Qualitative risk assessment of passive house design and construction processes

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Abstract. Global climate change and increasing energy costs as well as environmental concerns have led to increased worldwide interests in passive buildings, which have minimal energy consumption and reduced environmental impact. Passive houses design and construction processes are much more complex than it is in the case of buildings developed in the traditional standard and they are associated with many risks. In this work, the selected problems related to the design and construction of passive buildings were presented. The risks were divided into three categories: problems with the architectural and construction design, problems with the installation design, and problems at the building site. All in all, 30 risks in the design and construction of passive houses were identified. Their causes, consequences, and possibilities of detection were investigated. Qualitative risk assessment of passive houses design and construction applying Failure Mode and Effect Analysis was presented. That allowed it allowed to gather information for making decisions in the risk management process. The qualitative risk assessment results (the list of the most important risk factors, their causes, consequences, and detection possibilities) enhance avoiding undesirable problems and errors, as well as additional costs associated with the project failure and support meeting the deadline for the passive house investment. The qualitative risk assessment results are also the starting point for development of a comprehensive risk management model for the design and construction of a passive building.

1. Introduction
Thanks to the development of the Passive House Standard it was possible to significantly decrease the energy consumption of buildings, which was needed because of the global targets for climate change and energy savings. That is why in recent years we could observe increasing interest in passive house buildings [1]. It should be stressed that the design and construction of passive buildings are associated with the fulfillment of many requirements, which pose challenges for designers and contractors. Due to the high complexity of the passive house project and many requirements that should be fulfilled, passive house design and construction processes are associated with many risks that could threaten the final result of the project. The risks associated with passive house design and construction have not been comprehensively described in the literature so far. It should be stressed that there is a high number of passive building projects that are problematic both at the design and construction stage and result in creating buildings that do not fulfil the passive house requirements and fail to provide user satisfaction. It results in many conflicts and claims between an owner, designer, and contractor. That is why it is vital to identify and analyse all important risk factors (RF) in the passive house design and construction process.
The principles of the Passive House standard were given in [2]. The most important assumptions of the standard include: the compact body of the building and very good thermal insulation; minimisation of “thermal bridges”; high airtightness of the construction; effective mechanical ventilation with heat recovery; the use of solar energy; the use of energy-saving, certified passive windows; applying renewable energy sources and energy-saving household appliances.

The proper application of the above-mentioned principles should result in achieving annual space heating demand of the building not exceeding 15 kWh/m² of net living space or 10 W/m² peak demand (and in climates where active cooling is required, approximately the same values apply for the cooling component). Although passive house standard was developed in Germany, it can be applied for buildings all over the world. In different climate zones, the Passive House concept remains the same but the details (e.g. the windows parameters, insulation levels and mechanical services) need to be adapted to the specific climate zone. The improper adaptation of those parameters can pose a serious risk and result in not achieving the passive standard of the building. The way of proper adjusting parameters for 6 climates was described in detail in [3]. The fundamentals of Passive Houses planning were presented in [4].

According to the new ISO 31000:2018 [5], the typical risk management process should consist of 6 steps: risk management planning; risk assessment (risk identification, analysis and evaluation); risk treatment; recording and reporting; communication and consultation; monitoring and review. This paper focuses mainly on the second step of the risk management process, mainly on risk identification and the qualitative risk assessment in passive houses design and construction. Qualitative risk assessment is one of the key components of the project risk management process, as it leads to identification of the most important risk factors. Omitting any significant risk factor may result in an incorrect overview of the investment and the occurrence of an unwanted event leading to unsuccessful investment. In [6-10] it was shown that properly prepared proactive risk management process in complex building construction and environmental engineering projects resulted in effective project realization according to the predicted schedule and budget stated in the contract.

2. Selected problems related to the design and construction of passive buildings
Although the passive house concept seems to be simple, it is very complex indeed and requires extensive experience and knowledge both of designer and constructors. Even a margin mistake could be very expensive and lead to not fulfilling passive house standard requirements and result in not achieving user satisfaction [11]. In [12] several factors hampering the widespread implementation of passive houses standard were defined: limited information among potential builders, lack of experience among the participants of investment process, comparably low energy prices (e.g. gas price decrease), regulation issues, lack of experience among trade people, other competing technologies. In [13] several important problems associated with passive house design and construction were presented: improper design and construction of shading devices leading to overheating in summer, risk connected with lack of proper supervision at the building site and risk of the formation of water vapour condensation inside the building. In [14] some important barriers in passive house development were defined: problems with applying new techniques and technologies, inexperienced designers and builders, using cheaper materials and systems off-the-shelf, potential for overheating, problems with airtightness and building site influences. In [15] it was stressed that improper design or construction of the building could severely affect indoor air quality inside the building, which poses a significant risk to human health and the building structure condition. Unfortunately, many unaware owners ask the designers to use cheaper installation solutions, especially regarding ventilation, which results in a negative impact on human health and the building structure [16].

Practice shows that one of the mistakes made when designing a passive building is an incorrectly selected climate zone. An inappropriate definition of the climate in which the building will be operated...
may result in a failure to fulfil its function and hide the potential and advantages connected with passive construction. Another factor affecting the problem of maintaining a passive house quality is the inadequate selection of materials used when planning the construction process. Incorrectly selected materials that do not have the required parameters (e.g. U-factor) will affect the deterioration of the building’s strength and durability, and as a consequence may increase the cost of financing, which will result in a lack of user satisfaction. Architects often make mistakes by designing complicated building shapes and creating buildings that are not compact. There are also mistakes in the proper location of the building on the plot, as well as the location and size of windows. As a result, the facility does not use the maximum of passive solar energy gains, which is associated with an increase in the building operating costs. Another oversight of designers is improperly planned insulation of the building. Poorly designed or installed house insulation can cause many unpleasant consequences. Starting from mold and fungi, through stains on internal partitions, ending with the destruction of building materials.

As a result of poorly designed insulation, thermal bridges occur and the cost of heating of the building will significantly increase. It often happens that the designers forget about the most vulnerable places to the formation of thermal bridges, such as: structural nodes that connect various elements of the building’s external partitions (connecting the roof and external walls as well as the balcony and ceiling; places for fixing windows and doors; basement walls; wreaths including the ceiling above the basement and lintels). Thermal bridges can also lead to serious damage to building structure elements. The problem may occur, for example, in the area of uninsulated joining of the ceiling and balcony slab. Another important mistake related to passive house design is designing the installations in the airtight layer of the building. It is the most common reason for leakages in the airtight layer of the house. In the case of skeletal structures, it is recommended to mount the installation in a special, additional layer of the building, the so-called installation layer. In addition to the increase in heat loss, a leaky building air casing can result in: condensation of water vapour, mold development, reduction of thermal comfort, a decrease in the acoustic comfort of the rooms due to cracks and leaks in the partitions.

3. Risk identification

In this work various methods were used during the risk identification in the design and construction of passive houses: literature study, scenario analysis, risk interviews with passive house architects, constructors and contractors, manufacturers of building materials and systems, as well as own experience as “Certified Passive House Consultant” and observations of passive houses construction and operation. Table 1 presents all identified risks for the passive building design and construction process. They were divided into 3 categories: problems with the architectural and construction design, problems with the installation design, and problems at the building site.

| RF ID | Risk factor description |
|-------|-------------------------|
| X1    | Incorrectly selected climate zone |
| X2    | Incorrectly designed room layout |
| X3    | Improper design of sunlight control |
| X4    | Complicated building shape, not compact bodybuilding |
| X5    | Improper location of the building on the plot |
| X6    | Incorrect methodology of calculating energy balance and energy demand of the building |
| X7    | Incorrect user input into calculations related to the building characteristics |
| X8    | Choosing the wrong windows, doors and glazing parameters |
| X9    | Incorrect windows location |
| X10   | Selecting low quality materials |
| X11   | Inadequate selection of materials used when planning the construction process |
| X12   | Leakages in the airtight layer of the building due to improper location of the installations |
| X13   | Leakages in the airtight layer of the building due to designing or applying improper materials |
Leakages in the airtight layer of the building due to bypassing sensitive points in the design

Structural thermal bridges

Problems with the installation's design

Incorrectly designed noise protection of the ventilation installation

Incorrectly designed installations in the building

Incorrectly designed insulation of ventilation and heating pipes in the building

Incorrectly designed insulation of domestic hot water and circulation pipes in the building

Lack of fire protection design (*if required)

Lack of description of how to properly operate and maintain the ventilation system

Problems at the building site

Lack of description of how to properly operate and maintain the ventilation system

Choosing the wrong window installation technique

Errors in windows’ and doors assembly process itself

Leakages in the airtight layer of the building due to improper assembly

Errors in insulation layer assembly

Adverse weather conditions

No quality control of embedded materials

Improper interpretation of correctly made drawings and details received from the designer

Conscious assembly not in accordance with the project

Lack of inter-branch coordination

* the same risk for all 3 risk categories

4. Qualitative risk assessment using FMEA

FMEA technique can be applied to define and eliminate failure modes, identify their causes, consequences, and detection possibilities. It is aimed to enhance the reliability and safety of various systems [17]. That allows it to gather information for making decisions in the risk management process [18]. Its results can be a source of valuable information for architects, constructors, and installation designers helping them to improve their work. Tables 2-4 present qualitative FMEA sheets that were developed for three identified risk categories: problems with the architectural and construction design, problems with the installation design, and problems at the building site.

Table 2. FMEA sheet for problems with the architectural and construction design

| RF ID | Causes | Consequences | Detection possibilities |
|-------|--------|--------------|-------------------------|
| X1    | Lack of the designer knowledge, lack of the designer experience, designer’s fatigue | A failure to fulfill passive building function and requirements, lack of user satisfaction | Employing a certified passive house consultant or designer, applying double checking principle |
| X2    | Lack of designer knowledge, lack of the designer experience, designer’s fatigue | A failure to fulfill passive building function and requirements, lack of user satisfaction | The same as X1, checking if living rooms were placed from the south, children rooms, bedrooms and study rooms from the east, west or north; places exposed to overheating (e.g. kitchen) from the south |
| X3    | Lack of the designer knowledge, lack of the designer experience, designer’s fatigue, lack of sunlight control, improper location of shading pergolas | Overheating of the rooms in summer, lack of user satisfaction | The same as X1 |
| X4    | Lack of the designer knowledge, lack of experience, desire to create attractive visually complex | Additional geometric thermal bridges | The same as X1, checking if Surface to volume ratio for |
| No. | Issue Description                                                                 | Countermeasures                                                                 |
|-----|-----------------------------------------------------------------------------------|----------------------------------------------------------------------------------|
| X5  | Lack of the designer knowledge, lack of experience, lack of local vision, lack of consideration of the shading issues by neighboring objects and objects located on the plot, not including the slope of the plot | A failure to meet passive house criteria, a failure to achieve solar energy profits assumed in the calculations, unwanted increase in the building operation costs. The same as X1. |
| X6  | Lack of the designer knowledge, lack of experience, lack of local vision           | A failure to meet passive house criteria, unwanted increase in the building operation costs, lack of user satisfaction. The same as X1, using recognized computer programs dedicated for passive houses (e.g. PHPP). |
| X7  | Lack of the designer knowledge, lack of experience, lack of local vision, problem with moving files between programs | A failure to meet passive house criteria, unwanted increase in the building operation costs, lack of user satisfaction. The same as X1. |
| X8  | Lack of the designer knowledge, lack of experience, designer’s fatigue             | Additional expenses related to the operation of the building. The same as X1. |
| X9  | Lack of knowledge of the project, lack of experience, lack of local vision         | Too many windows located on the shaded sides of the building will not allow drawing on natural solar energy resources, increase of the costs of the building operation. The same as X1. |
| X10 | High prices of certified materials dedicated to passive buildings, designing the cheapest, not certified, sometimes off-the-shelf systems | Improper building operation and maintenance, deterioration of the building's strength and durability. The same as X1. |
| X11 | Lack of the designer knowledge, lack of experience, designer’s fatigue, incorrectly selected materials that do not have the minimum required parameters (e.g. U-factor) | Increased cost of the building operation and maintenance, lack of user satisfaction. The same as X1. |
| X12 | Installing the installation in airtight building layers or complete absence of installation layer | Thermal bridges, mold and fungi on walls, stains on internal walls, destruction of building materials, increased building energy demand, significantly increased cost of heating. The same as X1, in the case of skeletal building structures checking if the installations are designed in a special, additional layer of the building, the so-called installation layer. |
| X13 | Lack of the designer knowledge, lack of experience, designer’s fatigue; designing or applying untight materials such as: masonry wall construction, building panels made of wood wool and soft wood fibers, perforated foils, polystyrene boards made of hard foam, Condensation of water vapor in partitions, thereby affecting the deterioration of insulation and damaging the structure; mold development; reduction of thermal comfort resulting from the occurrence of thermal bridges, leading to the formation of local drafts, which leads to feelings of discomfort; a decrease in the | The same as X1, checking the materials are certified and dedicated for passive houses (e.g. have Passive House Institute Component Certification). |
system tongue and groove; designing or applying short durability materials: adhesive packing tape, too wet or dry concrete, gluing on a non-primed wall structure, polyurethane mounting foam, silicone seals acoustic comfort of the rooms, resulting from cracks and leaks in the partitions, causing the sound wave to travel outside.

X14 Lack of details drawings and hints for the contractor such as: the need to plaster under the sanitary/ventilation/electrical installation in front of the wall, put sealed strip near the windows, plaster on internal walls should reach the bottom of the wall, plaster the air seals at the roof/wall interface, tight electrical sockets A failure to meet passive house criteria, unwanted increase in the building operation costs, lack of user satisfaction

The same as X1, checking if cuff seals, system flanges, careful wrapping of installation passages through partitions were designed and shown on accurate, precise, suitably scaled drawings that could be easily interpreted by builders

X15 Lack of the designer knowledge, lack of experience, designer’s fatigue resulting in improper design of the connections of the roof and external walls as well as the balcony and ceiling; places for fixing windows and doors; basement walls; wreaths (including the ceiling above the basement) and lintels, improper design of insulation of the roller shutter box, improper outbuilding insulation, incorrect connection of the balcony slab with the building structure (a separate self-supporting balcony structure or the use of thermal insulation fasteners is recommended, joints in the roof structure, improper pulling wreaths at the gable wall

A failure to meet passive house criteria, unwanted increase in the building operation costs, lack of user satisfaction

The same as X1, checking if all required details are shown on suitably scaled drawings that could be easily interpreted by builders

| RF ID | Causes                                                                 | Consequences                                                                 | Detection possibilities                                                  |
|-------|------------------------------------------------------------------------|-----------------------------------------------------------------------------|------------------------------------------------------------------------|
| X16   | Lack of the designer knowledge, lack of the designer experience, designer’s fatigue resulting in: incorrect location of silencers, designing too long pipe sections instead of the shortest possible ones, no silencers in front of the air handling unit or between rooms, no flexible connectors at the air handling unit as noise protection | Excessive noise, lack of user satisfaction                                      | Employing a certified passive house consultant or designer, applying double checking principle, checking if silencers were designed |
| X17   | Lack of the designer knowledge, lack of the designer experience, designer’s fatigue resulting in: no or low quality filter in front of the air handling unit, no revision, indefinite frost protection of GWC ground heat exchanger/, glycol ground heat exchanger/, | Condensation, development of fungi and mold                                   | Employing a certified passive house consultant or designer, applying double checking principle |

Table 3. FMEA sheet for problems with the installations design
electric heater (*if present), incorrect calculations of the minimum required to fold air exchange, the wrong definition of supply and exhaust zones; lack of flow holes under the door; incorrectly designed air intake protection against rain and snow

X18 Lack of the designer knowledge, lack of the designer experience, designer’s fatigue resulting in: failure to consider the location of the recuperator (requirements for insulation are different for the warm zone and cold zone), lack of vapor barrier, improperly designed insulation of heating pipes outside the thermal coating of the building, no reduction of thermal bridges at pipe connections to fittings

Condensation, development of fungi and mold, unnecessary heat loss due to lack of proper insulation

Employing a certified passive house consultant or designer, applying double checking principle

X19 Lack of the designer knowledge, lack of the designer experience, designer’s fatigue resulting in designing too thin layer of insulation of domestic hot water and circulation pipes, designing too long sections of circulation pipes

Unnecessary heat loss due to lack of proper insulation

Employing a certified passive house consultant or designer, applying double checking principle

X20 Lack of the designer knowledge, lack of the designer experience, designer’s fatigue resulting in designing no fire protection (fire dampers, smoke dampers) in objects where it was required

Increased fire hazard

Employing a certified passive house consultant or designer, applying double checking principle

X21 Lack of the designer knowledge, lack of the designer experience, designer’s fatigue

Improper functioning of installations caused by improper use and improper maintenance

Employing a certified passive house consultant or designer, applying double checking principle

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**Table 4.** FMEA sheet for problems at the building site

| RF ID | Causes | Consequences | Detection possibilities |
|-------|--------|--------------|-------------------------|
| X22   | Lack of contractor’s knowledge and experience, not applying “the warm installation method”, not installing the window in the insulation layer, | Thermal bridges, mold and fungi on walls, stains on internal walls, destruction of building materials, increased building energy demand, significantly increased cost of heating | Employing a certified passive house consultant or builder, proper supervision by certified personnel at the building site, applying thermal imaging to locate leaks and thermal bridges |

X23 Lack of contractor’s knowledge and experience resulting in: the wrong position of the window relative to the wall cross-section (not in the thermal insulation line); the lack of proper preparation of the jamb surface and the failure to use a primer, which means that the materials do not adhere sufficiently to the substrate, and thus do not fulfill their intended purpose; not using insulating tapes, which guarantee accurate sealing, not using a vapor barrier film; applying not enough anchors or spacing them at the wrong intervals; forgetting about reliable isolation of metal elements, Appearance of thermal bridges at the window-wall junction, limitation in the airflow between the window and the wall, a decrease in the strength of the window structure, deformation of the frame, and moreover unsealing, thermal bridges at unsealed elements | Employing a certified passive house consultant or builder, proper supervision by certified personnel at the building site, applying thermal imaging to locate leaks and thermal bridges |
such as: mounting rails, anchors, support blocks

| X24 | Lack of contractor’s knowledge and experience, no plastering under the sanitary/ventilation/electrical installation in front of the wall, exposed strip near the windows, plaster on internal walls does not reach the bottom of the wall, not plastering the air seals at the roof/wall interface, untight electrical sockets, improper order of works (e.g. the connecting foil should be placed before the roof structure is installed above the attic wall) | Thermal bridges, fail to meet passive house standard (pass air tightness test) energy demand, significantly increased cost of heating | Employing a certified passive house consultant or builder, proper supervision by certified personnel at the building site, applying thermal imaging to locate leaks and thermal bridges, Leaks identification thanks to Blower door test, thermal imaging, smoke puffers and pencils application for determining draughts at specific locations, checking if the cuff seals, system flanges, careful wrapping of installation passages through partitions were designed |
| X25 | Lack of contractor’s knowledge and experience, gaps between foamed polystyrene boards, incorrect bonding | Thermal bridges, fail to meet passive house standard (pass air tightness test) energy demand, significantly increased cost of heating | Employing a certified passive house consultant or builder, proper supervision by certified personnel at the building site, applying thermal imaging to locate leaks and thermal bridges, certified training for contractor |
| X26 | Lack of contractor’s knowledge and experience, lack of proper supervision, in hot weather, window tapes peel off, problem with moisture of materials (e.g. insulation materials), improper storage of materials and equipment at the construction site, lack of adequate protection of performed works against the influence of weather conditions | Degradation of materials, a failure to fulfill passive building function and requirements, lack of user satisfaction | Proper supervision at the building site |
| X27 | No quality control of embedded materials and devices, lack of compliance of their parameters with the provisions in the project | A failure to fulfill passive building function and requirements, lack of user satisfaction | Proper supervision at the building site, buying certified materials |
| X28 | Lack of contractor’s knowledge and experience, lack of proper supervision | A failure to fulfill passive building function and requirements, lack of user satisfaction | Proper supervision at the building site |
| X29 | Lack of contractor’s knowledge and experience, lack of proper supervision | A failure to fulfill passive building function and requirements, lack of user satisfaction | Proper supervision at the building site |
| X30* | Lack of inter-branch coordination and communication between an architect, a constructor, installation designer and contractor, errors when exporting data between programs, no consultation with the contractor of the feasibility of the proposed | Unexpected complications at the building site, incurring additional costs related to the need to introduce changes to projects and | Applying BIM software (Building Information Modeling”) to identify collisions and inconsistencies in the inter-branch design, the |
design solutions in technical terms

dismantling at the construction site, a failure to fulfill passive building function and requirements, lack of user satisfaction

introduction of obligatory consultations of the proposed design with an experienced contractor

*the same risk for all 3 risk categories

5. Conclusions

The passive building design and construction processes are associated with the fulfilment of many conditions, which creates a big challenge and high risk for designers and contractors. When designing and constructing a passive building many factors that do not play a significant role in traditional construction should be taken into account. Meeting these requirements is not easy and requires extensive experience and knowledge of both designers and contractors, as well as a well-developed risk management process, which would take into account passive building specificity.

Risk identification and analysis are key sub-steps of any risk management process. Their results are the starting point for the feasibility analysis and project evaluation. The identification of 30 significant risk factors presented in this paper, defining their causes, consequences and the possibility of detection is the starting point for creating a comprehensive risk management model for the design and construction of a passive building.

Thanks to carrying out a qualitative risk analysis of passive building design and construction applying Ishikawa diagram and FMEA it is possible to prevent the serious economic and legal consequences. Knowing the list of the most important risk factors, their causes, consequences and detection possibilities it is possible to avoid undesirable problems and errors, additional costs associated with the project failure and meet the deadline for the investment.

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