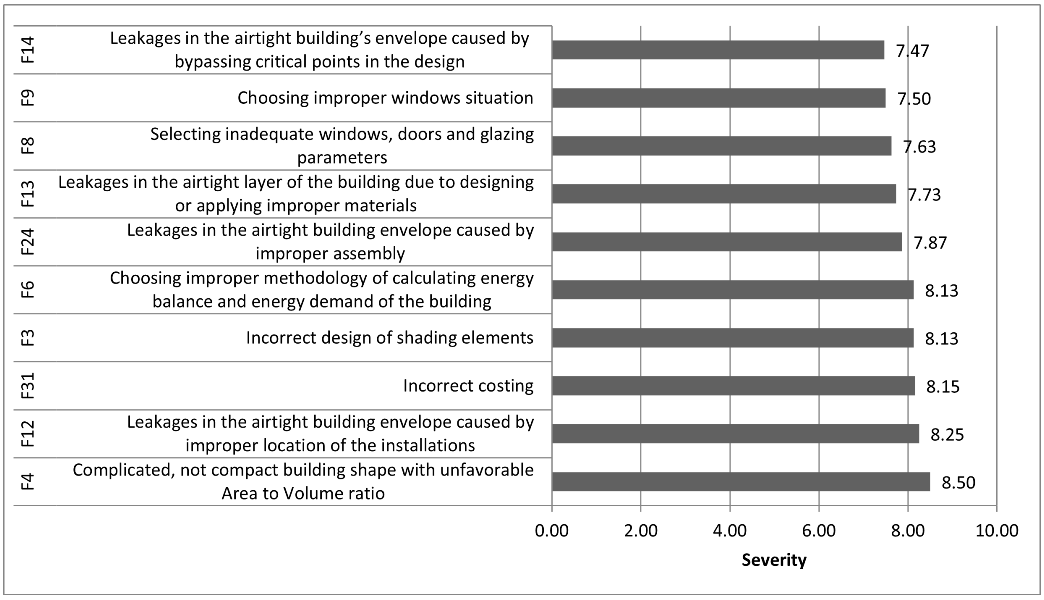

Figure 6. Risk factors in passive buildings projects with the greatest severity.

In this work, the authors identified 32 risk factors in passive buildings projects and analyzed their severity and the possibility of detection. The authors also conducted a quantitative risk analysis using the FMEA method and Pareto–Lorenz analysis. This made it possible to identify risk factors in passive buildings projects with the highest RPN, frequency of occurrence, severity of effects, and those that are the most difficult to detect. It should be noted that risks expressed using RPNs have various interpretations and different semantic implications. Therefore, it is suggested to analyze the frequency of occurrence of risk factors, their severity of effects, and the possibility of detection. In extreme cases, relying only on high levels of RPNs could result in ignoring or underestimating the risk factor associated with high risk, whose occurrence can lead to high costs.

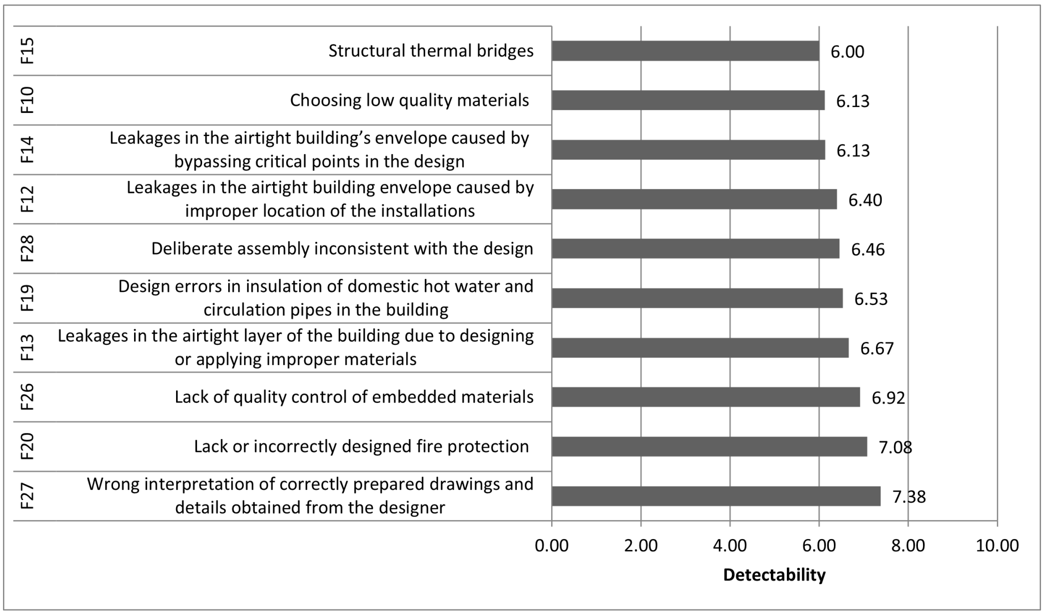

Figure 7. Risk factors in passive buildings projects with the least possibility of detecting the problem.

Figure 8 shows a comparison of the frequency of occurrence, the severity of the effects, and the detectability of the various risk factors in passive buildings projects.

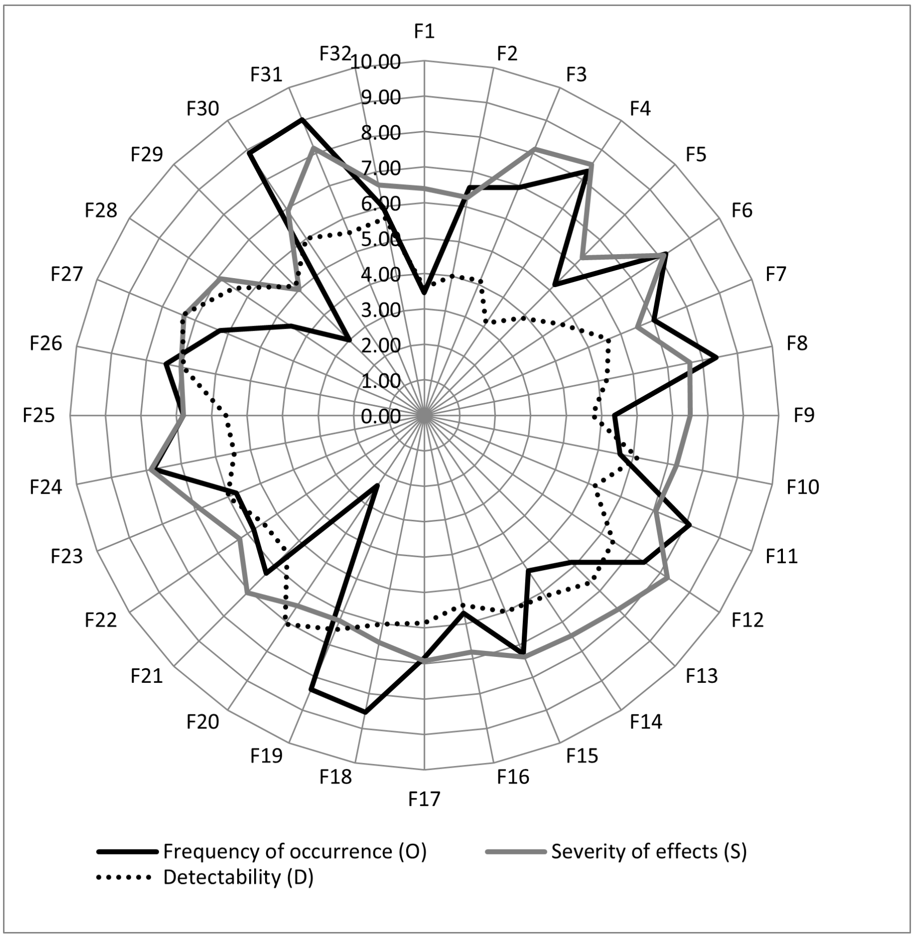

Figure 8. Comparison of the frequency of occurrence, severity of effects, and the ability to detect specific risk factors in passive buildings projects.

Figure 8 shows that for the following risk factors, both the high frequency of occurrence and the severity of the effects were obtained: F31 (incorrect costing), F26 (lack of quality control), F8 (selecting inadequate windows), F7 (wrong user input taken into calculations concerning the building characteristics), F6 (choosing an improper methodology of calculating energy balance and energy demand), F12 (leakages in the airtight building envelope caused by the improper location of the installations), and F4 (complicated building shape). The situation is different in the case of risk factors F20 (lack of or incorrectly designed fire protection), F1 (improper choice of climate zone), and F29 (unfavorable weather conditions), for which the frequency of occurrence is low but the severity of the effects is significant. In the case of an F1 event, high risk-detection capabilities (a low FMEA score) significantly reduce the risk that results largely deviate from the significant severity of its effects. Similarly, in the case of F4, the high risk-detection capacity significantly reduces the significant risk resulting from the high frequency of occurrence and the severity of its consequences.

Based on the analysis of the data and the calculation results in Table 4, it can be seen that two different risk factors have a similar RPN value (e.g., RPN (F30) = 369.03 points and RPN (F26) = 360.15 points), but they have different interpretations and various semantic implications of risk. F30 (interbranch coordination missing) has a higher risk than F26 (a lack of quality control of covered or concealed materials and works), although it has a lower possibility of detection than F26. This is due to the different values for the frequency of occurrence and the ability to detect the problem. Another example is RPN (27) = 338.50 points and RPN (28) = 335.66 points, where F27 (wrong interpretation of correctly prepared drawings) is associated with higher risk despite having a lower frequency of occurrence and a lower severity than F8 (selecting inadequate windows parameters). This is due to the different detectability values. Another example is the similar RPN values for F1 (improper choice of climate zone) and F29 (unfavorable weather conditions). F1 has a higher risk, although the possibility of detecting it is greater than for F29. This is due to the different frequency and severity values for these risk factors.

In this study, data and methodology triangulation was used to enhance the credibility and validity of the research, as can be seen from Figure 2 showing the methodology applied in this research and its description in Section 3. Qualitative and quantitative data were gathered from multiple resources (expert surveys around the world, a literature review, an analysis of failure scenarios, risk interviews, brainstorming sessions with passive building designers and contractors, and the author's own experience as a European Certified Passive House Consultant). Moreover, using a deliberate sampling method in the case of all types of research allowed us to gather high-quality data from experts in the field. All risk factors included in this research (listed in Section 3.1) were reported by respondents during the risk-identification stage and actually occurred during real passive buildings projects. Their occurrence was also confirmed by the results of expert surveys. The application of triangulation in this study allowed us to capture the complexity of risk in passive building projects, considering different aspects (from the point of view of architectural companies, installation designers, contractors, as well as owners, researchers, and persons who certify passive buildings from various countries around the world). Triangulation allowed for an increase in the validity and credibility of the research carried out. It enabled us to reduce the research bias coming from using only one perspective in the research. The consistency of the research with actual passive building projects is also stressed in the discussion section. The findings obtained are meaningful and useful for passive building owners, designers, contractors, and managers, answering the stated research questions.

The research conducted in this study (literature research, risk interviews, scenario analysis, brainstorm sessions with passive buildings specialists, and our own observations of passive buildings projects and expert surveys) indicated that the identified 32 risk factors occur in real passive building projects, causing various complications in the form of exceeding the budgeted cost, a significant reduction in the quality of the building, failure to meet the criteria of a passive building, and failure to achieve the intended user comfort. It may have serious economic, legal, and technical consequences.

This study revealed that incorrect costing was the most frequent risk factor. It should also be noted that this risk factor was among the factors that respondents indicated as those with the highest severity of effects (8.15). Furthermore, this risk factor received the highest RPN. Analyzing it more deeply, it can be noticed that it may result not only from the incorrect method, insufficient accuracy of determining the investment profitability limit, incorrect cost plan, ignoring some costs in the costing (the material, execution, and certification costs and costs of several tightness tests at the building site), mistakes in the take-off of works, lack of balance in exchange rates, type of contract, high inflation, and an increase in the interest rate, not considering costs of the risk pool, but it may also be influenced by other risk factors. For example, design errors (F1–F15) detected at the investment-implementation stage, construction errors detected too late (resulting in the need to dismantle the elements constructed so far), lack of interdisciplinary coordination, or unfavorable weather conditions (causing, e.g., damage on the construction site) may result in redesign and the need to purchase new materials or devices, simultaneously increasing the investment costs. Looking at this risk factor in the context of its ability to detect and the ability to effectively manage the risk associated with it, one can suggest responses to this risk factor, such as the use of Building Information Modeling software for accurate billing and detailed, automatic, and virtual costing. There are also models available that allow for the green and passive building optimization of life cycle costs and environmental impact; optimization of lightweight passive buildings; or optimization considering energy savings, thermal comfort, and economic aspects for PH design. Problems with incorrect costing were also indicated during risk interviews, scenario analysis, and brainstorm sessions with experts in the field. On the other hand, the literature states that passive buildings cost around 5–15% [68] or 5 to 10% more compared to typical buildings [7], indicating only a slight increase in costs. The results obtained from University College London indicate that the overall capital cost uplift for the development of a new passive building was only 0.9%, taking into account the life cycle costs [69]. Similarly, in [21], it was observed that passive buildings are likely to have a lower cost during their design life due to a lower energy consumption and a carbon footprint compared to traditional buildings. However, based on the experience of the authors and the information collected during meetings with passive house experts, in the author's opinion, the above-mentioned estimations from the literature concern exemplary, high-quality passive building projects, which were successfully completed without the occurrence of unwanted events. In practice, such passive buildings projects can be developed when risks are effectively managed; that is, when risks are identified, assessed, and risk-response strategies are implemented.

It was also found that complicated, non-compact building shapes with an unfavorable area-to-volume ratio had the highest severity of effects. This may be the result of the designer's lack of knowledge and experience; the desire to create visually attractive, usually complex shapes; or the investor's pressure. This factor was also included in the group of factors with the highest frequency of occurrence (8.29). Its moderately high detection capabilities contributed to the reduction in its RPN. Therefore, according to the Pareto–Lorenz analysis in terms of RPN+, it was classified into group C (the risk factors whose elimination results in the lowest risk reduction in passive buildings projects). The most important detection possibilities of this risk factor include selecting a certified or experienced passive house designer or consultant, applying the double-checking rule by a certified or experienced passive house consultant or designer, verifying the form factor of the building (the surface-to-volume requirement for a passive house $A/V \leq 0.7\,\mathrm{m}^2/\mathrm{m}^3$), checking if obtuse angles were selected, and using optimization algorithms, e.g., Refs. [46,48,51,52].

Moreover, this study revealed that the wrong interpretation of correctly prepared drawings and details obtained from the designer had the lowest detectability. Taking into account its high RPN (338.5), this risk factor was also classified as group A according to a Pareto–Lorenz analysis in terms of RPN+, meaning that its elimination is key to reducing risk in passive buildings projects. This is a risk factor independent of the designer, consisting of the incorrect interpretation of drawings and details correctly prepared by the designer. This results from the contractor's lack of knowledge and experience. In fact, the detection possibilities in this case are limited to strict supervision and quality control at the construction site. Its low detection possibilities were also confirmed during the author's own observation of passive buildings projects and risk interviews. This can be accomplished by employing a certified or experienced passive house specialist to supervise the construction site. Risk-response options other than detection include psychological effects achieved thanks to contractual penalties, carrying out certified training for contractors familiarizing them with the principles of passive buildings development, and requiring references from previous implementations of passive buildings with a similar specificity.

It is also worth comparing the critical risk factors obtained, for which risk management should be particularly careful, with the results of the risk assessment for real projects, which was carried out by experts. In [45], a comprehensive risk assessment was carried out for a single-family passive building of 175.16 m^2 located in Poland. Its walls were made of prefabricated polygon-reinforced concrete elements with styrofoam insulation. After the expert risk assessment, it was found that the critical risk factors were problems with interbranch coordination (F31), inadequate noise protection of the installations (F16), and errors in the design of the installations (F17). During the project execution without introducing the suggested risk-management strategies, the above-mentioned risks actually occurred. In [70], a comprehensive risk assessment was carried out for a passive hotel located in Germany. Its walls were made of concrete with mineral wool insulation, wooden formwork, and façade panels. After the expert risk assessment, it was found that the critical risk factors were incorrect costing (F31), problems with interbranch coordination (F31), wrong interpretation of correctly prepared technical drawings (F27), inadequate noise protection of installations (F16), and mistakes in the installations' design (F17). After the risk assessment, it was decided to introduce all suggested risk-management strategies, and the project was successfully completed. In those cases, the results of detailed expert risk assessment are consistent with the results obtained using the proposed methodology in terms of F30 (incorrect costing), F31 (problems with interbranch coordination), and F27 (wrong interpretation of technical drawings). Other risk factors that actually occurred in the case of the first analyzed project (F16 and F17) were classified as group B in the proposed model. When comparing the results obtained in the proposed approach with the many research papers concerning overheating in passive buildings, e.g., Refs. [23–26,28–30], it can be seen that the risk factors leading to overheating, such as design errors in the installations of the building (F17), connected, e.g., with overestimating design infiltration and the ventilation rate should be of particular attention and should not be neglected even if they were classified as risk factors of secondary importance (group B).

5. Conclusions

To sum up, this study presented here indicated that in the case of passive building projects, not only should potential opportunities be considered but also a number of risk factors that threaten the achievement of the standard requirements of the passive house. The lack of awareness in this matter calls into question the successful completion of the investment and may lead to the disappointment of the owner, legal claims, conflicts, and misunderstandings between the owner, designer, and contractor. It should be stressed that comprehensive risk management in passive building projects supports delivering truly passive buildings, meeting the expectations of all stakeholders.

In this work, the results of the evaluation of risk factors of 748 passive buildings projects from seven countries of the world were presented, in which a Failure Mode and Effect Analysis with a Pareto–Lorenz analysis were applied. Thanks to the conduct of a survey in various countries, it was possible to obtain a statistical picture of the risk factors that occur in the design and construction of passive buildings. It allowed us to assess the frequency of occurrence, severity, detectability, and Risk Priority Numbers of the identified 32 risk factors in passive buildings projects. Thanks to presenting the results of the frequency of occurrence, severity, detectability, and Risk Priority Numbers of the identified 32 risk factors, it was possible to reveal different interpretations and various semantic implications of risk factors. As a result of the research conducted in this work and their analysis, answers to the research questions were found:

RQ1: Which risk factors are the most frequent in passive building projects?

This study revealed that the following risk factors are the most frequent in passive building projects:

- Incorrect costing;
- Interbranch coordination missing;
- Design errors in the insulation of ventilation and heating pipes in the building;
- Selecting inadequate windows, doors, and glazing parameters;
- Design errors in the insulation of domestic hot water and circulation pipes in the building;
- Complicated, not compact building shape with an unfavorable area-to-volume ratio;
- Choosing an improper methodology of calculating the energy balance and energy demand of the building;
- Improper choice of materials to be used at the construction-planning stage;
- Leakages in the airtight building envelope caused by improper assembly;
- Leakages in the airtight building envelope caused by the improper location of the installations.

RQ2: Which risk factors are associated with the greatest severity of effects?

This study revealed that the following risk factors are associated with the greatest severity of effects:

- Complicated, not compact building shape with an unfavorable area-to-volume ratio;
- Leakages in the airtight building envelope caused by the improper location of the installations;
- Incorrect costing;
- Incorrect design of shading elements;
- Choosing an improper methodology of calculating the energy balance and energy demand of the building;
- Leakages in the airtight building envelope caused by improper assembly;
- Leakages in the airtight layer of the building due to designing or applying improper materials;
- Selecting inadequate windows, doors, and glazing parameters;
- Choosing an improper windows situation;
- Leakages in the airtight building's envelope caused by bypassing critical points in the design.

RQ3: Which risk factors have the lowest detectability?

This study revealed that the following risk factors have the lowest detectability:

- Wrong interpretation of correctly prepared drawings and details obtained from the designer;
- Lack of or incorrectly designed fire protection;
- Lack of quality control of embedded materials;
- Leakages in the airtight layer of the building due to designing or applying improper materials;
- Design errors in the insulation of domestic hot water and circulation pipes in the building;
- Deliberate assembly inconsistent with the design;
- Leakages in the airtight building envelope caused by the improper location of the installations;
- Leakages in the airtight building's envelope caused by bypassing critical points in the design;

- Choosing low-quality materials.

RQ4: Which risk factors are associated with the highest risk (Risk Priority Number)?

This study revealed that the following risk factors are associated with the highest risk (Risk Priority Number):

- Incorrect costing;
- Leakages in the airtight building envelope caused by the improper location of the installations;
- Interbranch coordination missing;
- Lack of quality control of covered or concealed materials and works;
- Design errors in the insulation of domestic hot water and circulation pipes in the building;
- Wrong interpretation of correctly prepared drawings and details obtained from the designer;
- Selecting inadequate windows, doors, and glazing parameters;
- Design errors in the insulation of ventilation and heating pipes in the building;
- Leakages in the airtight building envelope caused by improper assembly;
- Structural thermal bridges.

They are included in a narrow group of critical risk factors that are the most significant (have the highest RPN) and to which special attention should be paid to them in the risk-management process.

To sum up, the contribution to the body of knowledge of this paper includes the following:

- Gathering data from expert surveys of 748 passive buildings projects from seven countries (Poland, Germany, Great Britain, the United States, Australia, Spain, and Austria), which allows us to assess the frequency of occurrence, severity, and detectability of 32 risk factors in passive buildings projects;
- Presenting a methodology that
  - fits into a preventive risk-management approach (takes into consideration detection possibilities for risk factors) thanks to identifying and evaluating risk-detection possibilities;
  - enables preliminary risk assessment without involving external experts for passive building projects with a modest budget;
  - reflects the statistical view of risk factors that occur the most frequently, are the most severe, the most difficult to detect, and associated with the highest risk;
  - is simple (can be easily adopted by architects, constructors, installation designers, managers, and owners without the need to employ experts);
  - is versatile (not tied to a particular country and its specific conditions, making it useful in various countries in the world).
- Revealing three groups of risk factors in passive building projects for which risk management should be particularly careful (the most frequently occurring risk factors, the most severe risk factors, and risk factors that are the most difficult to detect);
- Revealing the group of top risk factors threatening the successful completion of passive buildings projects (associated with the highest risk expressed using Risk Priority Numbers).

The presented results of the quantitative risk assessment of 748 passive building projects are a helping hand to all passive building professionals and managers willing to develop successful and attainable truly passive buildings that provide user satisfaction. Although each construction is slightly different and can be considered individually, such information from the statistical analysis of many passive house projects is crucial for owners, architects, installation designers, and constructors as it indicates critical points to which special attention should be paid during the preparation and execution of the investment. This is especially valuable in the case of preliminary risk assessment and projects with a modest budget, where funds for performing an expert risk assessment of an individual project were not included in the budget.

The main limitation of the application of the FMEA method and the Pareto–Lorenz analysis for risk assessment in passive buildings projects is that the ranks for the frequency of occurrence, severity, and detectability of risk factors come from the statistical analysis of the survey results. Although they correctly present the statistical view of risk factors and are sufficient for preliminary risk evaluation for many passive building projects, they may not be relevant or satisfactory for each specific PH project. This may be the case with projects of challenging passive buildings with innovative installation solutions planned to be introduced. In addition to this, when applying the FMEA technique, there is a risk that risk factors with a low RPN will be overlooked. In specific cases that significantly differ from typical passive buildings, it is possible to add additional risk factors (e.g., difficulties with introducing new technologies, innovative and prototype solutions, a lack of qualified specialists in the area of innovative solutions, and the unknown behavior of innovative elements during the guarantee period) or to make one's own adjustments to the parameter values necessary to calculate the RPN. Therefore, in the case of innovative passive building projects, the presented approach should be treated as a decision support tool, not as the final firm opinion.

Future work is oriented toward developing a new model using artificial intelligence to assess risk in passive building projects, taking into account the project specificity. In this model, a risk-management module will be applied to select the most appropriate risk-management strategy dedicated to a particular case.

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