Risk reduction for Building Energy Efficiency investments

Project H2020 n° 833112

D2.1

Report on technical risks in renovation

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Abstract

EEnvest project aims at supporting investors´ decision making process by translating building's energy efficiency technical requirements into economic indicators. These indicators are in turn used to evaluate financial risks associated with deep renovation investment and to include non-energy benefits in asset evaluation models.

WP2 focuses on technical risk, developing a structured process able to determine reliability of a renovation project based on technical risk level. This latter is assessed through two independent economic indicators, energy gap and damage, presented to the reader or user as percentage of investment. Additionally, technical risk reduction actions are being investigated, classified, and implemented as correction factors in the technical risk calculation process, and later reported to the final users, as mitigation measures.

The calculation methodology as developed in WP2 permits to determine technical risk through two outputs (indicators), whose combination is able to describe the probabilistic trend of several occurrences linked to the renovation scenario set case by case. The EEnvest technical risk calculation runs thanks to a technical risks database, created ad hoc in WP2. The database collects several occurrences data that serve as technical risk benchmark, described through probability and impact. The technical risk calculation process extracts the amount risk related to the selected energy renovation measures from the technical risk database, and re-sizes the risk based on inputs of the building renovation project. Project input features are: building geometry (dimension, shape, etc.), planned energy performance (Primary Energy, Heating, cooling demands, etc.), including boundary condition (building site, etc.) and verification protocols.

The two technical risk indicators, energy gap and damage, will be integrated in the EEnvest web-based investment evaluation platform.

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Deliverable	**Number**	D2.1	**Full Title**	Report on technical risks in renovation of commercial buildings, including risk identification, mitigation measures and their impact on technical and financial performance
Work Package	**Number**	WP2	**Title**	Technical risk evaluation framework
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Abstract (for dissemination)	EEnvest project aims at supporting investors´ decision making process by translating building's energy efficiency technical requirements into economic indicators. These indicators are in turn used to evaluate financial risks associated with deep renovation investment and to include non-energy benefits in asset evaluation models. The technical risk of renovation a project is in EEnvest web-platform classified and collected a database. In WP2 is been performed a calculation method developed "ad hoc" for commercial building renovation process able to determinate through two indicators, energy gap and damage, the economic deviation of a planned project. It calibrates the building data (inputs) with technical risk benchmark collected in a database, re-size the indicators (outputs), also integrating correction factors. These last are strictly connected at the renovation project and will be reporting to the users as mitigation measures, it will be performed in the D2.2.
Keywords	Technical risks in renovation, commercial buildings, risk identification, technical and financial performance

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Table of Contents

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement n° 833112

List of figures

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement n° 833112

List of tables

List of abbreviations and acronyms

This list must be as short as possible as abbreviations and acronyms hamper an easy understanding of deliverables by reviewers.

EE	Energy Efficiency
RES	Renewable energy source
LCC	Life Cycle Cost
ROI	Return on investment
HVAC	Heating, Ventilation and Air Conditioning
MC	Monte Carlo calculation
S/V	Compact building shape (Surface / Volume)
WWR	Window-wall ratio

Common language	ISO/Guide 73:2009- ISO 31000:2018
Consequence	Outcome of an event (2.17) affecting objectives [1]
Consequence	Outcome of an event (3.5.1.3) affecting objectives [1]
Exposure	Extent to which an organization and/or stakeholder is subject to an event

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Level of risk	Magnitude of a risk (2.1) or combination of risks, expressed in terms of the combination of consequences (2.18) and their likelihood [1]
Probability	measure of the chance of occurrence expressed as a number between 0 and 1, where 0 is impossibility and 1 is absolute certainty
Risk	Effect of uncertainty on objectives. An effect is a deviation from the expected — positive and/or negative. Risk is often expressed in terms of a combination of the consequences of an event (including changes in circumstances) and the associated likelihood (probability) of occurrence.
Risk evaluation	Process of comparing the results of risk analysis (2.21) with risk criteria (2.22) to determine whether the risk (2.1) and/or its magnitude is acceptable or tolerable. [1]
Risk analysis	Process to comprehend the nature of risk (2.1) and to determine the level of risk (2.23). [1]
Risk identification	Process of finding, recognizing, and describing risks
Vulnerability	Intrinsic properties of something resulting in susceptibility to a risk source (3.5.1.2) that can lead to an event with a consequence. [1]
HDD	Heating Degree Day

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INTRODUCTION

EEnvest -Risk reduction for building energy efficiency investments - project aims to develop, a web-based investment evaluation platform for building owners and private investors, which validates the investment security level of an energy renovation project for commercial building, through a solid and structured assessment method. EEnvest web-based investment platform will determine different risk levels analysing a series of economic indicators coming from technical and financial risks evaluation models.

The level of guarantee of the investment will be evaluated through eight economic indicators, divided between technical (energy gap and damage from WP2), economic (payback time, maturity, internal rate of return, net present value on investment and debt-service coverage ratio from WP3) and multi-benefit group (increase market value, environmental, thermal comfort and health from WP4), among them two are specific for the technical risk assessment of the renovation projects and have been elaborated within WP2. The first one is the energy gap, defined as energy performance deviation between planned and measured energy consumption, and the second one is the building damage, defined as possible inconvenience due to component malfunctioning, failures or breakages.

WP2 aims at assessing technical risks connected to the renovation processes of commercial buildings, from the definition of indicators to their impacts, developing a tailored calculation methodology. This calculation methodology, implemented in the EEnvest web-platform based on input data of a specific renovation project, will determine the impacts of different economic indicators (outputs), in terms of energy gap and damages. It calibrates the building data (inputs) with the probability trend of the technical risks collected in the database and fine-tune the indicators impact range (output), integrating also correction factors (as climate conditions, building shape, etc.). Part of the above are also considered as mitigation measures and will be more thoroughly performed in the D2.2.

Technical risk calculation method, as presented in D2.1, will be included in financial risk modelling evaluation (WP3) and later implemented in the EEnvest web-platform, developed in WP5.

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EXECUTIVE SUMMARY

This report presents part of the work under WP2 - Technical risk evaluation framework.

WP2 objective is to identify the technical risks of energy renovation of commercial office buildings projects, based on the indicators and their impact to the benefits and mitigation measures. As the project aims at maximizing replicability with an eye on residential buildings, all possible renovation measures are taken into account, even when they do not apply specifically to commercial office buildings.

Chapter 1 focuses on technical risk in the building sector, from the definition to the identification process used for the determination of the economic indicators. Two indicators are chosen to describe the impact on the investment, as a consequence of possible occurrences connected to the energy renovation process and the implemented solutions: (i) the energy performance gap, defined as the missed energy performance compared to project estimation, and (ii) the damage, defined as problem caused by a breakage, a deterioration or a malfunction.

Chapter 2 presents an overview of EEnvest technical risks assessment, and the data flow of the calculation process, from the inputs to the outputs. The technical risk calculation method is described for both indicators (energy performance gap and damage), starting from a technical risk probabilistic data distribution collected in the EEnvest technical risk database. Through a complex iteration process with well-known inputs, the economic deviation of each indicator can be determined case by case, as percentage of the investment. Their variability depends on several issues, as renovation building project (such as solution set scenario), boundary conditions (such as building site, climate rigidity) or other external parameters identified and scheduled in the EEnvest technical risk database as correction factors. These factors run in the technical risk calculation, modifying the indicators impact. Part of them, together with the risk alerts, which are specific risk-bearing circumstances, are deeply investigated in WP2, and will be converted in mitigation measures and suggestions for the users (further details on these results will be presented in D2.2).

Chapter 3 presents an overview on EEnvest technical risk database, focusing on:

(i) The classification process of technical risks through a breakdown process, from building macro areas (envelope and technical systems) to building elements, energy renovation measures, and related possible negative occurrences.

(ii) The quantification of technical risk indicators for each occurrence, identified as a percentage of investments. Technical risk is identified by a probabilistic data trend distribution (defined through impact and probability).

EEnvest technical risk database collects data coming from literature, real experiences (expert interviews) and parametric energy simulations.

Furthermore, in chapter 4 it is reported an application of the data process development used for the identification of the probabilistic trend impact for both indicators, energy gap and damage in two different building elements (envelope and building system).

The methodology presented in this report will be replicated for all passive and active buildings elements, providing:

- WP3 with relevant input to elaborate the financial risk model

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- WP4 with a set of renovation measures for which to determine the impact of multi-benefits on commercial asset value
- WP5 with relevant input on which to ground the EEnvest platform design.

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1 TECHNICAL RISK ANALYSIS

1.1 DEFINITION

The International Organization for Standardization publication ISO 31000 (2009) / ISO Guide 73:2002 defines the risk as the *'effect of uncertainty on objectives'*. In this definition, uncertainties include events caused by ambiguity or a lack of information. The events could have both negative and positive impacts on the objectives. Many definitions of risk exist in common usage, but the consortium decided to rely on this definition that was developed by an international committee representing over 30 countries and is based on the input of several thousand subject matter experts. [2]

Within EEnvest a technical risk is considered as "*an exposure to loss arising from activities such as design and engineering, manufacturing, technological processes and test procedures*" [3]. This definition is based on a deep analysis of literature and results coming from field experiences, as well as knowledge of technical experts involved in the process.

The formula adopted to calculate the risk is:

Risk = Probability * Consequence (Impact)

Where "*probability*" is the frequency of an event occurrence, times the "*consequence*" of this event, considered as the outcome of an event with a negative or a positive impact [4].

1.2 TECHNICAL RISKS IN EENVEST PROJECT

Related to the building sector, in particular during the renovation process, a technical risk is the probability or threat of damage or any other negative (or positive) occurrence (thermal bridge, air or water infiltration, failure, malfunctioning, breakages, etc.) at the building components (implementation of energy measures to the architectural elements of the building envelope, HVAC systems or RES systems) caused by different reasons in different moments, such as errors in design, project, calculation, installation, construction, or management phase.

In a building renovation project, the technical risks negatively affect the economic trend of the investment, producing some deviation from what expected in the business plan. These differences can depend on several factors (errors or breakages) and occurred in different phase of the renovation project (mistakes in the design phase, installation, or operation phase).

Starting from these considerations, within technical risk analysis the main result was the identification of the two economic indicators for the technical risks of renovation process of commercial buildings, such as (i) the energy performance gap and (ii) the damage, both strictly connected at the decision-making choices, with a directly influence in the economic investment.

It is important to remember that in EEnvest the technical risk definition refers to the occurrences that happen occasionally (such as extraordinary maintenance), while all the costs related to ordinary maintenance programs are excluded, since they should be already considered in the life cycle cost analysis of each renovation measure. EEnvest technical risks, here identified, come from possible errors made in the construction or operation phase, but it is supposed that each solution set does not have associated technical risk (being covered by constructor warranty).

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1.2.1 TECHNICAL RISKS IN BUILDING SECTOR

The technical risks analysis connected to the buildings sector includes a wide number of different topics, issues and parameters involved, each one with a very high-level of complexity, from the building physics to the statistic risks calculation methods, passing from the design, construction, and operation issues.

One of the most complex and common occurrences found in the technical risks analysis is the energy performance deviation between predicted and real measurement of energy consumption. Energy gap is a very common and important topic analysed in numerous articles, from different points of view. It can depend on several issues due to (i) changes between design, construction, and operation phase, or (ii) difference between data sets of the calculation phase (planning, modelling) and real building use in terms of working hours, n. persons, lighting condition, temperature, etc. or (iii) external condition, as climate (temperature, solar radiation, humidity, wind…) or (iv) difference between building code requirements and final use/implementation. Table 1 reports a series of energy performance gap studies where the above is defined as "*the difference between predicted and actual/measured building energy consumption .. for a large group of buildings*" [5].

Study	Number and type of buildings	Measured performance gap	Summary/issues
Frankel & Turner 2008: How Accurate is Energy Modeling?	90 buildings that have achieved a LEEDarating	Around 8% Energy Use Intensity (EUI) difference for all of the buildings	The review included both buildings that achieved LEED ratings with normal expected uses, but also some high energy intensity buildings. The overall average measured EUI was close to predicted, though varied quite widely, and the high energy use buildings (laboratories, data centers and health care) consumed nearly two-and-a-half times the predicted energy.
Carbon Trust 2011: Closing the Gap	28 buildings from the UK DECCb Low Carbon Buildings Programme	Average gap was about 16% higher operational energy consumption than predicted performance	The average gap among the 28 low carbon demonstration buildings (covering many sectors, including retail, education, offices and mixed-use buildings) was 16%, though 75% of designs did not perform as well as expected, and in one building, operational energy use was five times the modeled estimate.
Green Building Council of Australia(GBCA) 2013: Achieving the Green Dream: Predicted vs Actual	70 Green Star office buildings with valid NABERSc Energy Certificates	About 25% gap (finding that around 75% of modeled energy savings are achieved in practice)	As analyzed and reported in ABCB 2018, the relationship between predicted and actual GHG emissions is weak, and there are several outlier buildings where actual emissions are significantly higher than predicted. When the outliers are eliminated, the analysis found around 75% of modeled energy savings were achieved in practice. The original GBCA study stated that 57% of Green Star certified office buildings achieved their modeled GHG performance
Innovate UK Building Performance Evaluation Programme (2016)	48 projects with 56 "leading edge" nondomestic buildings	Average carbon emissions 3.8 times higher than predicted	Only one building performed similar to predictions, and the remaining buildings produced emissions between 1.8 and 10 times the predicted levels. However, predicted emissions only included "regulated loads," including heating, cooling, ventilation and lighting, and did not include other energy uses that would need to be used in any building.
van Dronkelaar et. al. Review of Non-Domestic Buildings Performance Gap (2016)	62 non-domestic buildings, as detailed in a variety of technical sources	Gap between predicted and measured energy use deviates by 34%	The buildings reviewed consisted mostly of offices, schools, and multipurpose buildings. Schools were identified to have a larger gap (37% more energy per one study, and higher in others), while offices were found to be more variable, but a smaller gap (22% higher than predicted, but greater standard deviation than schools).
CarbonBuzz (ongoing, started in 2012)d	About 60 buildings, mostly schools, general offices, and university campuses	Found that on average, buildings consume between 1.5 and 2.5 times their predicted energy use	CarbonBuzz is a joint initiative between the Royal Institute of British Architects, the Chartered Institute of Building Services Engineers (CIBSE) and other industry partners intended to provide a platform to benchmark and track project energy use from design to operation. Detailed case studies are published on the platform.
Sidewalk Labs Toronto Multi-Unit Residential Building Study (2019)	19 recently constructed multifamily buildings in Toronto	Buildings use 13% more energy than predicted by modeling	The study compared metered energy use intensity against calibrated energy models to understand performance gap. The performance gap for certain end uses was much higher than other (space heating having the biggest absolute difference).

Table 1 Summary of key studies quantifying performance gap. [5]

In some energy performance gap investigations, the analysis process used to determinate the technical risks follow a decomposition of the topic based on "project phases" as showed is Figure 1, or in other case on "building elements", as Figure 2.

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TABLE 3 | Potential risk on energy use from reported underlying causes assessed based on general consensus in the literature.

	Underlying cause	Evidence from literature[a]	Rated impact on energy use	Estimated quantitative effect on energy use	Compliance modeling related
Context	Energy performance target	Low	High		Yes
	Impact of early design decisions	Medium	High		
	Complexity of design	Low	Medium		
Model	Specification (geometry, material, equipment)	High	High	20–60%	Yes
	Modeling (simplification)	Medium	Medium	<10%	Yes
	Numerical (discretization)	Low	Low	<5%	
	Scenario (weather, schedule, operation)	High	Medium	10–30%	Yes
	Heuristic (user)	Low	High	<70%	
	Inter-model variability	Medium	Medium	5–40%	
Construction	On-site workmanship	Medium	Low		
	Changes after design	Low	Low		
Commissioning	Poor commissioning	Medium	Medium	<20%	
Operation	Poor practice in operation	High	High	15–80%	
	Occupant behavior	High	High	10–80%	
	Degradation of system and materials	Low	Low	<10%	
	Measurement system limitation	Low	Low	<10%	
	Energy use variability in operation	Low	Medium	5–15%	

[a]Based on the number of mentions in the literature and their consensus of the impact on performance.

Figure 1. Potential risk on energy use from reported underlying causes assessed based on general consensus in the literature. Source: [6]

Table 6. The percentage table of respondent evaluation of the quality failures (N = 92).

Technology Measurements	No.	Quality Failures	The Percentage of Respondents on Linguistic Variables: Very High	High	Moderate	Low	Very Low	Total
Door and window (D)	D1	Incorrect installation of the steel nails	3.0	14.0	29.0	42.0	12.0	100.0
	D2	Incorrect size of new window frame and door frame	5.0	30.0	18.0	25.0	22.0	100.0
	D3	Misalignment between the new doors and windows and the wall	1.0	10.0	27.0	36.0	26.0	100.0
	D4	Untreated wall around the new windows	8.0	12.0	21.0	37.0	22.0	100.0
Roof (R)	R1	Missing vapor barriers	3.0	10.0	24.0	27.0	36.0	100.0
	R2	Non-specified fire resistance of EPS boards	8.0	11.0	29.0	27.0	25.0	100.0
	R3	Non-specified volume-weight and thickness of EPS boards	7.0	12.0	16.0	40.0	25.0	100.0
	R4	Adhesive area problems	4.0	12.0	25.0	27.0	32.0	100.0
	R5	Detachment between the different EPS boards	4.0	13.0	32.0	29.0	22.0	100.0
	R6	Cracks of the roof levelling blanket	10.0	8.0	27.0	28.0	27.0	100.0
	R7	Detachment of roof waterproof layer	3.0	9.0	28.0	42.0	18.0	100.0
	R8	Misalignment of roof waterproof layer	5.0	25.0	25.0	22.0	23.0	100.0
	R9	Cracks of roof concrete	4.0	18.0	28.0	27.0	23.0	100.0
External wall (E)	E1	Uncleaned wall	3.0	15.0	34.0	32.0	16.0	100.0
	E2	Missing interface treating mortar	5.0	21.0	26.0	30.0	18.0	100.0
	E3	Unacceptable levelness of the control wire	2.0	12.0	24.0	35.0	27.0	100.0
	E4	Non-specified fire resistance of EPS boards	7.0	10.0	25.0	32.0	26.0	100.0
	E5	Non-specified volume-weight and thickness of EPS boards	4.0	14.0	20.0	34.0	28.0	100.0
	E6	Adhesive area problems	4.0	9.0	23.0	37.0	27.0	100.0
	E7	Detachment between the different EPS boards	4.0	10.0	29.0	34.0	23.0	100.0
	E8	Missing rivets	5.0	10.0	34.0	31.0	20.0	100.0
	E9	Non-specified rivets	5.0	12.0	20.0	38.0	25.0	100.0
	E10	Incorrect drilling	4.0	10.0	25.0	39.0	22.0	100.0
	E11	Non-specified anti-crack mortar	4.0	14.0	21.0	39.0	22.0	100.0
	E12	Non-specified nylon net	7.0	11.0	18.0	38.0	26.0	100.0

Figure 2. Occurrence Frequency of Quality Failures in percentage. [7]

This kind of analysis takes shape from the investigation method developed to evaluate failure risks in engineering sector, as Failure Mode and Effect Analysis (FMEA). FMEA is a structured systematic procedures approach to identify the reliability, the safety and quality of specific components. It permits to classify and weigh hypothetic cause - effects occurrences for different project phases (design, process, construction). FMEA analysis supports the final quality, determining prevention measures, right managing procedures and higher efficiency levels [8]. FMEA method describes the failure considering three range of variable factors, probability occurrence (O), severity effect (S) and detection (D). When applied in building

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sector it results very complex due to the large number of elements, parameters, and multicriteria possibilities of data and its variability [9]. In WP2 the FMEA method has been tested on an energy renovation measure, insulation of an external wall. The result obtained confirms the high difficulty level of implementation of such method in the analysis of the failure in buildings. FMEA in building components has an excessive level of complexity, due to the high number of running parameters and value (O,S,D), which are often difficult to determine (Figure 3.). From FMEA approach, EEnvest project takes two aspects: the failure concept, as one indicator of the technical risk, later called damage, and the systematic approach integrated in the technical risk evaluation process. Thanks to the latter, technical problems are been classified through a decomposition process of the building in elements, energy renovation measures, and related occurrences, with the aim of identifying unique effects (impacts-probability).

Subsequently, the identification of the impact and probability of each occurrence has been addressed. The missing data on this topic were very frequent. We investigated possible approaches to gather these data, as the Analytic Hierarchy Process [10]. It is a qualitative decision-making approach, which permits to quantify some issues, in our case technical risks frequency, through a risk score obtained from several opinions of experts in building construction sector, and to classify the level of probability, addressing the best decision [11] . Within WP2 it was used to compare technical risk frequency of different energy renovation measures and related occurrences. In the testing phase, the Analytic Hierarchy Process resulted very complex to be implemented in the interviews with technical experts, due to the high number of comparisons required (Figure 4).

At the end of these considerations, the expert's involvement was considered a necessary step to finalize data collection of technical risk impact and probability for each occurrence.

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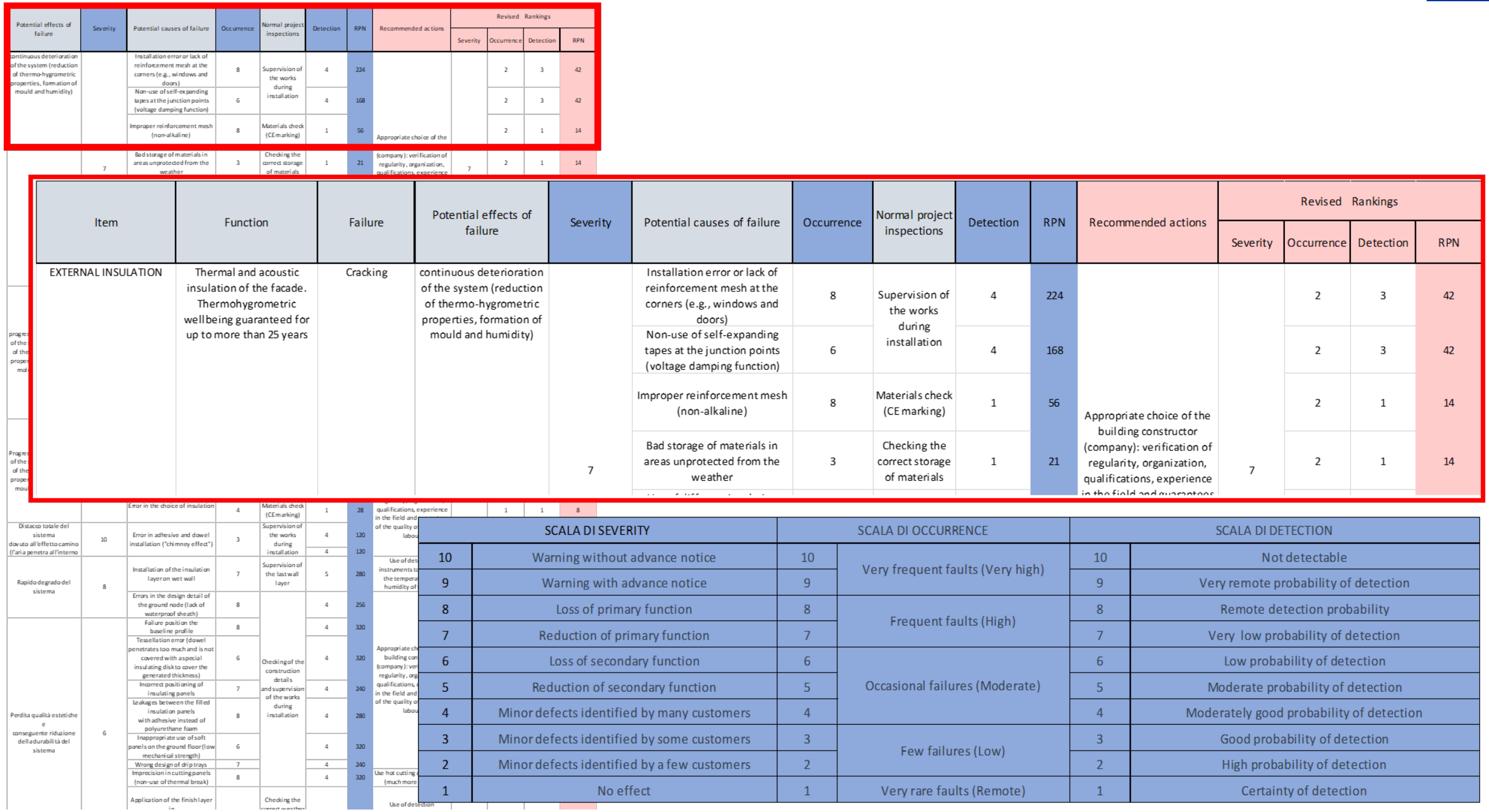

Item	Function	Failure	Potential effects of failure	Severity	Potential causes of failure	Occurrence	Normal project inspections	Detection	RPN	Recommended actions	Revised Rankings: Severity	Revised Rankings: Occurrence	Revised Rankings: Detection	Revised Rankings: RPN
EXTERNAL INSULATION	Thermal and acoustic insulation of the facade. Thermohygrometric wellbeing guaranteed for up to more than 25 years	Cracking	continuous deterioration of the system (reduction of the thermo-hygrometric properties, formation of mould and humidity)	7	Installation error or lack of reinforcement mesh at the corners (e.g., windows and doors)	8	Supervision of the works during installation	4	224	Appropriate choice of the building constructor (company): verification of regularity, organization, qualifications, experience in the field and guarantees	7	2	3	42
					Non-use of self-expanding tapes at the junction points (voltage damping function)	6		4	168			2	3	42
					Improper reinforcement mesh (non-alkaline)	8	Materials check (CE marking)	1	56			2	1	14
					Bad storage of materials in areas unprotected from the weather	3	Checking the correct storage of materials	1	21			2	1	14

SCALA DI SEVERITY		SCALA DI OCCURRENCE		SCALA DI DETECTION	
10	Warning without advance notice	10	Very frequent faults (Very high)	10	Not detectable
9	Warning with advance notice	9		9	Very remote probability of detection
8	Loss of primary function	8	Frequent faults (High)	8	Remote detection probability
7	Reduction of primary function	7		7	Very low probability of detection
6	Loss of secondary function	6	Occasional failures (Moderate)	6	Low probability of detection
5	Reduction of secondary function	5		5	Moderate probability of detection
4	Minor defects identified by many customers	4		4	Moderately good probability of detection
3	Minor defects identified by some customers	3	Few failures (Low)	3	Good probability of detection
2	Minor defects identified by a few customers	2		2	High probability of detection
1	No effect	1	Very rare faults (Remote)	1	Certainty of detection

Figure 3. FMEA application in the failure analysis of an energy renovation measure: insulation of external wall

Figure 3 reports the application of the FMEA at an energy renovation measure external insulation of the wall. There are listed (i) several failures, effects with a level of severity, (ii) potential causes with the relative level of occurrences, (iii) the detection occurrences level. Risk Priority Number (RPN) identifies in number the risk priority level of a failure mode. It is calculated by multiplying Severity (S), Occurrence (O), and Detection (D). Through recommendation action (highlighted in rose colour) the RPN should be reduced.

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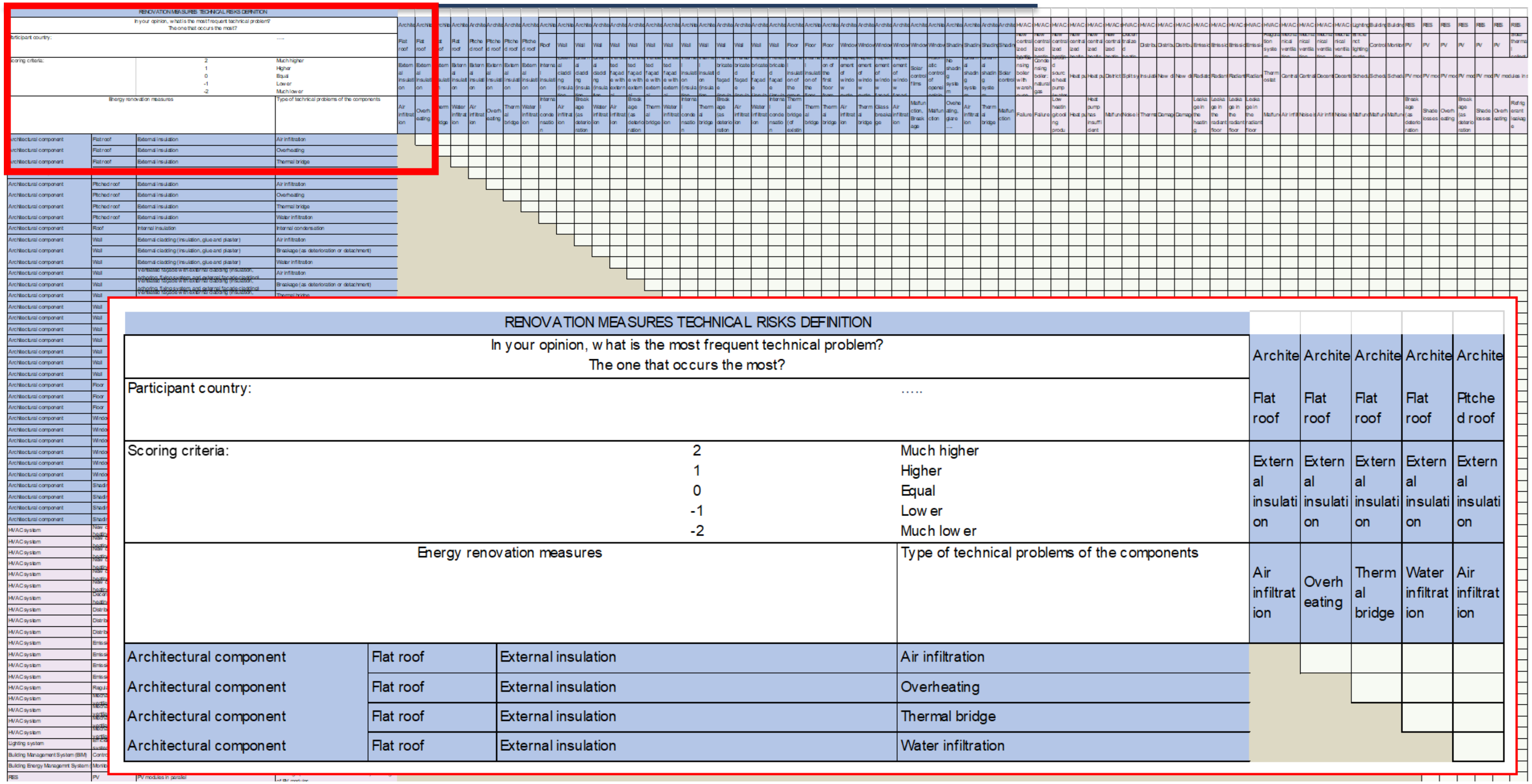

Figure 4. Analytic Hierarchy Process application in building sector for risk probability determination.

Figure 4 shows how works Analytic Hierarchy Process applied in the building sector. This qualitative approach permits to identify, in this case, the frequency level of the occurrences, comparing two different technical risks.

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2 EENVEST TECHNICAL RISKS ASSESSMENT

The main task of the WP2 of EEnvest project was the development of a strategy able to identify the technical risk of energy renovation in commercial buildings. This chapter focuses on EEnvest technical risk assessment. An overview on how the information flow for technical risk analysis runs in the EEnvest web-platform from the inputs to the outputs is shown in paragraph 2.1. Paragraph 2.2 reports the technical risk calculation methodology used within EEnvest web-platform, with a complete description of the technical risk data collected in the EEnvest technical risk database for two different envelope and building system component, as benchmark data value for energy gap and damage indicators, correction factors, and alerts.

2.1 OVERVIEW ON EENVEST WEB-PLATFORM TECHNICAL RISK CALCULATION METHOD

In this paragraph an overview on the technical risk calculation process through inputs outputs flow is illustrated. The data building inputs, inserted by the users, will be processed in the EEnvest web-platform, obtaining as a result, two outputs of technical risks indicators: the energy gap and the damage (Figure 5).

Figure 5. EEnvest Platform Information flow and calculation method of technical risk of EEnvest platform.

WP2 work was mainly focused on (i) development of a strategic method for calculation of technical risks of renovation of existing commercial buildings, and a related (ii) technical risk database, used to modify (resizing) the impact of the technical risks associated at each energy renovation measures

The technical risks calculation method, as planned in WP2 and approved by SINLOC (who is developing the financial model in WP3 and will use WP2 results as input for the model), permits to match several probability-impact data distributions of possible occurrences extracted from the data inputs of the building project. In EEnvest web-platform, the EEnvest technical risk database is uploaded (chapter 3.1), together with (i) several probabilistic impact data of possible occurrences and failures that can happen at the building elements and technical system, (ii) correction factors used to modulate the final cause-effect and (iii) alerts. The technical risk calculation process runs online on the EEnvest web-platform extracting from the EEnvest technical risk database, all the possible technical risk combinations, producing a technical risks probabilistic trend of impact and probability for both the indicators, energy gap deviation and damage.

An overview on technical risk calculation process in the EEnvest web-platform is reported in Figure 6. The inputs, inserted by users based on own renovation set scenario and building features, activate the risk calculation process, extracting the probabilistic impact of the occurrences of the energy renovation measures implemented from the EEnvest technical risk database (see M1 and M2 in Figure 6). The risk amount of energy gap and damage indicators are sized on building dimension and weighed in relation to the boundary conditions (correction factors). Final outputs of technical risk calculation process are determined through a mathematic combination, called *"probability mass function"* able to combine the investment

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increases (deviation in energy gap and damage) and respective probabilities of occurrences caused by each single issue (see Annex I for further details).

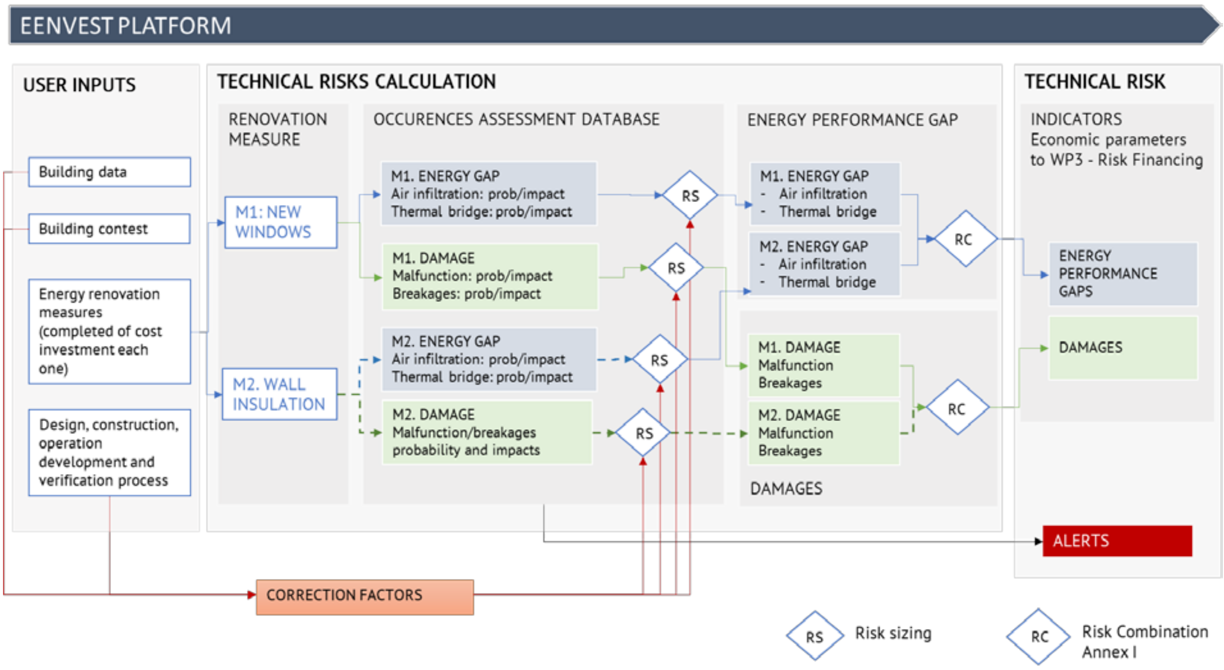

Figure 6. Overview of Technical risk process assessment in EEnvest platform

2.2 METHODOLOGY USED FOR EENVEST TECHNICAL RISK ASSESSMENT

Within WP2, two technical risk calculation and assessment methods were tested, the Failure Mode and Effects Analysis (FMEA) and the Analytic Hierarchy Process (see chapter 3). Due to the limitations found in their implementation, and the high level of complexity of the building renovation topic, it has been decided to follow a different approach to determine the technical risks of the renovation of existing buildings. The novel approach built on purpose for the EEnvest project, consists of decomposing the process in actions, following a step by step process (Figure 7), from the identification of the buildings' elements and their problems, to the quantification of energy performance deviation costs as a percentage of the initial investment. These outputs will be the economic inputs parameters for EEnvest platform technical-economical evaluation (WP5).

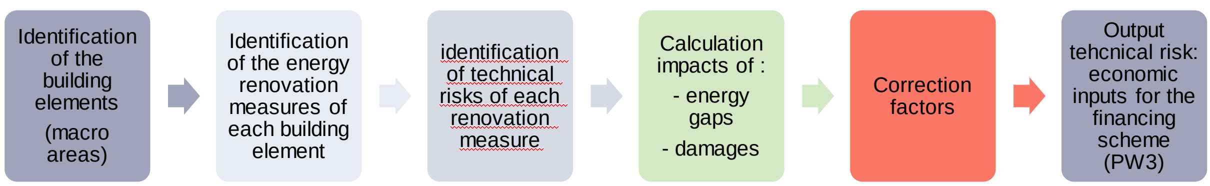

Figure 7. EEnvest technical risk assessment approach.

The whole building was decomposed in macro areas, distinguishing between building envelope and technical systems, identified according to the nomenclature of the ISO 15686-5:2008: "Buildings and constructed assets — Service-life planning — Part 5: Life-cycle

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costing". Consecutively, the energy renovation measures have been identified, and divided among building envelope, building services, RES, other installations, equipment, site and external works.

Successively, through a deep literature and expert based investigation, technical risks were analysed as negative occurrences (problem) connected to each energy renovation measure, that affect negatively business plan expectations (and the planned investment) and hinder the building renovation processes. Occurrences deemed to produce damages, as failures, malfunctioning, or breakage events and energy performance gap, are investigated and catalogued in WP2.

A wide work made was the organization of the EEnvest technical risk database, classification and cataloguing technical risk benchmark, with a probabilistic distribution between predicted and real trend found (in literature) or estimated (experts, energy simulation). For each renovation measure of building element and technical system, the team elaborated a datasheet that contained occurrences with relative probability-impact value (3.2) for both technical risks indicators:

- energy performance gap (Paragraph 2.2.1.1) used for calculating the energy performance deviation between predicted (planned) and real energy consumption, in kWh/m^{2}year;
- damages (paragraph 2.2.1.2) used for malfunctions, breakages at building elements, in Euro (€).

These indicators are independent from each other and not exhaustive if considered separately.

Figure 8 reports the EEnvest breakdown methodology used to determine the technical risks (cause – effect) related to a single energy renovation measure, in this example "*new windows installation*". Energy performance gap triggering indicators in case of a "*new windows installation*" are: "*air infiltration and thermal bridge*", while damage triggering indicator is "*breakages and water infiltration*".

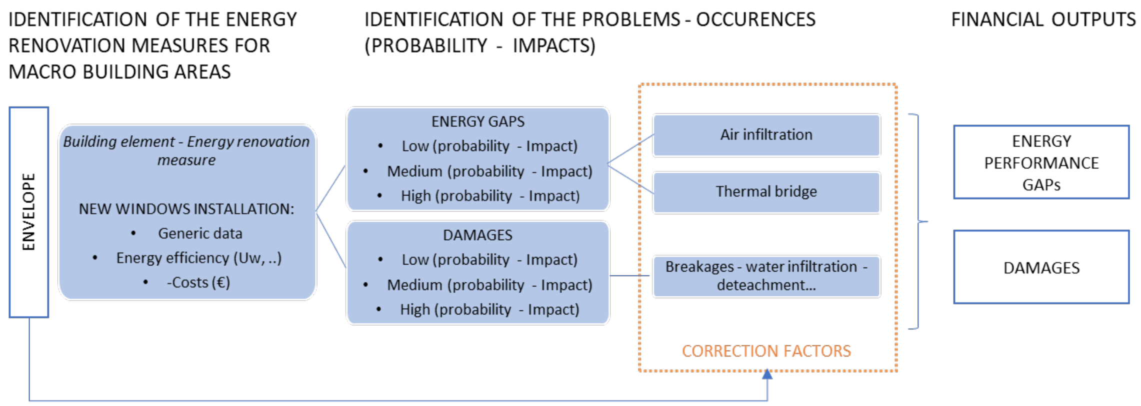

Figure 8. EEnvest methodology to determine technical risks of a single energy renovation measure.

Each occurrence is identified through two parameters, *probability* and respective *impact*, that show the trend distribution of the deviation variability. The technical risk data collection process used to create the EEnvest technical risk database of these two indicators (energy gap and damage) followed a top-down approach, passing from a general to a specific issue, from

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literature reviews (3.3.1), interviews to building professionals and experts (3.3.2) to be completed by parametric energy performance simulations (3.3.3).

Furthermore, correction factors (paragraph 2.2.2) related to the boundary building condition as climate, building features or protocols are used in the calculation to increase or reduce the problem impact (Figure 9). Alerts, like the correction factors, are suggestions for the users (paragraph 2.2.3). All these data are collected in the EEnvest technical risk database.

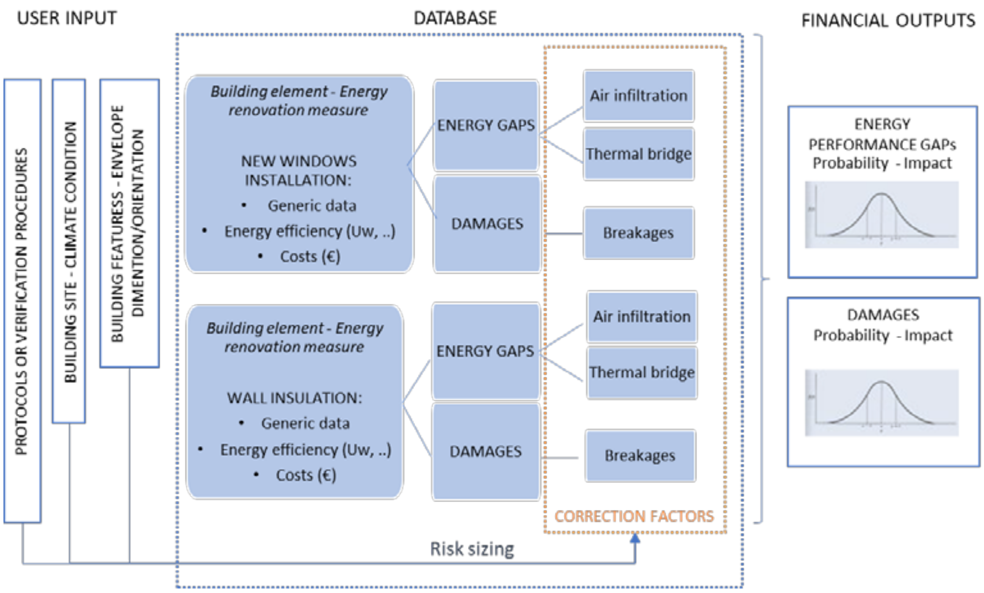

Figure 9. Technical risks calculation – form data inputs to the financial indicators.

The building inputs, inserted case by case from the users, will activate some technical problems extracting them from the EEnvest technical risk database. The technical risk benchmark of each occurrence of the energy renovation measures implemented in the renovation project will be extracted from the EEnvest technical risk database, and risk impacts amount resized in relation to the project data inputs (building data) and correction factors (building boundary condition, protocols or verification procedures used, etc.). These last are identified as correction factors (paragraph 2.2.2) and run in the quantification process of the indicators, Figure 10. In term of outputs measurement unit, both technical risk indicators, energy performance gap and damage, are in percentage of the investment.

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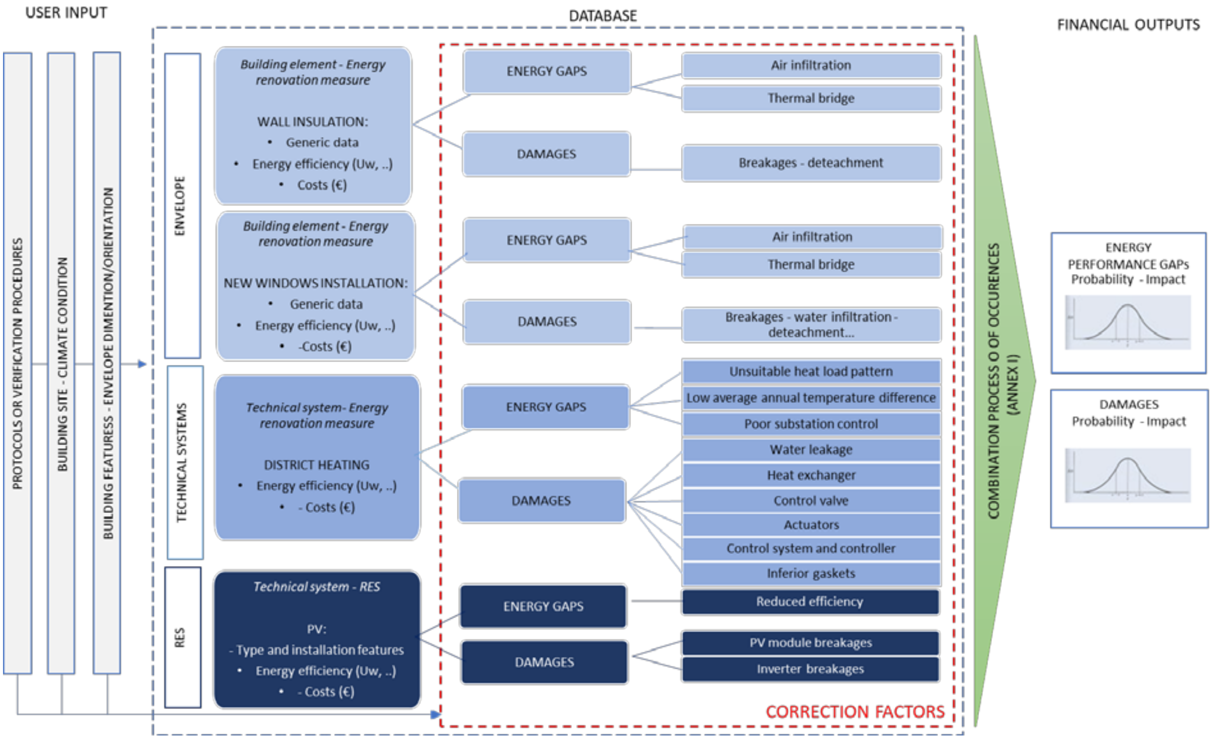

Figure 10. EEnvest top down approach to determine the technical risks database and the use of correction factors.

Once the occurrences, the impact and the probability have been identified, and through "*probability mass function*" will be combined the occurrences (Annex I) will generate all the technical risk probabilistic combination of occurrences for both indicators, energy performance gap and damage. Annex I presents the determination process used to combine the technical risk of several occurrences that will be implemented in the EEnvest platform (WP5). At the end the complete probabilistic trend of combination of technical risks of these two indicators (outputs of WP2) will be used in the WP3 in the Financial Risk Assessment process, where a random sampling of the probabilistic technical risk of a specific energy renovation scenario will be extracted and then applied to project cash flows through a Monte Carlo simulation (D3.1).

2.2.1 Technical Risk Database Indicators

Data collection process used to gather the technical risks for EEnvest web-platform database was developed according to a top-down approach, passing from a general to a specific issue, in relation to the users' inputs (building features, renovation solutions sets, boundary condition) by two indicators: energy renovation gap and damages. Probability and respective impacts where identified through literature, real data (experts), and parametric energy simulation.

During the identification of each occurrence, mitigation measures were also collected, as correction factor able to modify the cause-effects result.

The two indicators, energy performance gap and damage describe two different economic aspects, both related to the decision-making choices, but with different meaning. For example, in Figure 11 there are two identical buildings, located in two different area condition, one in a city and one close to the sea. Hypothesising similar climate conditions, the technical risk indicator of the energy gap results the same affecting the investment for a 15%, while the damage indicators, in the building located close to sea results three times more higher,

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producing an impact that should increase the final investment by 60%, due to the external condition, namely the salt presence in the air.

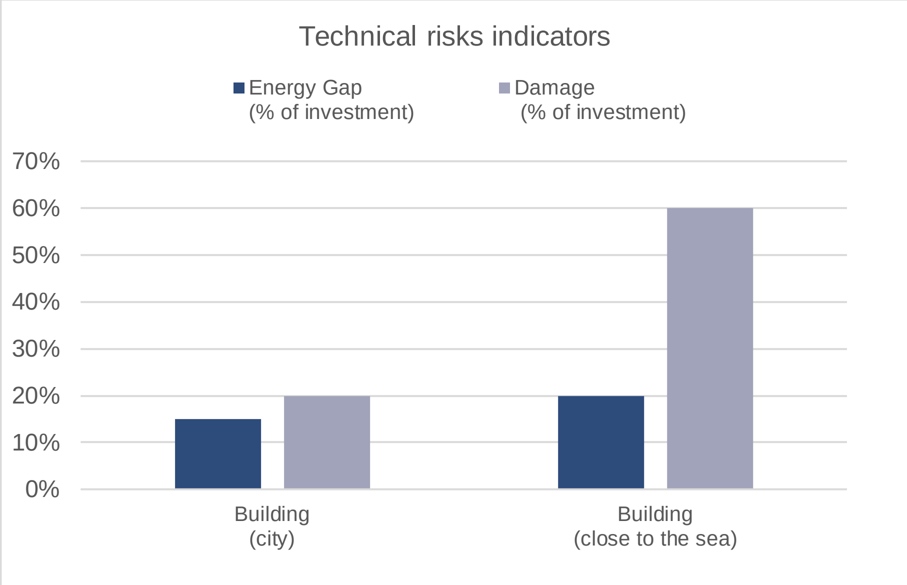

Figure 11. Technical risks indicators: energy gap and damage, as % of the investment.

The procedure developed to define the impacts is reflected in the simplified validation data process (described in section 4.1.5) with a good level of approximation even if the high value is higher than the range defined with the general literature data. Moreover, it is necessary to underline that, in the EEnvest technical risk assessment, each impact is referred to a specific probability that event occurs.

It is important to highlight that, even though design errors can lead to performance gaps and damages, the literature review and the expert interviews underline the difficulties to define and quantify the impacts of design errors, due to the excessive number of possible cases and the difficulty to quantify designing effects. Therefore, in the EEnvest technical risk assessment the effect of design errors has been neglected because we start from the assumption that in the design phase the experts have already considered this issue in the planned project. Furthermore, potential risk deriving from design errors should be beard by the designer, i.e. hedged for the investor.

2.2.1.1Energy performance gap

One of the most common problems connected to the energy renovation of existing buildings is the energy performance gap (chapter 1.2) between energy performance predicted in the design stage and actual energy consumption usually measured in the occupation stage (Cuerda et al., 2020; Shi et al., 2019) [12] [13].

Energy performance gap is defined as the deviation value between building energy performance predicted (calculated) and real energy consumption measured. This gap depends on several factors:

- *calculation model,* such as the type of energy performance simulation tool used, the detail level of building model (inputs) and the level of simplification (or complexity) adopted (Van Dronkelaar et al., 2016) [6].

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- *building boundary conditions*, such as external conditions, difference between the trend of outdoor temperature estimated and real one [14]
- *building regulation parameters* commonly used in the simulations (as indoor temperature) are sometimes different from the real ones, due to the difference in the building occupancy schedules working/hours, lighting, shading systems, appliances, that the final users select to increase the indoor comfort (occupant behaviour). (Stoppel and Leite, 2013) [15],
- errors in design, workmanship/installation, or operation (as general systems' control settings).

As reported by van Dronkelaar et al. (2016) [6] the energy performance gap deviation between the predicted energy performance and measured energy consumption in office buildings in a UK context, is about 16%, due to modelling issues (20-60%), occupant behavior (10-80%) and poor operational practices (15-80%).

A result presented in this report Shi et al. (2019) [12] shows that there is a reliable correlation between building features, such as type, climate, floor area, etc. and the energy performance gap analysis.

Furthermore, deviations between predicted and actual energy consumption occur during the operation phase of the building but they are strictly connected with the choices made in the design phase, and with the final quality of the installation/construction phase. In the EEnvest technical risk determination process of the energy performance gap indicator is been used a method based on benchmarks of risks, cause-effect occurrences completed of relative impact-probability information. Deviation amounts, as modification of the planned energy performance, are estimated in percentage of kWh/m^2year, and depends on the building features, boundary condition and renovation scenario. The magnitude of the energy gap (level of deviation from the planned energy performance) is a variable value of each outcoming event of the renovation measures that affects the final prefixed targets. The impact of energy performance variation (value) was estimated in a range of values (with a minimum and a maximum, and their probability) that depends and changes in relation to the renovation scenario settings inserted by users. Within the EEnvest technical risk database the energy performance gap of each renovation measures is collected. The measurement unit used is a percentage of the investment and it is determined through a top-down analysis and verified by a bottom-up approach. The energy gaps have been determined through an extensive literature review, interviews to building experts or estimated by energy performance simulation. As already explained in paragraph 3.2.2, in the EEnvest technical risk assessment the effect of design errors has been neglected. Within the proposed method, the inputs that enable to assess the technical risk of renovation measures were identified, based on specific inputs and uncertainty values considering the risk into the simulation through the deviation of the energy performance.

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ENERGY PERFORMANCE GAP - DATABASE

	Low		Medium		High	
	Prob. %	Impact	Prob. %	Impact	Prob. %	Impact
Air infiltration						
Thermal bridge						
…						

- Literature review
- Interviews
- Other database from EU research projects

- Literature review
- Interviews
- Real experiences or energy simulation

Figure 12. Energy performance gap assessment process

2.2.1.2 Damage

Damage is the second category that was adopted to define technical risk of energy renovation measures. Damages are breaking events, deteriorations or malfunctions that may occur during the building operation phase. In this regard, it is important to underline that extraordinary maintenances only are considered as damages. These events require a technical intervention to carry out the required repair and replace the damaged components, for the description of the damage level, three levels of cost impact (low, medium and high) have been defined as cost amount deviation due to company call fee, kind of repair intervention from a localized damage to a substitution's parts, or demolitions with relative finishing works, plus workings hours of building expert, materials and mechanical tools used.

These indicators will be transformed into numerical percentages of the initial investment cost at a later stage of the damage evaluation. In EEnvest damage evaluation assessment, damages included in the component's warranty are not considered.

DAMAGE - DATABASE

	Low		Medium		High	
	Prob. %	Impact	Prob. %	Impact	Prob. %	Impact
Air infiltration						
Thermal bridge						
Water infiltration						

- Literature review
- Interviews
- Other database from EU research projects

- Literature review
- Interviews
- LCC
- Price building works (public database)

Figure 13. Damages assessment process

2.2.2 DATABASE CORRECTION FACTORS

A correction factor is a "value" used in a multiplication equation to correct the results. Correction factors have been defined within EEnvest technical risk calculation method to

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consider all those aspects and boundary conditions deviating from the base case, which may affect the risk size. They have been classified in several topics (Figure 14) in relation to the building boundary conditions and their field of activity:

- Climate conditions: these influence the building energy efficiency performance, increasing or reducing energy losses.
- Building site: for instance, wind intensity influence on air infiltration is different if the building is located in a city centre or in an industrial zone in the city outskirts. This is an important information in the determination of the air infiltration and the energy losses connected with that. At the same time, knowing if the building is close to the sea, is an important input for the "damage" calculation, as this condition can reduce the service life of the building components. In this case, a possible mitigation measure can be to require a specific "maintenance program", in which covers the special needs of this contest.
- Building features and building scale factors: parameters strictly connected to the pilot proposed by the user. These are parameters, which affect the building energy behaviour, such as building shape (from EN 15217:2007), or transmission heat loss coefficient (from UNI EN ISO 13789:2001), together with all the parameters connected to the renovation measures (material, dimensions, etc.). Correction factors are also used to adapt the influence of several energy renovation measures when applied together. An example is, when in the energy renovation strategies both insulation of external walls and new windows installation are planned and implemented together. In this case, the probability to have thermal bridge is reduced compared to the case where new windows only are installed, due to some real limitations during the installation works.
- Protocols used in the design, construction, operation phase. In case of presence of an energy performance and quality protocol already approved, such as LEED, KlimaHouse, Passive House, the technical risks directly related to the protocol's ambit can be considered as reduced or in some cases zero. For example, in case of KlimaHouse or Passive House certification, the technical risk associated to air infiltration can be assumed zero. In fact, to achieve KlimaHouse certification some verification processes during the development of design and construction phases, like the Blower Door Test, are mandatory. This means no (or very low) deviation from planned energy performance, with a consequent increment of the guarantee value of the business plan, due to the achievement of the performance results. Starting from these assumptions, in the technical risk calculation the presence of energy losses due to air infiltration is not considered. The achievement of the KlimaHouse certification, in this technical risk calculation method, reduces to zero (null probability) its influence in indicator "energy gap".
- Managing innovation process or other verification processes. The same concept of protocols. Technical risks can be reduced if these "process measures" as blower door test, thermography, maintenance program, ETICS guarantee, BIM, Maintenance program, automatic meter reading systems installed, etc. are implemented.

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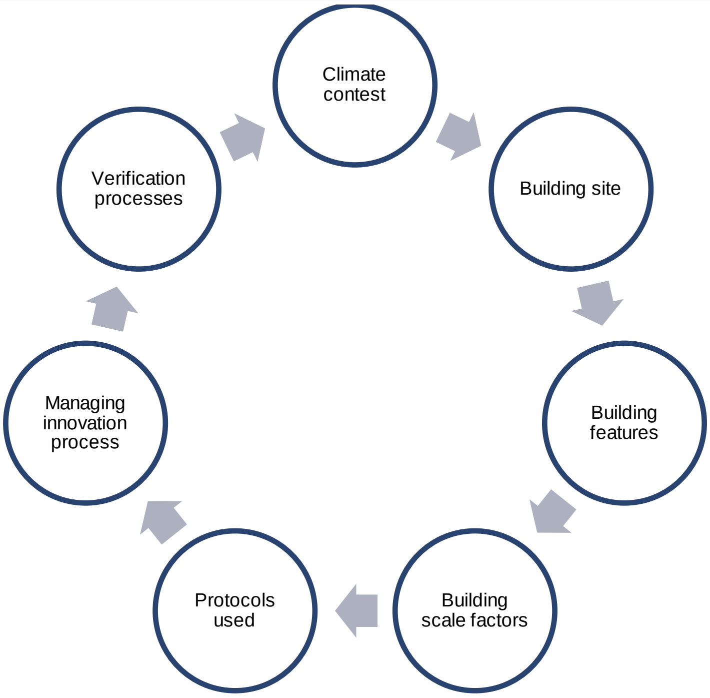

Figure 14. Type of correction factors

Here below are reported the correction factors relation between the boundary condition and technical risks (Table 2).

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Parameters that affects the technical risks					
	Building physic and Technical system				
Boundary condition – mitigation action	Air infiltration	Thermal bridge	Overheating	Loss on energy efficiency	System and components performance
Climate contest					
Heating dominated (Mediterranean)	X		X		X
Central Europe conditions (Temperated)	X	X	X	X	X
Cooling dominated (Nordic)	X	X		X	X
Building site					
Urban contest: city center (low wind, urban heat island)	X	X	X	X	X
Extra-urban contest: industrial zone or close to the sea (high wind)	X	X		X	X
Building exposure: mostly shaded			X	X	X
Building exposure: mostly sunny			X	X	X
Difficult construction site (reduced space, or other kind of difficulties ...)	X	X			
Building features - building scale factors					
Building shape - S/V	X	X		X	X
Window-Wall Ratio - WWR	X	X	X	X	X
Protocols used in the design, construction, operation phase.					
International performance measurement and verification protocol (IPMVP)	X	X	X	X	
Passive House certification	X	X	X	X	
LEED certification	X	X	X	X	
Other energy performance certification (Casaclima, Bream, Greenstar, etc.)	X	X	X	X	
Managing innovation process or other verification processes					
Blower door test	X			X	X
Thermography		X	X	X	X
Maintenance program (LCC evaluation)	X	X	X	X	
specific ETICS guarantee	X	X		X	
Integrated energy performance process	X	X		X	
BIM (in design and implementation)	X	X	X	X	X
Maintenance plan completed of management and verification actions and reference persons	X	X	X	X	X
BMS (automatic meter reading systems, system control strategy, etc.)			X	X	X
Monitoring system (sensors, alert, user feedback, etc.)	X	X	X	X	X
X: presence of correction factor – it will be positive or negative, to reduce or increase the final occurrence					

Table 2. Boundary condition to supply the correction factors

2.2.3 DATABASE ALERT

In the EEnvest technical risk calculation method so-called “alerts” have been defined and introduced. Alerts are meant to warn the users of the EEnvest web-platform against dangerous situations which may arise during the implementation of some energy renovation measures.

Alerts are suggestions for the users, which can be considered mitigation measures as well, if adopted. In fact, they can reduce the number of negative occurrences, or their impact, also in terms of commercial value, validating the benefits coming from the renovation project.

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Furthermore, some alerts do not have a quantifiable impact and depend on several variables, such as (i) the end user behaviour of the buildings (e.g. open/close the windows, turn off the monitors), or (ii) technical aspects such as the water condensation on internal glass, due, to physical issue (e.g. presence of thermal bridge) or more factors that happen together (e.g. internal humidity, no ventilation, number of people, activity done…). In this case, an alert highlights an unquantifiable occurrence, suggesting a design-technical problem-solving action proposing more attention in the design phase, with a mechanic ventilation system with emission system towards glass-windows.

For building components, lifespan is the economic lifetime expectancy, normally specified in years. Alert, as an EEnvest web-platform output, is a fundamental goal to reduce damage, it provides information about when replacement cost for the building components need to be taken into account. In case of building services, the EN 15459:2018 provides the lifespan and yearly maintenance costs of each element, as a percentage of the initial investment. Both data will be integrated in the EEnvest platform in form of a warning, which is displayed when the selected business plan timing exceeds the components lifespan of the investigated renovation measure, causing in this way an extra-cost due to the component replacement.

Final users, using the platform, can receive recommendations coming from alerts, for the reduction or technical risks and relative negative effects in term of costs, of a single project (D2.2).

2.2.4 MITIGATION MEASURES

Mitigation measures are actions for EEnvest web-platform users, identified in WP2, to prevent, reduce or control negative occurrences during or after the energy renovation of commercial buildings. Mitigation measures are adopted to reduce as much as possible damage at the building elements or technical systems, that cause negative effects, technical replacement, or restoration. Mitigation measures will be deeply presented in the D2.2.

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3 EENVEST TECHNICAL RISKS DATABASE

In this chapter the EEnvest technical risk database is presented, from organization of the data (paragraph 3.1), the classification of datasheet for building elements and technical system (paragraph 3.2) and process used to collect and identify the technical risk data (paragraph 3.3).

3.1 EENVEST TECHNICAL RISK DATABASE ORGANIZATION

The data collected in the EEnvest technical risk database came from literature reviews, interviews, and simulations, applying a top-down approach, that decomposes the building in macro-areas (envelope and technical systems, including the RES) – building elements – renovation measures. At this level, we identified the negative occurrences that can happen during the renovation phases, from design to operation one, and the parameters that affect, modifying, the energy performance or the damages (increasing or reducing) with different intensity, case by case.

At the end, all the technical risks of renovation process were collected in a EEnvest technical risk database, able to assess and determine the indicators impact (outputs) through a top-down approach, passing from a general building to a specific pilot, in relation to the users inputs (building features, renovation solutions sets, boundary condition). The results are two indicators, energy gap and damage, on economic variation of the investment, identifying through Monte Carlo method, and with a certain level of randomness or fall within a fairly wide range.

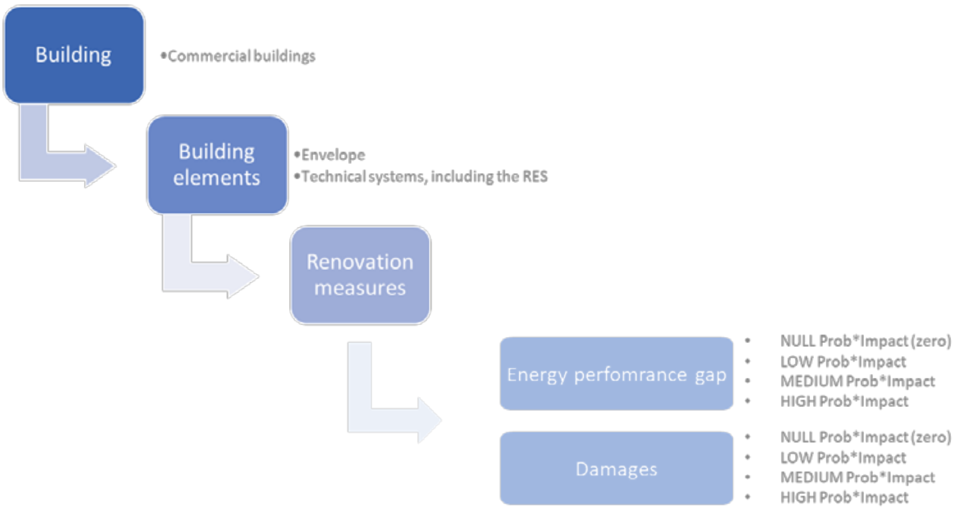

Figure 15. Organization of technical risk assessment.

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3.2 IDENTIFICATION ON TECHNICAL RISKS FOR EACH BUILDING ELEMENTS

In this paragraph the datasheets of each building element renovation measure are reported. Each datasheet aims to collect the technical problems, the parameters that affect the impact variation, included the probability, and the mitigation measures (correction factors). The list below helps navigate through the developed contents, referring to a set of figures showing datasheet excerpts.

BUILDING ENVELOPE ELEMENTS

1. Roof (Figure 17):
    - Flat roof
    - Pitched roof
2. Floor (Figure 18):
    - Next to the ground (outside)
    - Next to air (outside)
    - Floor next to unheated area (es. Garage)
3. Walls (all typologies) (Figure 19-Figure 22):
    - External wall:
        - External Cladding
        - Prefabricated facade
        - Internal Insulation
        - Window facade system:
            - Curtain wall
            - Double skin
    - Wall next to unheated area:
        - New insulation
    - Wall next to ground:
        - New insulation
4. Windows (Figure 23)
5. Shading system (Figure 24)
6. External doors (Figure 25)
7. Other elements (Figure 26)

BUILDING SERVICES AND RES SYSTEMS

8. Heat pump (Figure 27Figure 27):
    - Air/air HP
    - Air/water HP
    - Geothermal HP
9. District Heating (Figure 28)
    - District Heating Substation
    - Customer's internal heating system
10. Gas Boiler (Figure 29):
    - Condensing boiler
11. Biomass boilers (Figure 30)
    - Condensing boiler
12. Emission system (Figure 31)
    - Radiant floor
    - Radiant ceiling

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- Radiators

13. Distribution system (Figure 32)
14. Cooling system (Figure 33)
    - Chiller
15. Mechanical ventilation system (Figure 34)
16. Electric system (Figure 35)

DATASHEET LEGEND

In Figure 16 the legend of the information contained in the datasheet is reported, as follows:

- The technical risk indicators
  - o Energy gap in a yellow rectangle
  - o Damage in a violet rectangle
- Correction factors in orange rectangle
- Alerts in red rectangle.

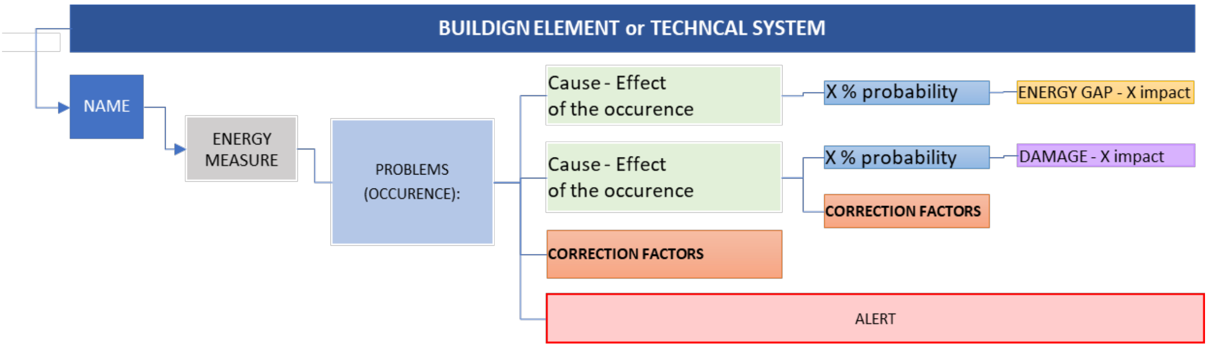

Figure 16. How to read the datasheet information

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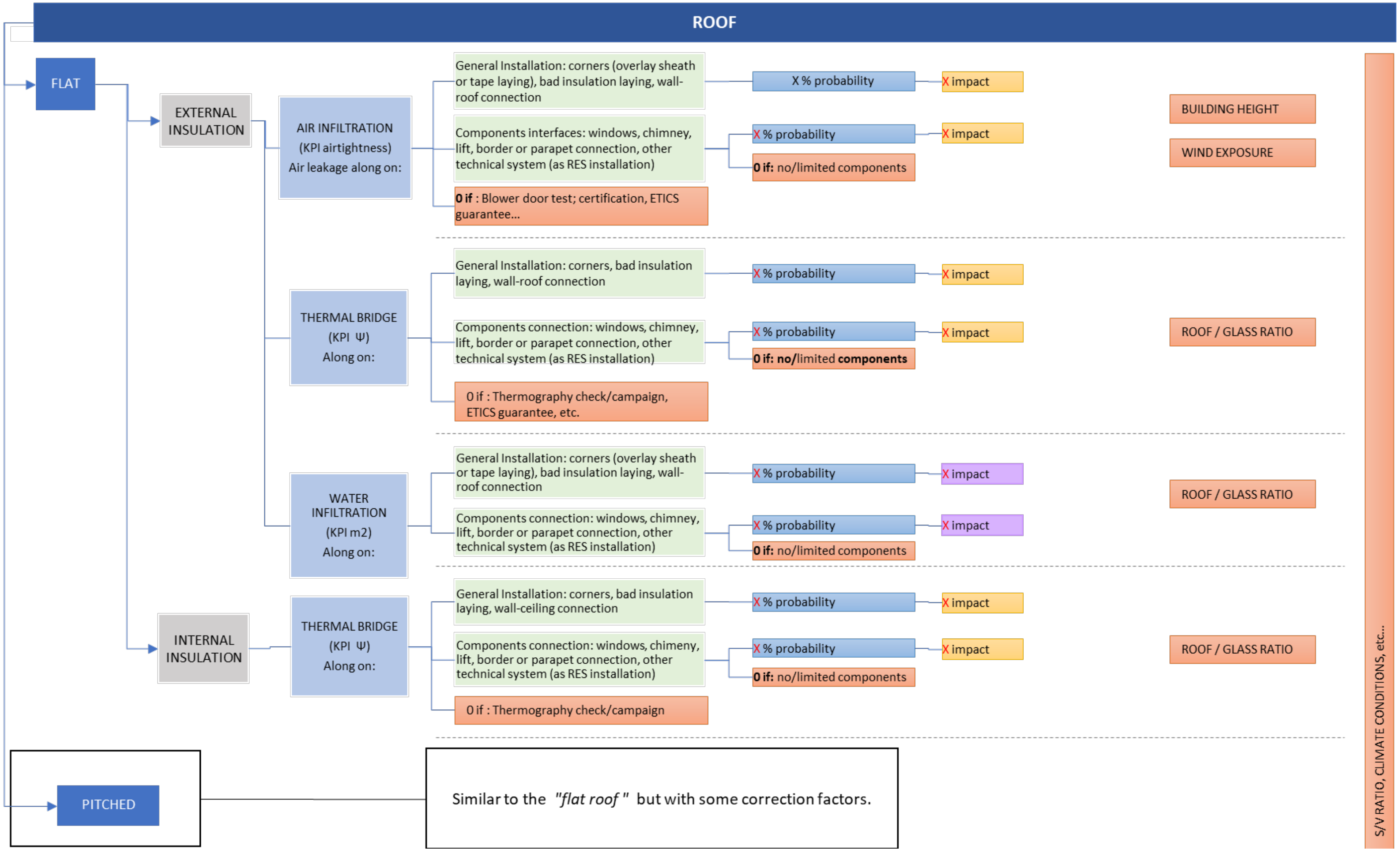

Figure 17. Roof risk probability breakdown definition

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Figure 18. Floor risk probability breakdown definition

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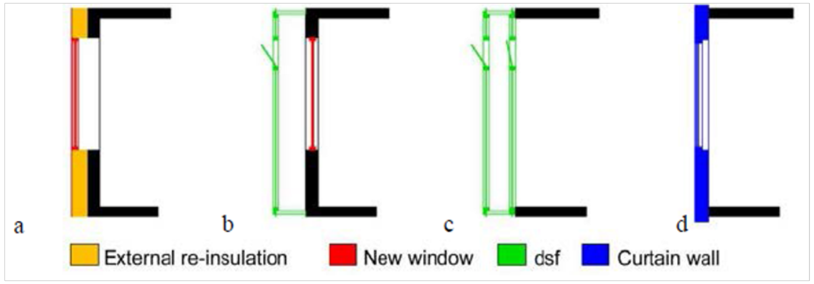
WALLS

- EXTERNAL WALL
  - 1. EXTERNAL CLADDING (insulation, glue and plaster)
  - 2. VENTILATED FAÇADE WITH EXTERNAL CLADDING (insulation, anchoring, fixing system, and external façade cladding)
  - 3. PREFABRICATED FAÇADE (insulation, final cladding, anchoring, fixing system,)
  - 4. INTERNAL INSULATION (insulation, glue and plaster)
  - 5. WINDOW FAÇADE SYSTEM - Curtain wall
  - 6. WINDOW FAÇADE SYSTEM - Double skin (replacement or addition)
- WALL NEXT TO UNHEATED AREA (GARAGE..)
  - New insulation (of any kind)
- WALL NEXT TO GROUND (OUTSIDE)
  - New insulation (of any kind)



Renovation strategy: (a) External re-insulation, (b-c) Double-skin facade (d) Curtain wqall. (SOURCE: Façade system for existing office buildings in Copenhagen - Loay Akram Hannoudia,, Jørgen Erik Christensenb, Michael Lauringa*

Figure 19. Wall risk probability breakdown definition: overviews solutions (1/4)

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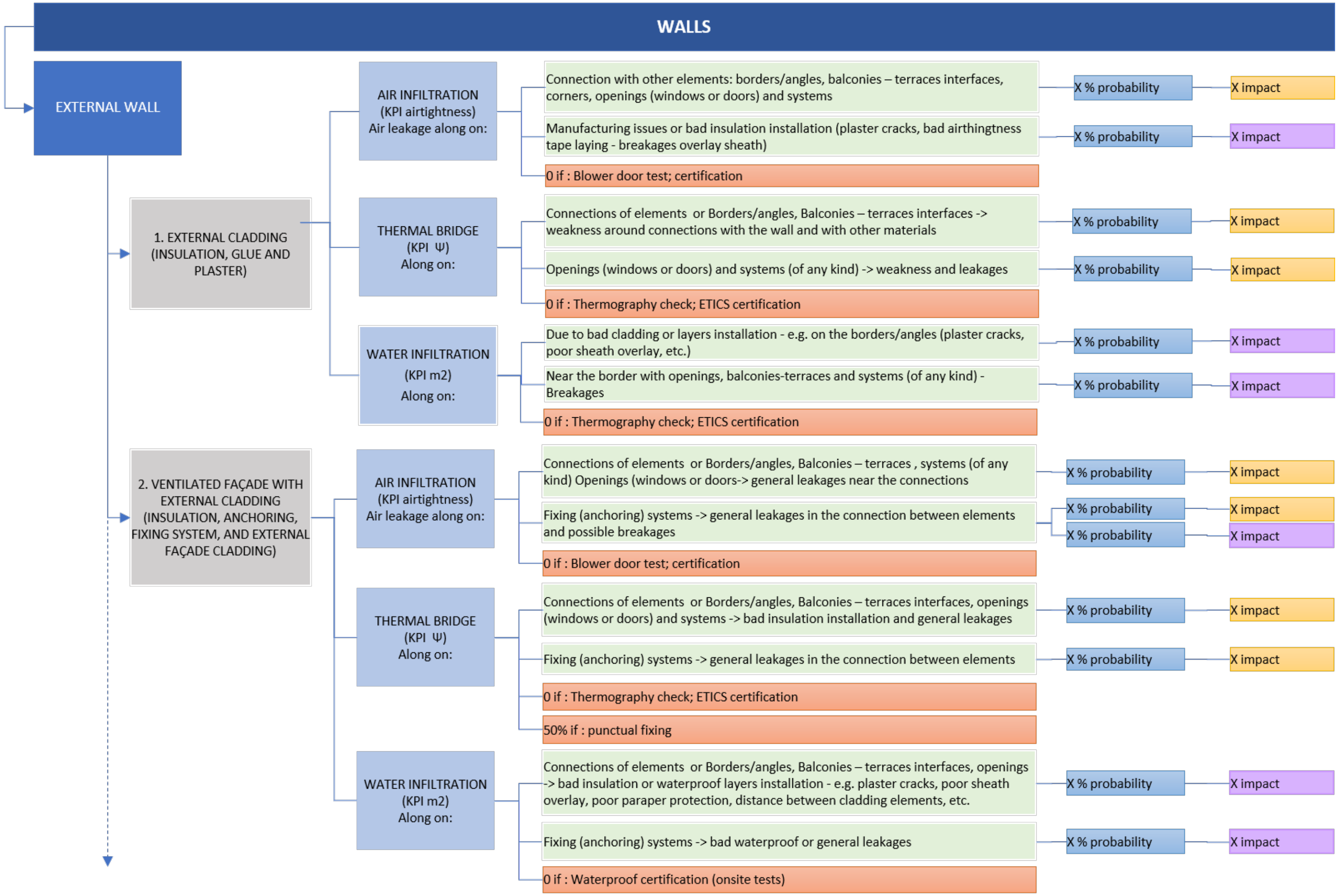

Figure 20 External wall risk probability breakdown definition: external cladding, ventilated façade with external cladding (2/4)

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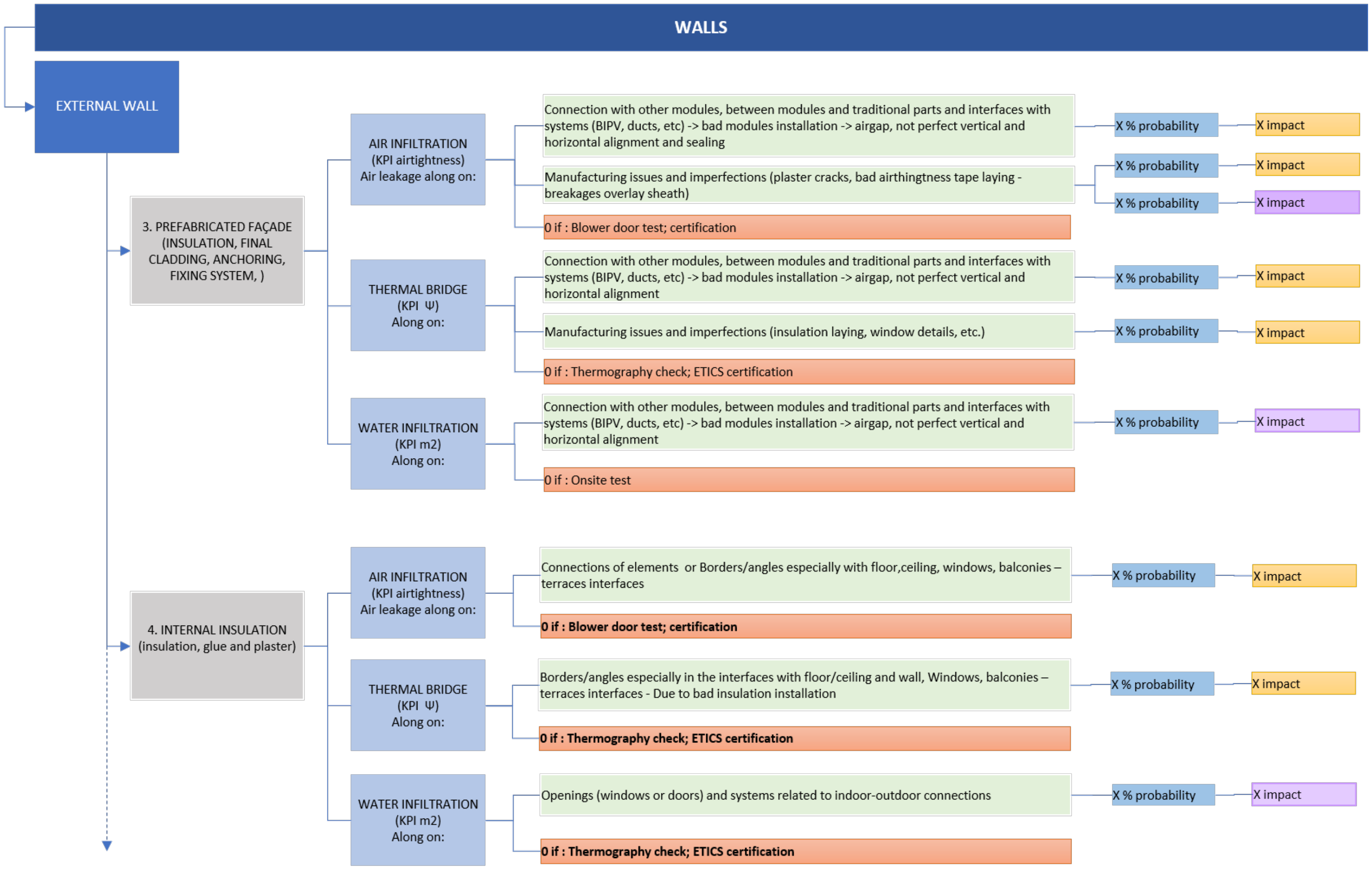

Figure 21. External wall risk probability breakdown definition: external cladding, ventilated façade with external cladding (3/4)

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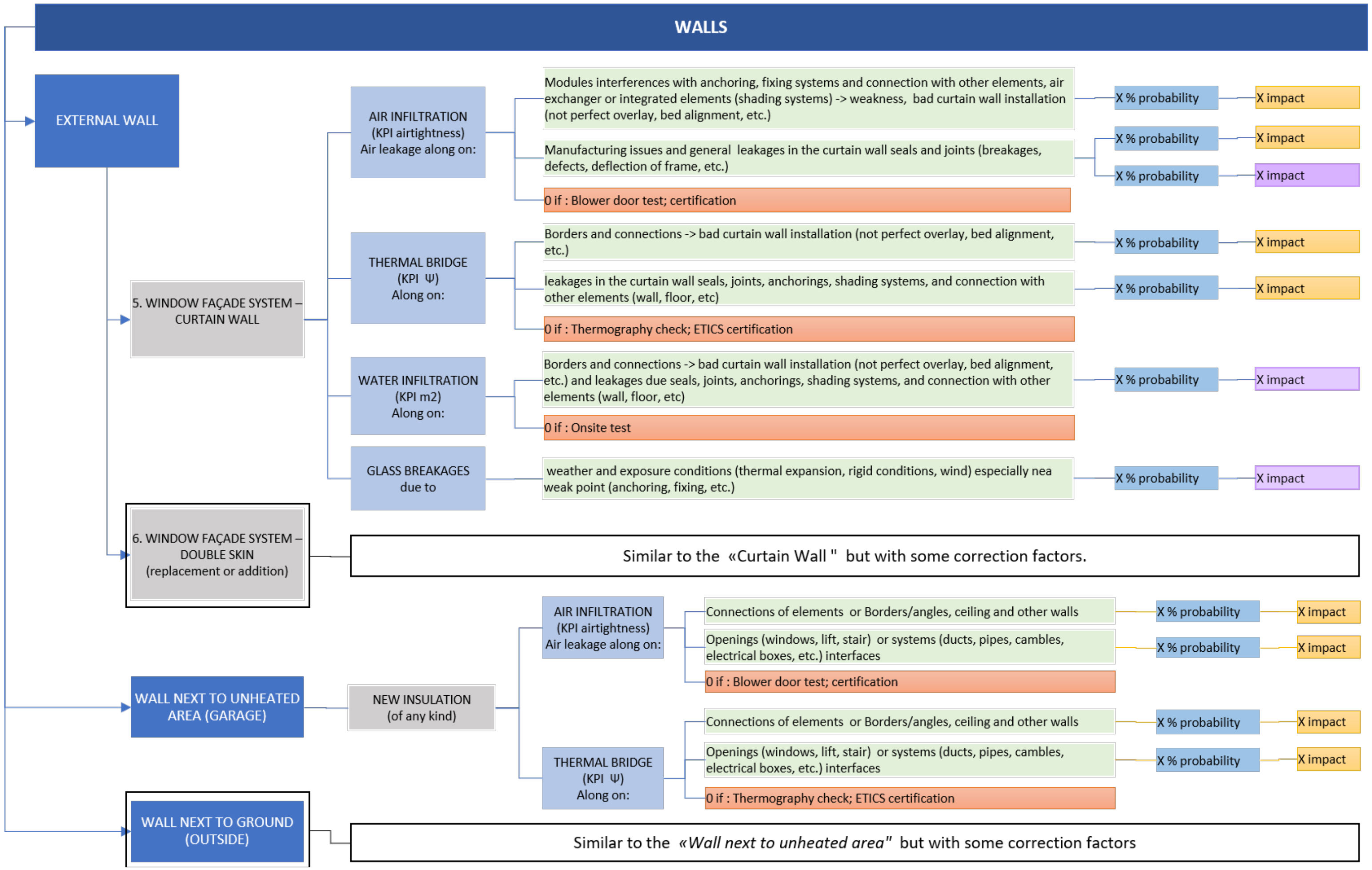

Figure 22. External wall risk probability breakdown definition: external cladding, ventilated façade with external cladding (4/4)

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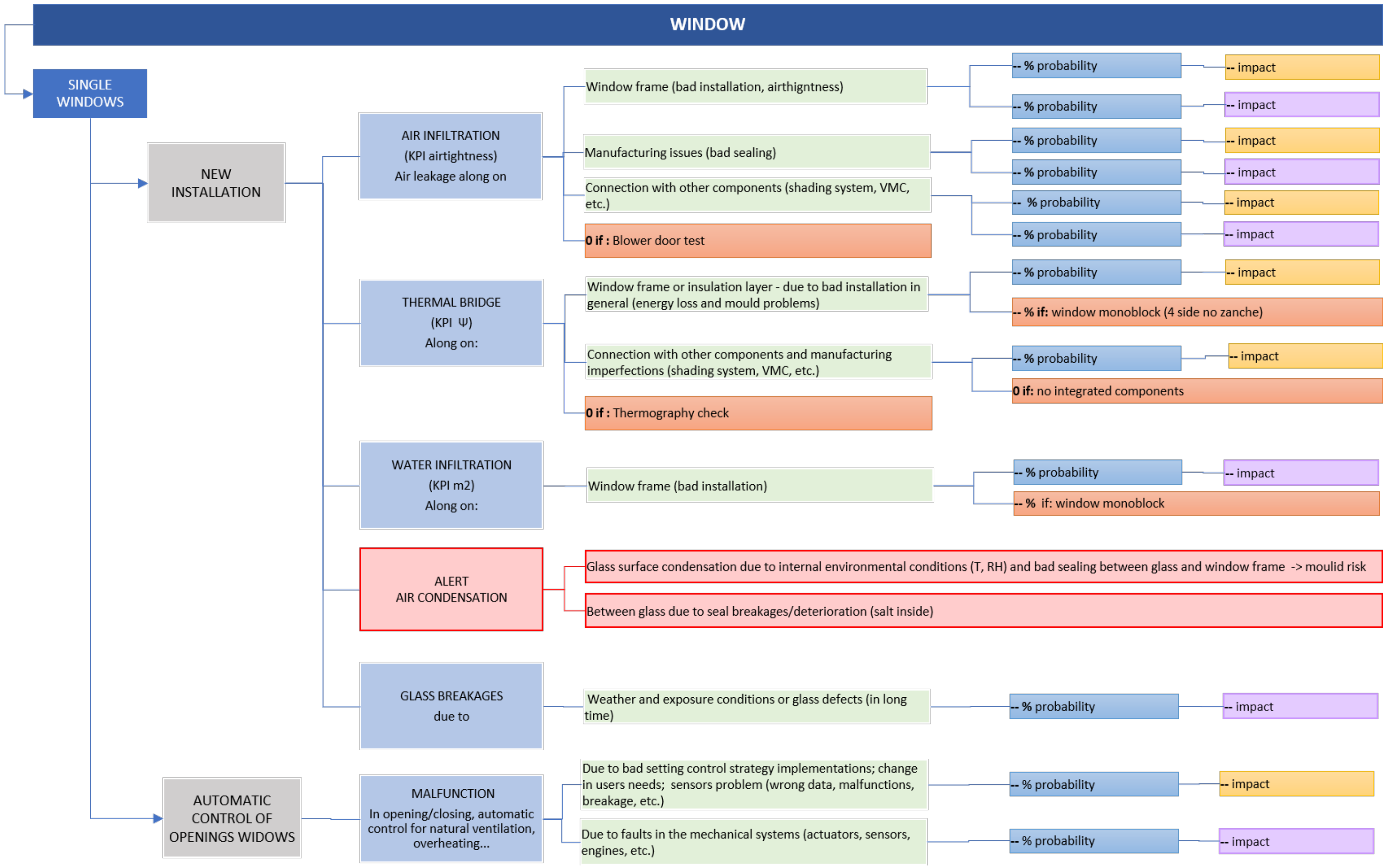

Figure 23. Window risk probability breakdown definition

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Figure 24. Shading system risk probability breakdown definition

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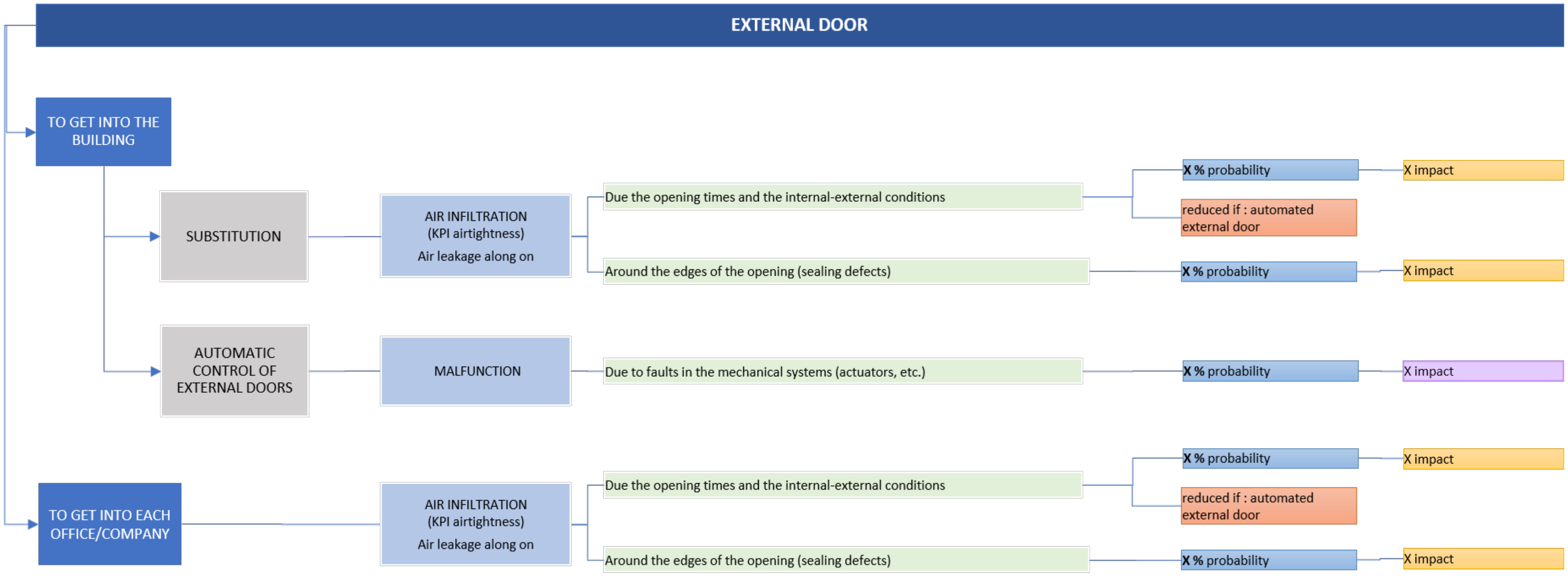

Figure 25. External Door risk probability breakdown definition

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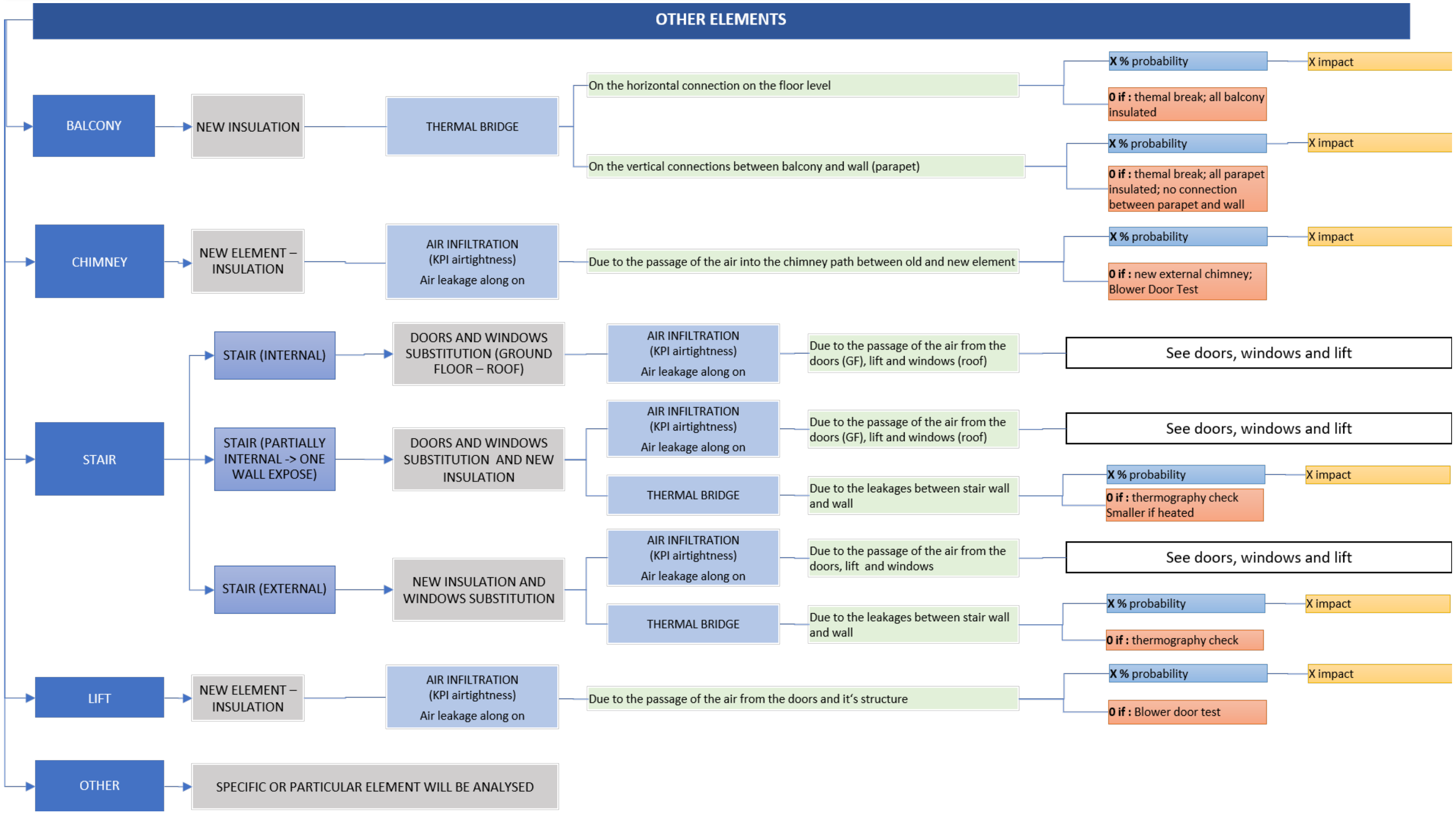

Figure 26. Other elements risk probability breakdown definition

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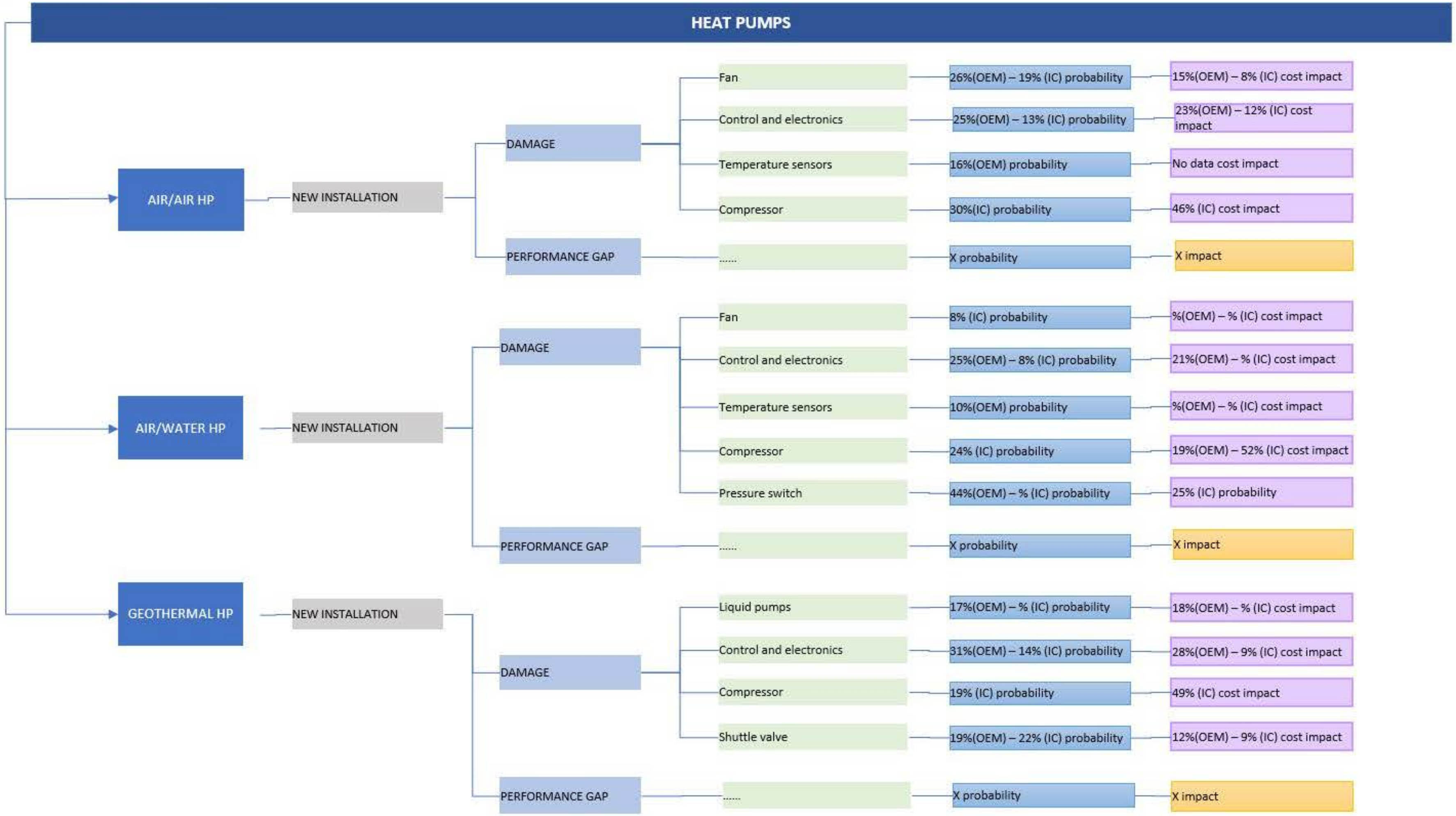

Figure 27. Heat pump risk probability breakdown definition

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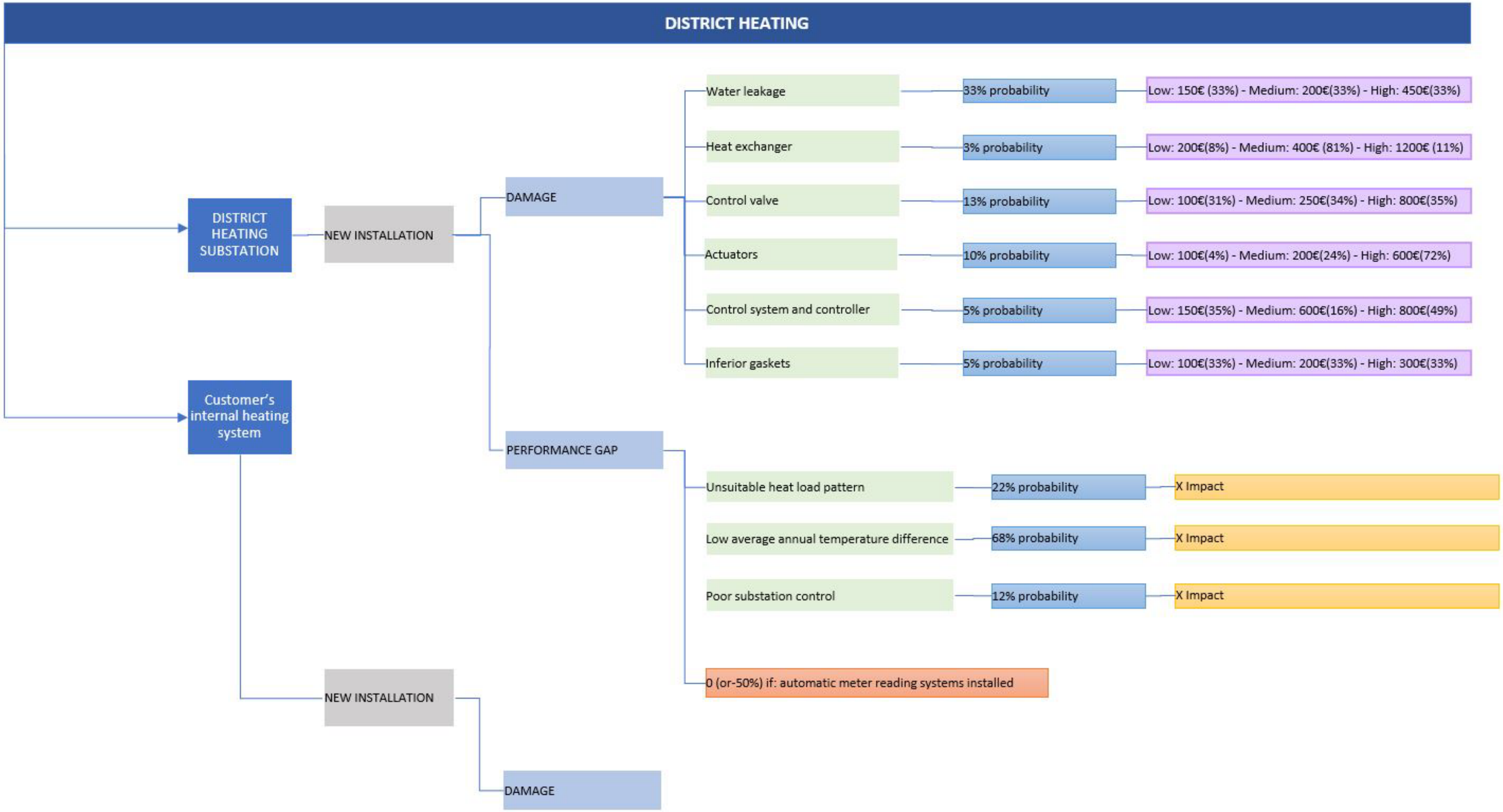

Figure 28 District heating risk probability breakdown definition

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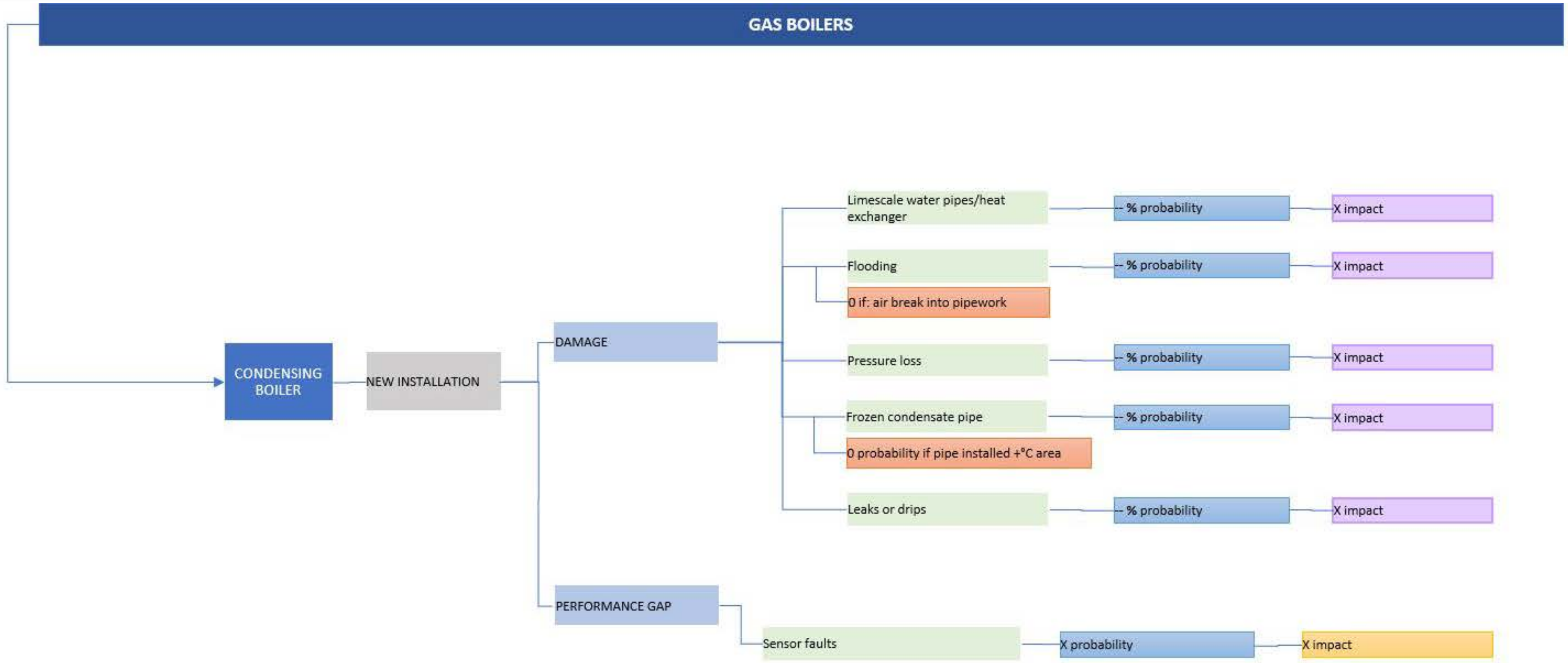

Figure 29 Gas boilers risk probability breakdown definition

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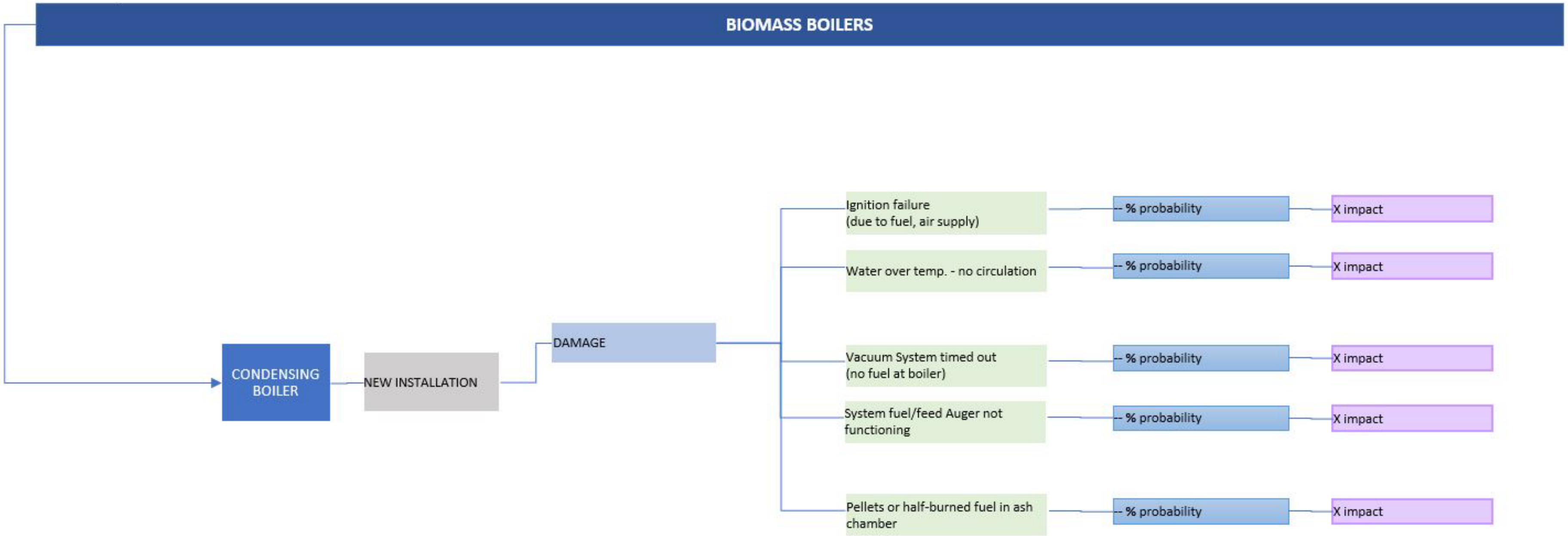

Figure 30 Biomass boilers risk probability breakdown definition

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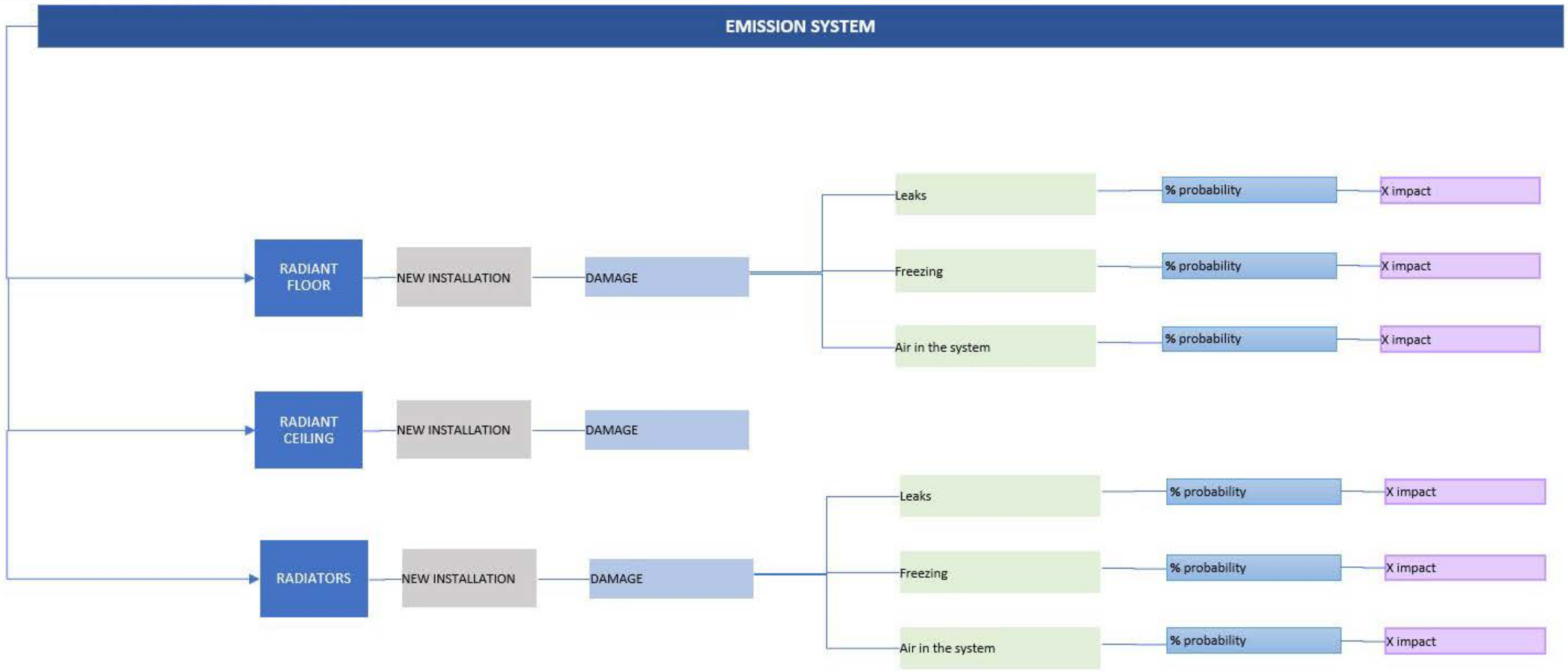

Figure 31 Emission system risk probability breakdown definition

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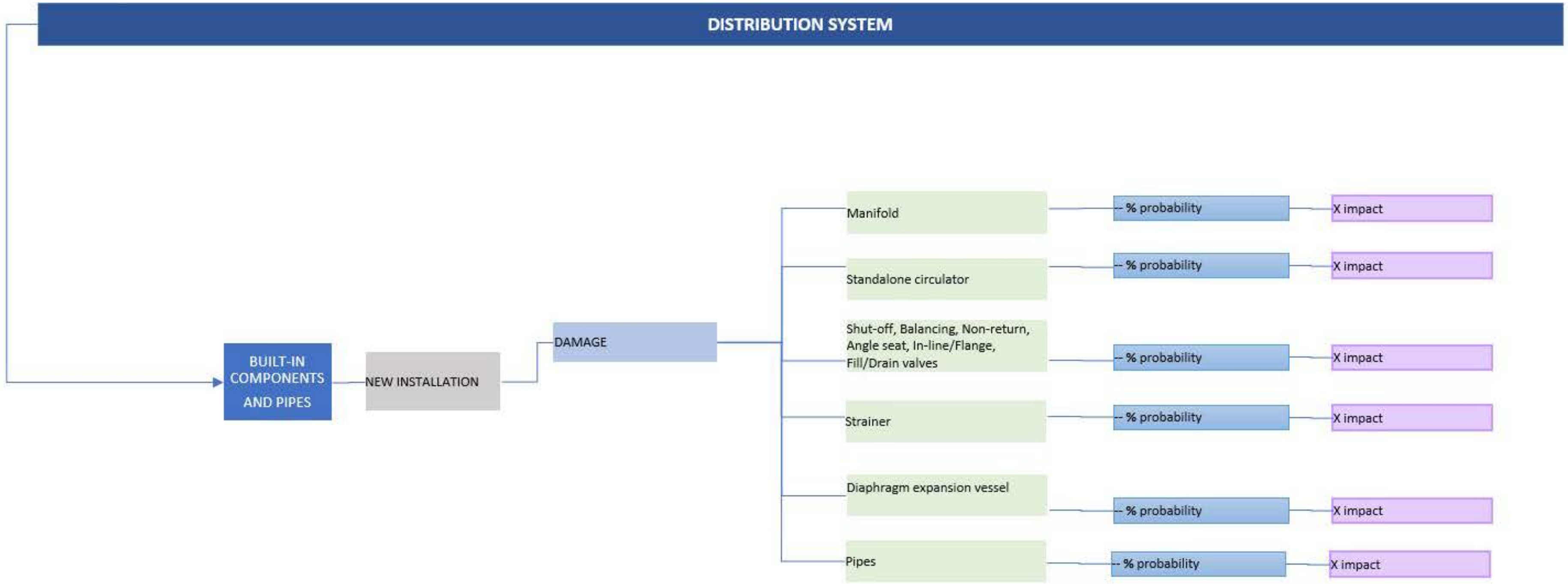

Figure 32 Distribution system risk probability breakdown definition

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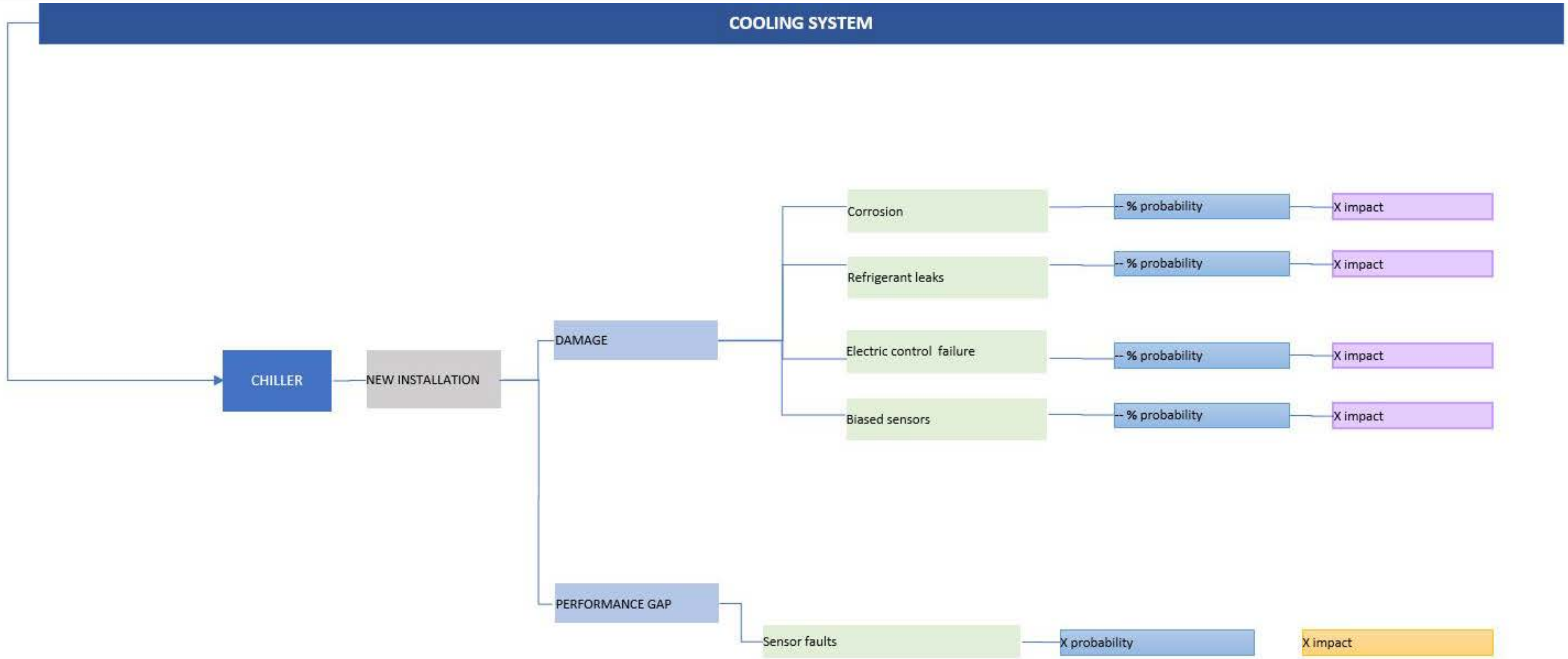

Figure 33 Cooling system risk probability breakdown definition

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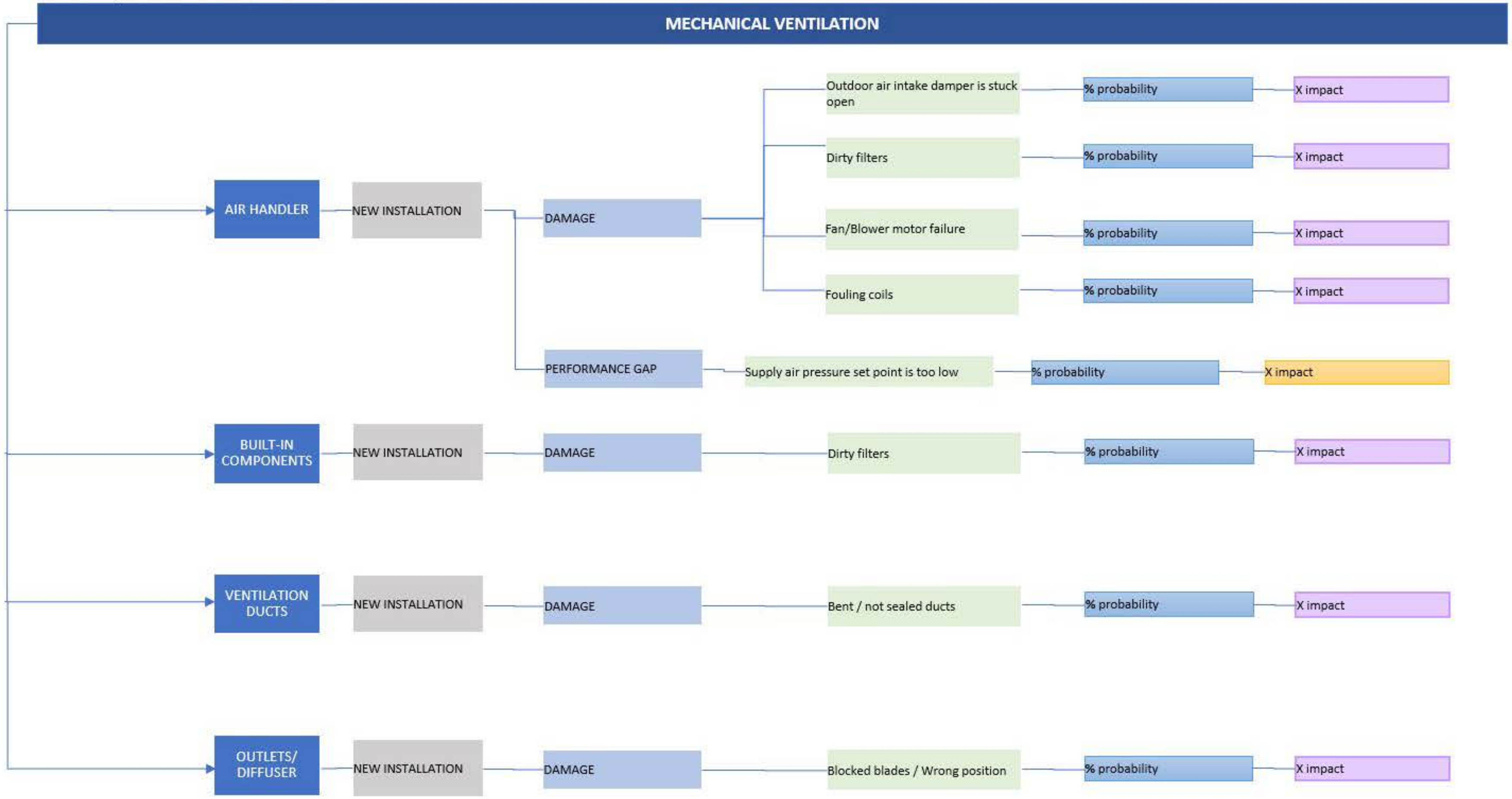

Figure 34 Mechanical ventilation risk probability breakdown definition

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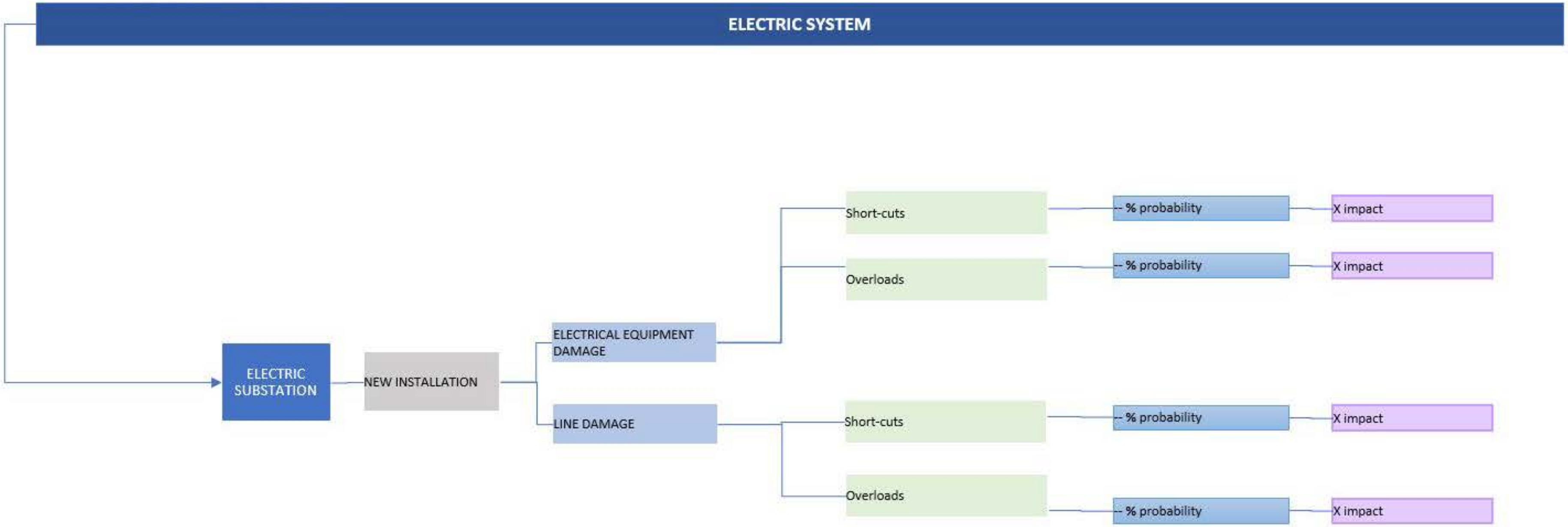

Figure 35 Electric system risk probability breakdown definition

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3.3 TECHNICAL RISKS DATA COLLECTION: PROBABILITY AND IMPACTS IDENTIFICATION

In this paragraph is reported the collection strategy used to identify the value of the parameters of preidentified technical issues for each building elements (paragraph 3.2).

3.3.1 Literature review

The literature review is mainly based on several topics, to identify the cause-effects impact, running parameters and mitigation measures (reported in alphabetic order):

- Air infiltration: air changes, volume, heat exchange, wind, pressure, …
- Analytic Hierarchy Process
- Cost Optimal
- Energy Performance Gap
- Facade systems for office buildings
- FMEA
- Glass breakage
- HVAC faults
- Impact automatic lighting control
- Internal condensation
- Internal insulation
- Maintenance office buildings
- Overheating: shading management, final users, indoor comfort, glare
- Prefabricated façade
- Protocols, certification, or verification processes (LEED, PassiveHouse, CasaClima, ….)
- Shading system
- Technical risks
- Thermal bridge
- Thermal insulation failure
- WWR

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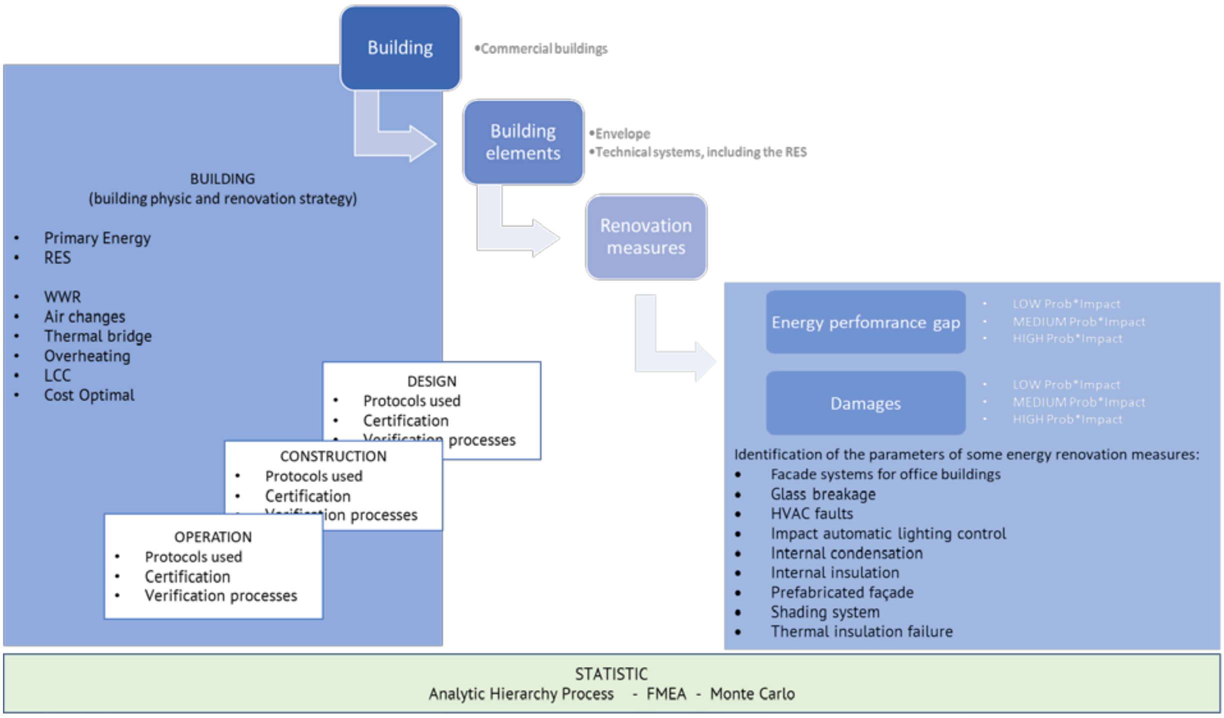

Figure 36 Literature reviews topics to identify the parameters that affects the cause-effects technical risks.

Concerning building services, a general definition and classification of faults was established. Three main categories have been identified: physical faults, faults related to inappropriate control sequencing and soft faults. Hard faults are breakages, deteriorations, malfunctions and failures. These problems may cause both a damage and a performance gap. In the case of inappropriate control sequencing and biased sensors (soft faults) the hypothesis of only a performance gap has been adopted. In this way we assume that the deviation from the planned investment weights negatively only on the energy efficiency building indicator.

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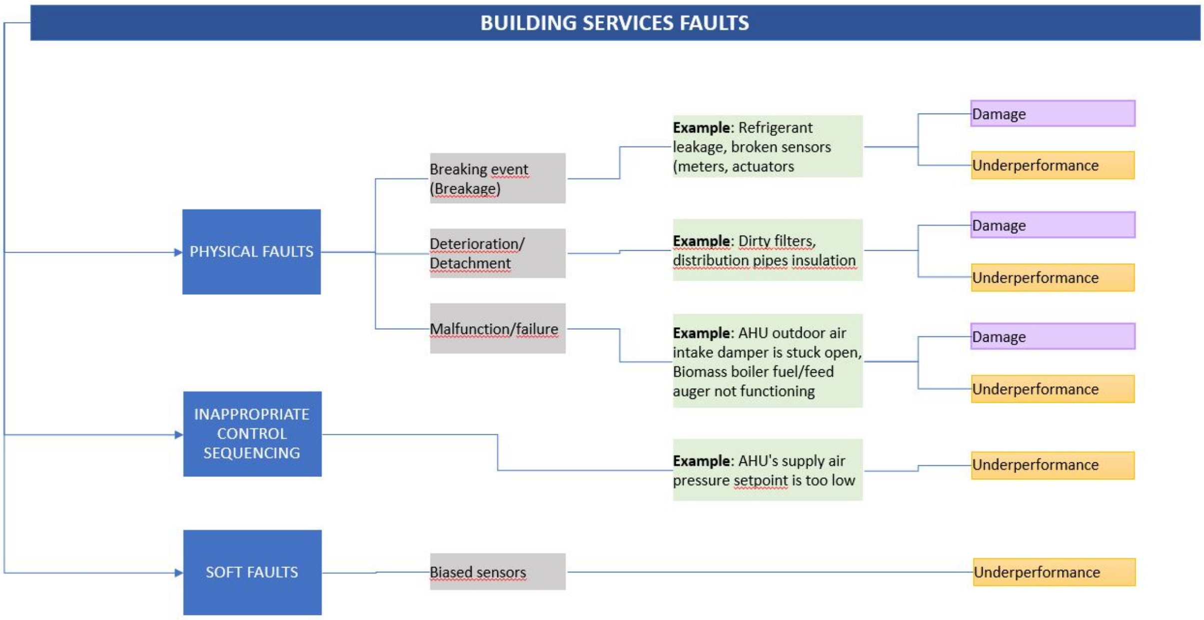

Figure 37 Building service faults structure.

3.3.2 Interviews

Interviews were carried out to identify the probability and the impact of each problem connected to each renovation scenario, composed of either one measure or a group of renovation measures.

Stakeholders involved in the interview:

- ESCO: building envelope elements and technical systems
- Building and facility managers: building envelope elements and technical systems (maintenance issues)
- Constructors: building envelope elements and technical systems
- Building experts: as architects for building envelope elements, or mechanic engineers for technical systems

The interviews are conducted in several steps. The first step is to take contact with the stakeholder, usually by mail and phone call. Once they accepted to participate at the interview, we organize a first call (teleconference call) where we present EEnvest project, final objective, WP2 and relative database. Showing the "Template on building elements and technical system", modified ad hoc for the interview, on the top a specific area to collect the unit measure that the stakeholder used (square meters, percentage of volume, number of buildings,…) in relation of his/her own personal experiences, Figure 38. During calls with the stakeholders an active dialogue is activated, and positive results achieved, as improvements on information and content template, and probability-impacts data collected. Currently three interviews have been made through online technology (also for COVID-19 issue) and 5 more are planned.

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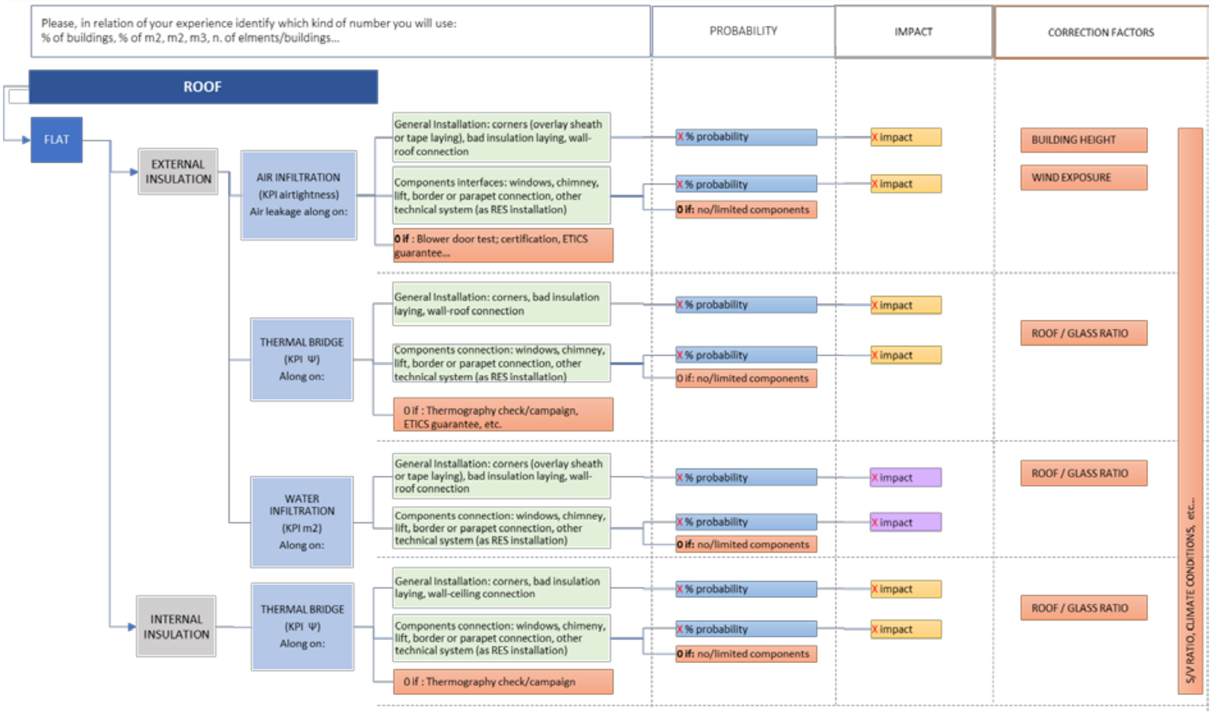

Figure 38 template for the interviews

3.3.3 Parametric energy performance simulation

Parametric energy performance simulation was used to determine the functional deviation, in terms of energy losses due to different reason, from malfunctioning to technical problems, both for the envelope and for the technical systems. We focused our efforts to identify missing data impacts that we did not extrapolate from the literature review or building experts knowledge (by interviews).

Parametric simulations were performed to estimate different impact levels of each predefined problem, varying building physic parameters or other technical parameters within a range of values coming from literatures or real experiences. The energy performance calculation tool was PHPP (Passive House Planning Package) in parallel with in-house tool elaborated ad hoc for parametric simulation (made by EURAC) developed to perform parametric analyses on many design input variables. [16].

Case by case, in relation to the building elements or technical system analysed, the inputs parameters are changed, to simulate several energy deviation scenarios, changing the parameters value of standard condition.

Here below a list of parameters and relevant assumptions used for the simulations:

Building parameters:

- climate conditions: three climates, HDD, wind exposure, orientation, etc.
- building dimensions: heating area, volume, Window/Wall ratio (WWR), etc.
- building shape: surface/volume ratio, etc.

General assumption used in the parametric simulation:

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- Good design level (design error effect is not considered)
    - Thermal bridge should be implemented in the calculation process by the user.
    - Related problems as indoor condensation should be verified by the user (or his experts).
    - These losses should be introduced in the energy performance calculation.
- Tool used: PHPP together with EURAC in-house parametrization tool
- Office building models, three different buildings with different dimension and architectonic features:
    - S/V ratio:
        - compact (0 < S/V < 0,20)
        - slightly irregular (0,20 < S/V < 0,70)
        - irregular complex (S/V >0,70)
    - Dimensions
    - WWR ratio:
        - low (WWR between 0-20%) as single windows
        - medium (WWR between 20-40%) important fenestration
        - high (WWR between 40-60%)
        - total fenestration (WWR over 60% - curtain wall)
- Building site, three climates:
    - North Europe (Nordic), Sweden, Stockholm
    - Central Europe (Temperate), France, Paris
    - South Europe (Mediterranean), Italy, Rome
- Other parametric inputs (as variable) will be identified step by step, in relation to the building elements evaluated and occurrences found. For example, in the windows we considered the energy losses coming from air infiltration and thermal bridge. Within PHPP we varied the parameters that describe it, like air change rate and the air pressure normally used for the Blower Door Test (50 Pascals).

Parametric simulation process is also used to verify the data found. It means that the value of the data found in the literature review on energy performance deviation (between predicted and real energy consumption of several commercial buildings) is been verified by energy simulation tool. The final value calculated should be close enough to the deviation value found in the simulation. Significant deviations from the comparisons with general data should be justified.

The parametric simulation results will be reported in the next deliverable, in each technical risk datasheet elaborated for the EEnvest technical risk database.

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4 DATABASE INDICATORS RESULT: TWO EXAMPLES

This chapter reports the results obtained from the research conducted on two building elements. We decided to show two positive examples in terms of collection and determination process of technical risk data details. Those elements are window element and district heating technology system.

4.1 WINDOW ELEMENT RISK INDICATORS

Focusing on the windows building element as renovation measure to improve energy efficiency, a breakdown structure referred to the main technical risks has been done (Figure 39). The definition of the breakdown structure has followed an iterative procedure that started with a very detailed technical issue list, both for the main problems (second column) and for the specific causes (third column), thanks to the literature review and real experiences. Subsequently, the breakdown structure has been improved and optimized thanks to the specific review through building experts' interviews, to arrive at the most suitable and representative technical risk assessment structure.

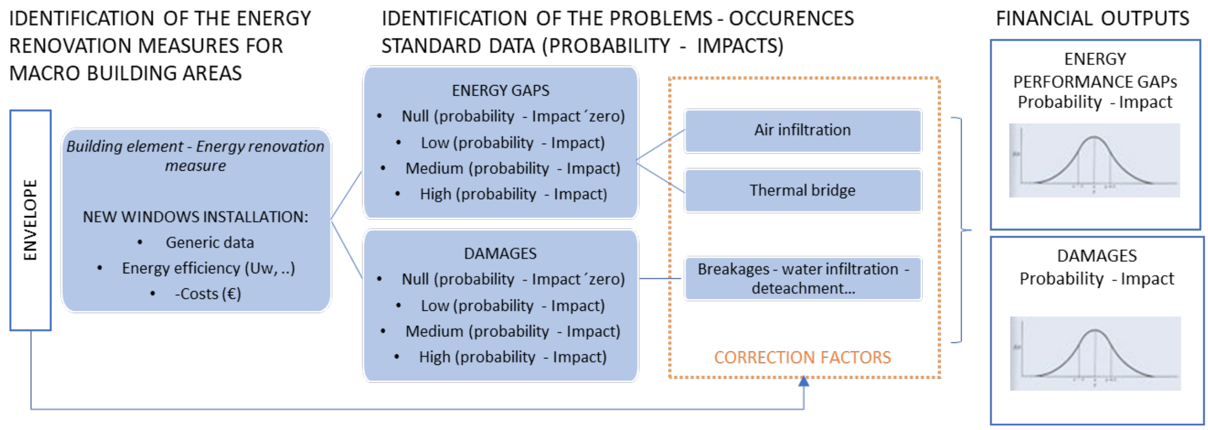

Figure 39. Windows - breakdown approach

4.1.1 Literature review

The literature review laid the foundation for the elaboration of the technical risk breakdown structure of each building elements, from the problem identification, to the definition of their impact-probability. Figure 40 displays how the data have been collected and structured: in yellow rectangle the impact of the energy performance gap, and in violet rectangle the impact of damage. In the datasheet alerts and correction factors are collected as well.

On the one hand, alerts are highlighted in red rectangles, as they represent potentially dangerous or difficult circumstances that users must consider. As an example, Figure 40 shows an alert on air condensation; this will be considered in both phases of the project development.

On the other hand, correction factors, highlighted in orange rectangle, report an indication, as in this case: "*0 if: Blower door test*". It means that in case of Blower Door Test the probability of this specific occurrence (air infiltration) is null.

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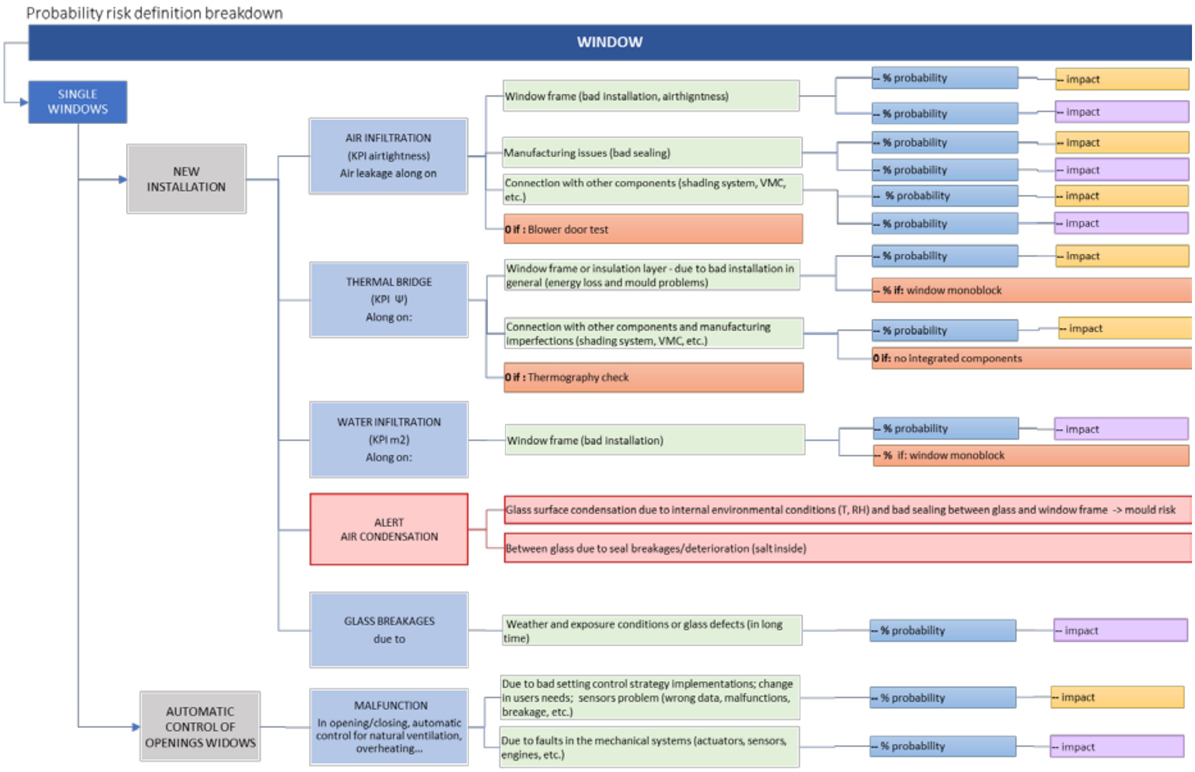

Figure 40. Window breakdown template: datasheet for EEnvest technical risk database.

An extensive literature review has been conducted, mainly focusing on the most common problems that affect the overall predicted performances of buildings and the main related damages that occur referred to the specific measures. This review has underlined the importance and the interest in these topics among the scientific community but also a poor quantity of reliable and specific data analysis reported in articles and scientific papers. This information lack can be referred due the unpredictability of these phenomenon and the poor reliable data set coming from real building performance monitoring. However, the literature review focused on the windows element presents some useful information, mostly related to the energy performance gap, from a large scale to a specific issue:

- Regarding the definition of the technical issues, in addition to the previous literature review, some further scientific papers have been analysed. As an example*, Yuting Qi et all,2019* defines, thanks to specific surveys among experts in the constructions sectors, a list of 25 quality failure problems in the renovation process of a building [7]. Even if the paper referred to residential buildings, the results are useful because the type of problematics related to windows replacement can be assimilated also in the non-residential buildings such as untreated wall around the new windows; misalignment between the doors and window and the wall; incorrect installations, etc. *(Yuting Qi, Queena K. Qian, Frits M. Meijer and Henk J. Visscher*) – see Figure 2 p. 14.

- Regarding the energy performance gap between the predicted and the real measurement, several papers have been analysed. In the IPEEC Performance gap report [5] the energy performance gap between the predicted and measured (Table 1– page 13) is well summarized and going deeply in some aspect such us a list of possible causes and construction quality defects such as bad airtightness of the windows and doors, etc.

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- Regarding the air infiltration impacts several sources have been retrieved. Som Shrestha et al. (2019) [17] and the Department of Energy USA 2014 [18] report in several papers, that the air infiltration in buildings is a fundamental part that can vary the impact on the energy performance between 15% to 20% of total energy consumption (data used for the data validation process, in Figure 34). Emmerich et al., (2005) [19] demonstrates that the impacts of the air infiltration in the U.S. office buildings, referred to the leak-free building, is up to an average of 33% of the total heating loads. Emmerich and Persily (2014) [20] also deeply analysed the variability of the air infiltration in commercial buildings referring to the building age, height, floor area, type of envelope and based on HDG. This information has become useful in defining the correction factors. Younes et al. (2012) [21] re-elaborated the data from Dickerhoff et al. (1982) [22] that performed a specific test regarding the air leakages in a residential building. Dickerhoff et al. (1982) defined, for each building component, the percentage impact related to the windows and doors, as an average of 15% of the total air infiltration. Even if this last paper is referred to the residential buildings, the specificity of the tests performed can give an important feedback and a useful percentage range regarding the single components air leakages impacts.

- Van Den Bossche and Janssens (2016) [23] performed and tested in lab conditions, water and airtightness on more than 437 windows with different configurations (sliding, single or double window) and materials (wood, PVC, aluminium). The results showed the differences between windows typologies and materials. Barnes et al. (2013) [24] investigate, through a finite-element analysis, the “installed thermal bridge” of a window frame especially referred to the sill connection comparing a well design detail with a traditional one. These data results useful among others being a reference data range for the thermal bridge impacts.

4.1.2 Interviews

A series of targeted interviews to window specialists were conducted. Interviews resulted very helpful for the final configuration of the technical risk structure breakdown, because the on-site and factual experiences of professionals in the field helped to identify specific problems and impacts. In this case, for new windows installation, during the interviews with the external experts and windows manufactures is been discussed and improved the technical risk structure (windows breakdown template and collected impact and probability of each occurrence. Figure 41 reports the data obtained by an interview, as impact information.

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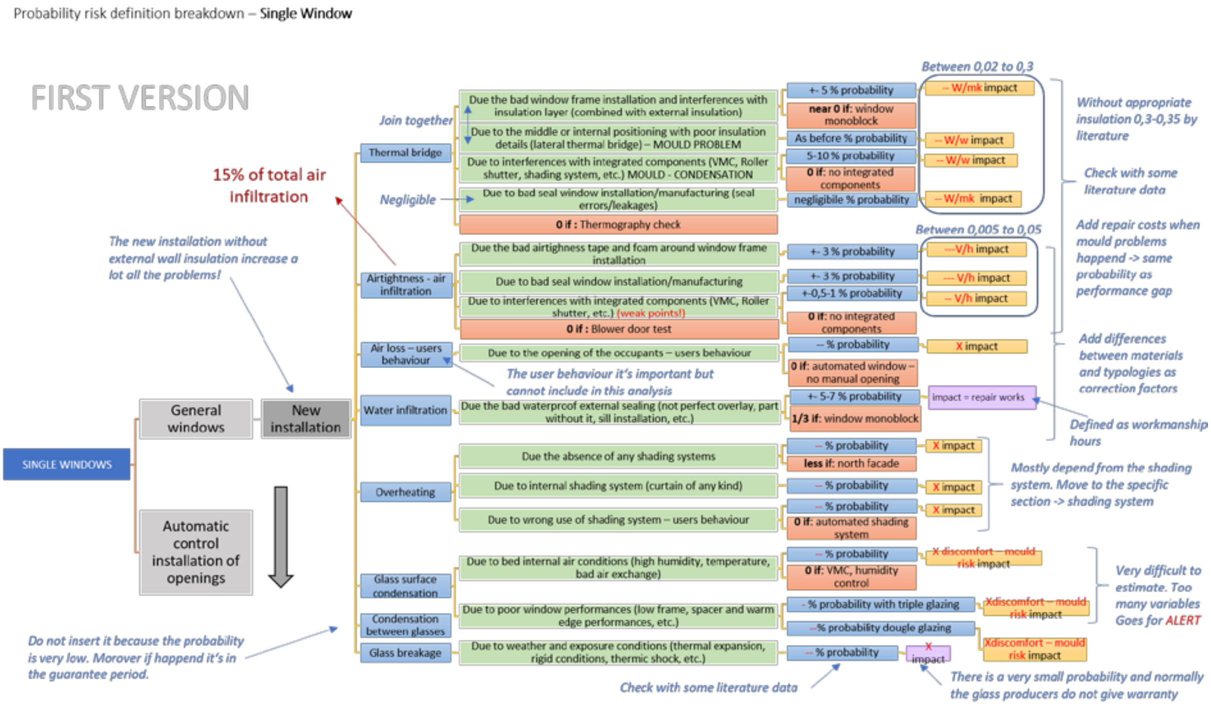

Figure 41. Example of window breakdown template with, in blue colour, the data values collected during an interview on energy performance gap and damage indicator.

In terms of energy performance gap (impact in yellow rectangle) window has two negative occurrences, air infiltration and thermal bridge. In terms of damage (impact in violet rectangle), the economic deviation is the cost due to repairs, with three level of configurations impact related to: company call fee, workmanship hours and materials. In this case, the measurement unit of the impact data is collected in rate change amount - volume/hour, in relation to the expert knowledge. Data inputs are being homogenized prior to use in the risk evaluation model. Through parametric energy simulation the energy performance gap in percentage of heating demand is determined, see next paragraph 4.1.3.

The damages identified in the new window installation are several, the same of energy gap as thermal bridge and air infiltration, plus water infiltration and glass breakage. The three level of damages identified for the windows are:

- low: company call fee, plus small intervention to repair a localized damage, plus reduced costs for the materials (foam, tapes, sheat, etc.);
- medium: company call fee, plus localized repair intervention with some substitution parts, or small demolitions with relative finishing works, plus costs for the materials (foam, tapes, plaster, painting, etc.);
- high: company call fee and an extensive repair intervention in both side (internal and external) with demolitions, relative repairing, and materials to the substitution of the part.

At the end, the team elaborated a window breakdown sheet (Figure 42) where information and data on both indicators (energy gap and damage) as % of investment was collected and later used in the energy performance simulations.

In the datasheet of the window breakdown all the data collected from literature and professional experts are reported (Figure 42 -Figure 45). For each occurrence a number is assigned (white rectangle on right side) that is later deeply analysed.

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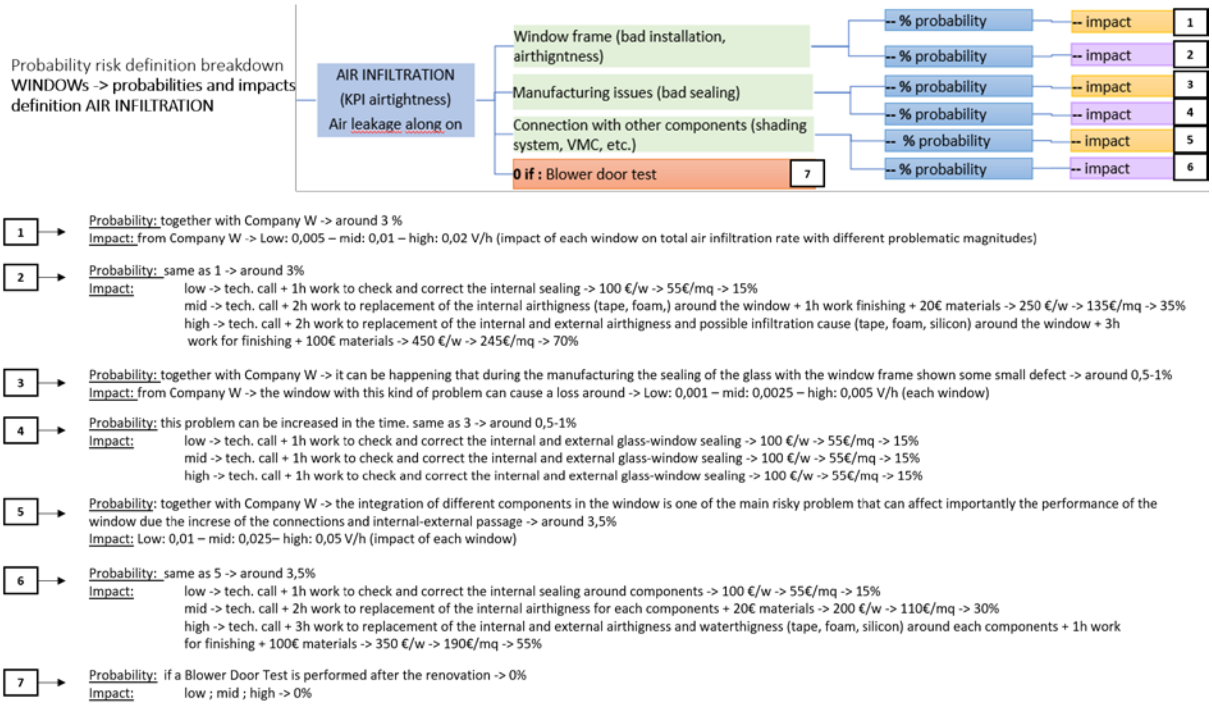

Figure 42. Window breakdown datasheet (1/4)- air infiltration occurrence - generated after the interviews.

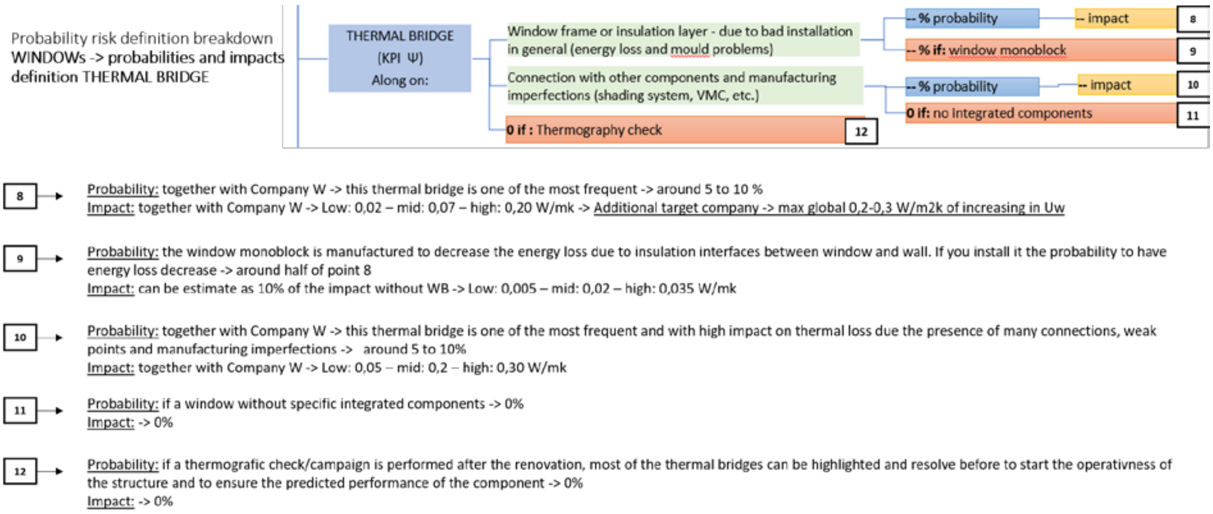

Figure 43 Window breakdown datasheet (2/4)- thermal bridge occurrence - generated after the interviews.

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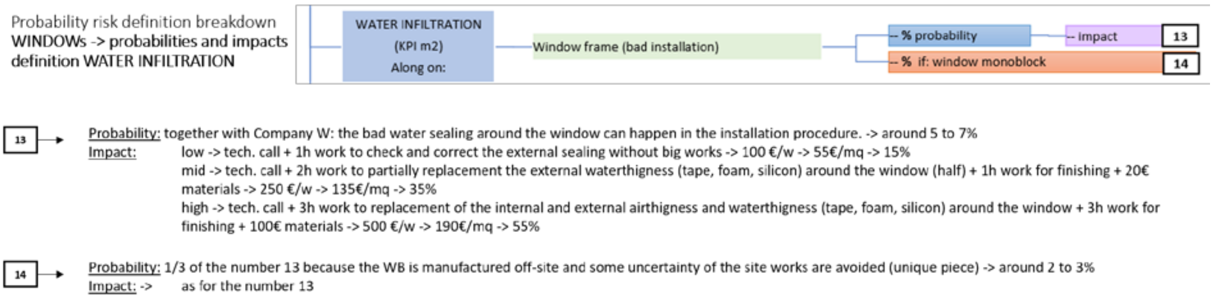

Figure 44 Window breakdown datasheet (3/4)- glass breakages - generated after the interviews.

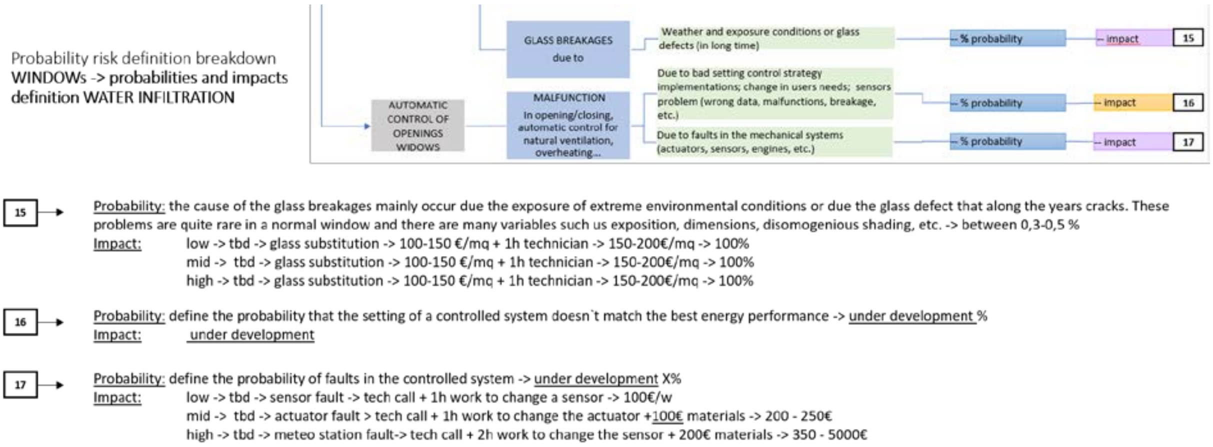

Figure 45 Window breakdown datasheet (4/4)- automatic control system failure-generated after the interviews.

Some data are missing because of lack of information and due the fact that the interviews are still undergoing. Most updated information on this activity will be provided in D2.2, together with the risk mitigation measures and design recommendations.

4.1.3 Parametric energy performance simulation

In the window element analysis, the energy gap as a deviation between planned energy performance and real energy consumption, can be produced by two occurrences: such air infiltration as thermal bridge. Parametric simulations are used to estimate (and later to verify) the possible variable impact of these occurrences, changing the inputs in the simulation from the standard condition (as air infiltration rate, or linear thermal bridge etc.).

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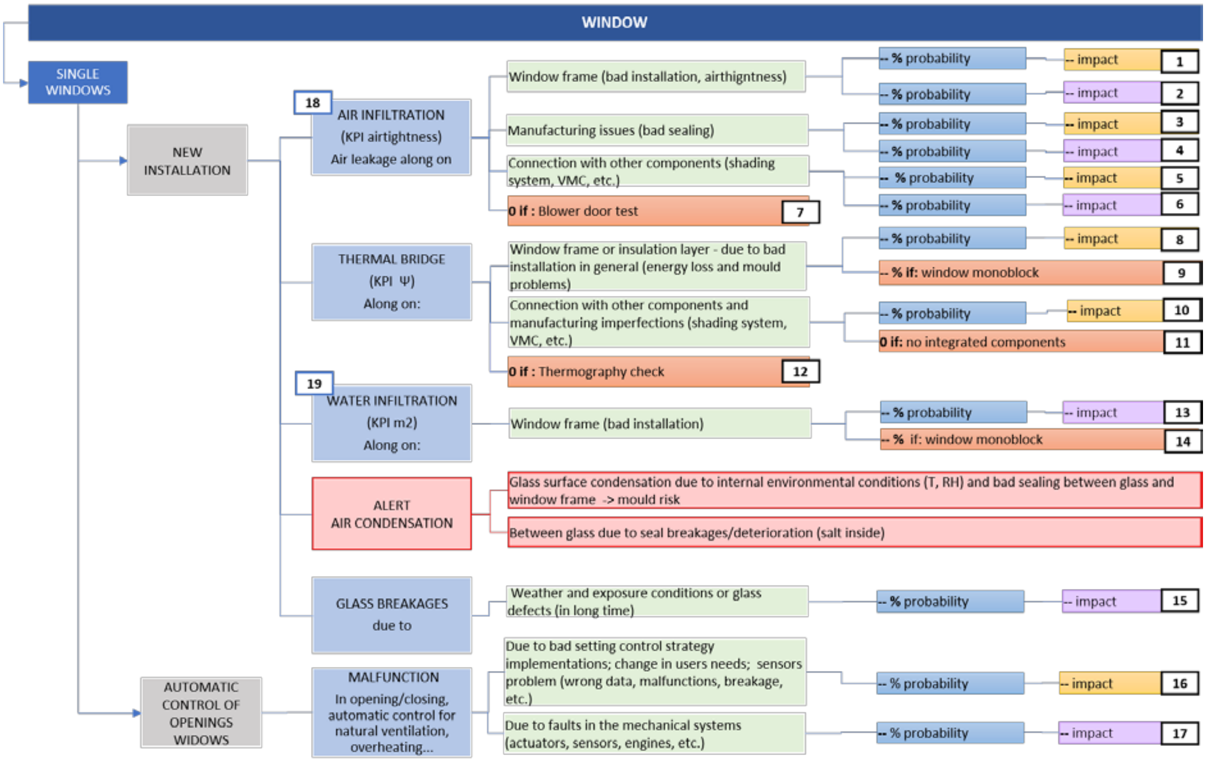

Figure 46. Windows risk probability breakdown definition template.

General assumption used in the parametric simulation:

- office Building site in Sweden NZEB as baseline
- calculation tool: Passive House Planning Package (PHPP)
- «standard» window dimensions from UNI EN ISO 10077
- variation values in the air infiltration and thermal bridge coming from literature and interview of companies
- prices/costs are defined with a simplified approach (see paragraph 5.1.2)

4.1.3.1 Parametric data inputs used for window – energy gap indicator

In the datasheet of the breakdown window, Figure 46, each occurrence (number in the white rectangle on right side) is deeply analysed, and a range of variable input values for parametric energy simulation is identified.

Air infiltration occurrence considered along window frame, integrated components, and manufacturing issues is deeply explained in Figure 47. Numbers 1,3,5: (i) definition of three different impacts (low, medium, high) of the air infiltration rate (n50) expressed in V/h that a standard window can have. (ii) definition of the infiltration rate (n50), from real data collected from literature and interviews and used in the simulation. (iii) energy deviation calculated in heating demand, is the differences between the baseline model and the parametric model, this last one calculated with a variable range of air infiltration rate, (iv) parametrization of the results in percentage (%) of the heating demand every sqm of windows area (%/m^2).

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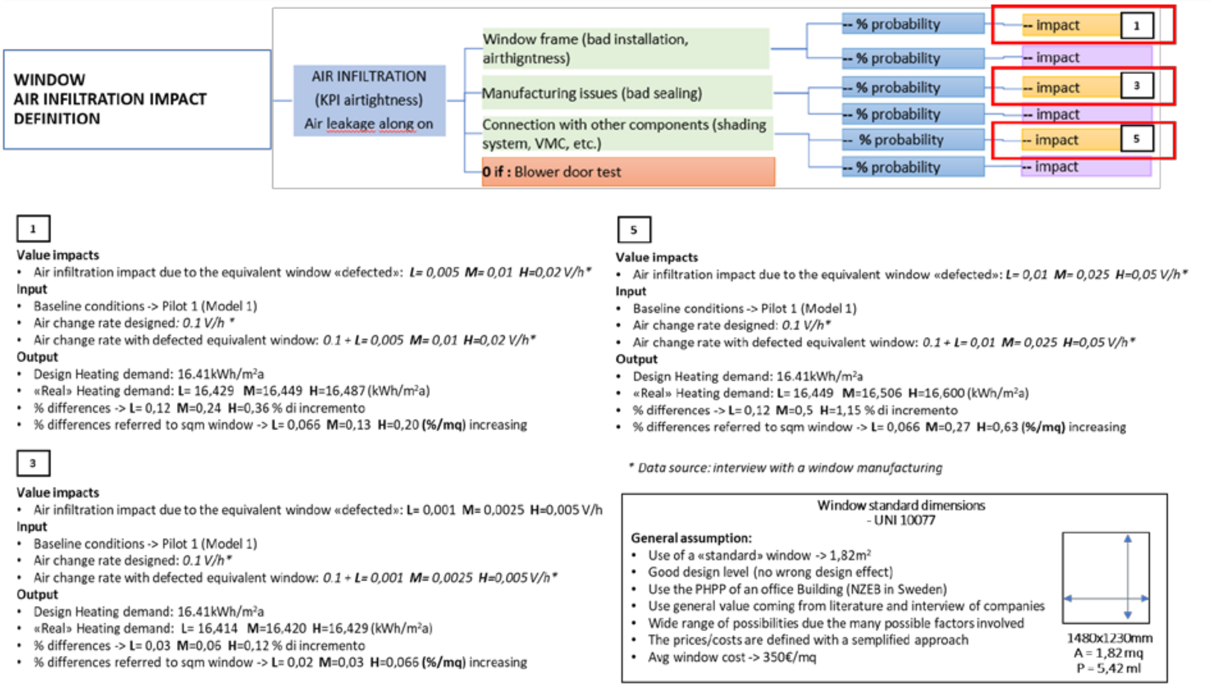

Figure 47. Example of data used in PHPP tool to define the air infiltration impact

Thermal bridge occurrence considered along on window frame and integrated components is reported in the Figure 48. Numbers 8, 10: (i) definition of three different configuration impacts (low, medium, high) expressed in W/mk (linear thermal bridge) that a standard window can have; (ii) increasing the linear thermal bridge values data in the PHPP baseline model; data value collected from literature and interviews, (iii) energy deviation calculated in heating demand, is the difference between the baseline model and the parametric model, this last one calculated with a variable thermal bridge length range; (iv) parametrization of the results in percentage (%) of the heating demand every sqm of windows area (%/ m^2).

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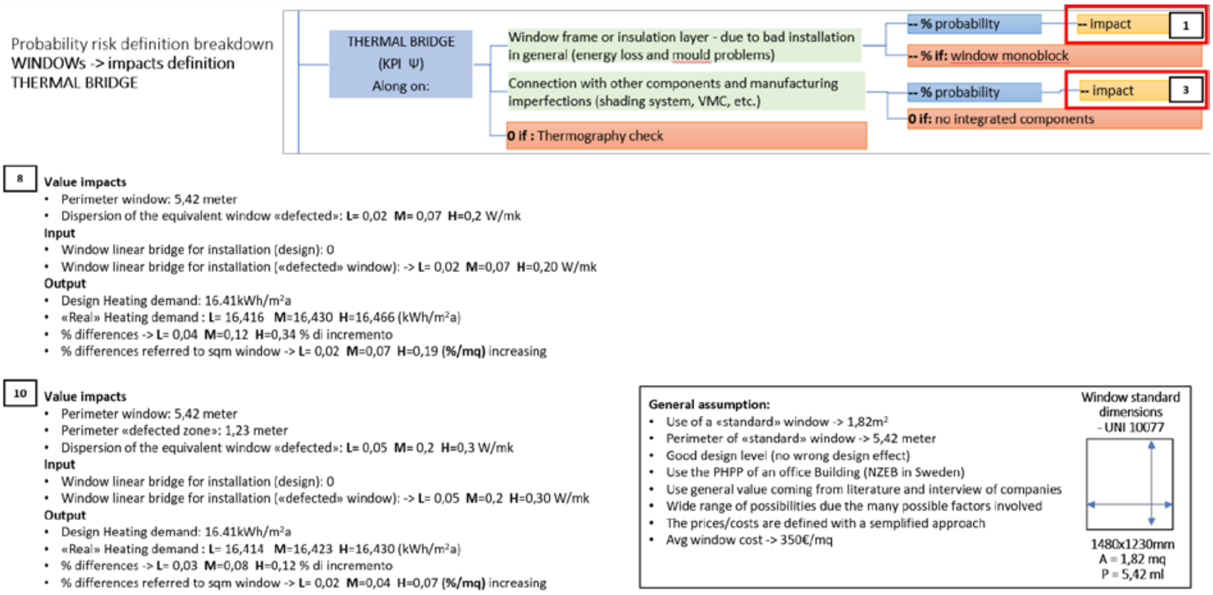

Figure 48 Example of data used in PHPP tool to define the thermal bridge impact

4.1.3.2Parametric data inputs used for window – damage indicator

Due to air infiltration, thermal bridge, and water infiltration. Numbers 2, 4, 6, 13, 15, 17: the definitions of these damages have been carried out defining three different possible magnitude impacts for each cause defining: (i) intervention cost; (ii) hours needed to perform the works multiply the unit cost; (iii) materials cost. (see paragraph 5.1.2)

4.1.4 Correction factors

Numbers 7, 9, 11, 12, 14, 18, 19: these correction factors have been defined as a percentage of reduction of a specific occurrence. In this case, in window element the Blower Door Test reduce to zero the presence of energy performance deviation due to the air infiltration, because the BDT made in the operation phase, verifying the final quality of the renovation work (installation phase) and the measures adopted in the design phase (planned phase).

4.1.5 Data validation/control process

Further general data coming from literature has been used as reference to check the overall impact of some problems. In order to validate the overall impact magnitude (probability combined with impacts) previously, defined (from literature, experts and simulation) a series of data comparisons have been done. The main scope of this task is to “validate” the impact probability trend for each energy renovation measure, matching different data found from literatures and interviews or obtained by energy performance simulation.

As example, the air infiltration problem calculated (paragraph 4.1.3.1) was compared with the general value coming from the literature (paragraph 4.1.1) and the results shown an acceptable deviation (Figure 49).

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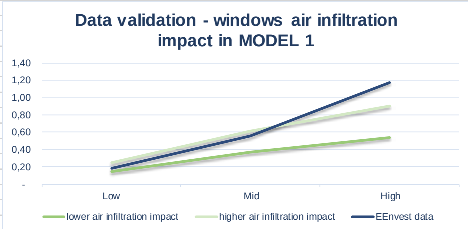
BASELINE			
Baseline Heating Demand MODEL 1 (NZEB Sweden)	16,410	kWh/m2a	
Totale window surface (glazing)	250,0	sqm	
Literature values			
OVER-CONSUMPTION (increases) -> for ventilation only! - GENERAL DA	overconsumptio	Baseline + overconsumption	
15%	2,4615	18,8715	
25%	4,1025	20,5125	
Literature values			
AIR INFILTRATION IMPACTS in each components - GENERAL DATA	min	avg	max
walls	18,0%	35,0%	50,0%
ceiling details / roof	3,0%	18,0%	30,0%
Forced air ventilation	3,0%	18,0%	28,0%
windows and doors	6,0%	15,0%	22,0%
fireplace (corridors, garages, stairs)	0,0%	12,0%	30,0%
vents leakages	2,0%	5,0%	12,0%



				on Baseline Heating Demand MODEL1					
				overconsumption (kWh/m2a)			Baseline + overconsumption (kWh/m2a)		
SIMPLIFIED WITH GENERAL DATA				low	mid	high	low	mid	high
components	15%			15%			15%		
windows and doors	0,90%	2,25%	3,30%	0,15	0,37	0,54	16,56	16,78	16,95
components	25%			25%			25%		
windows and doors	1,50%	3,75%	5,50%	0,25	0,62	0,90	16,66	17,03	17,31

AIR INFILTRATION WINDOW - Eenvest DATA			probability	sqm of windows		low	mid	high	
Validation / check!	Window frame	probability	3,00%	7,50		0,066%	0,130%	0,200%	
		if all probab				0,495%	0,975%	1,500%	
		impact				16,49	16,57	16,66	
	Components connection	probability	3,50%	8,75		0,066%	0,270%	0,630%	
		if all probab				0,578%	2,363%	5,513%	
		impact				16,50	16,80	17,31	
	Manufacturing	probability	0,75%	1,88		0,020%	0,030%	0,066%	
		if all probab				0,038%	0,056%	0,124%	
		impact				16,42	16,42	16,43	
					full probab togethe	0,18	0,56	1,17	(kWh/m2a)

Figure 49. Excel datasheet with comparison results for air infiltration impact

Figure 49 reports a summarization scheme of air infiltration impact with the description of the values used in the PHPP tool and the relative results, normalized in percentage on square meter of window (%/sqm w), following the process explained in the next paragraph.

On the top there is the heating demand of the baseline model, and below the increase amount due to air infiltration found in literature, corresponding to 15% and 25% of heating demand (calculated in kWh(m^{2}year). It is also reported the energy demand increase due to air infiltration divided for each building elements, in windows and door is 6-22%. At the end, air infiltration data variation are used as inputs in the energy parametric simulation to calculate for each different occurrence (window frame, components connections, manufacturing failures) three level of impact due to three level of air infiltration. The air infiltration impacts obtained from the simulation (EEnvest results blue line) were compared with the literature data (green lines), results in Figure 50.

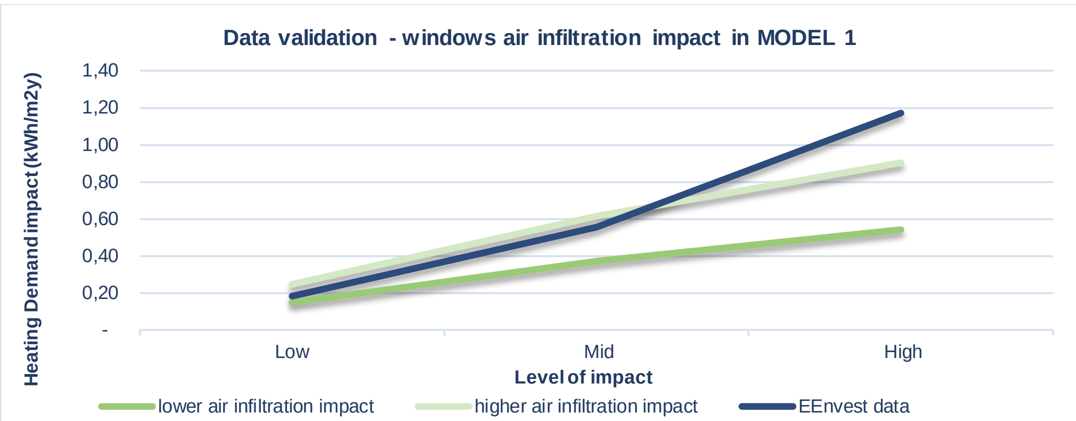


Figure 50. Results of the data validation for the air infiltration impact on windows

The data trend shows that for the low and medium impacts, EEnvest data are in line with the general data while the high impact, at first glance, seems over-estimated. This discrepancy could arise from certain main aspects linked to this calculation where the correction factors are not considered, as well as the fact that the dependency/independence between problems, and

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the general data usually found in the literature come from high energy performance commercial buildings.

4.1.6 Conclusion

The procedure developed to define the impacts is reflected in the simplified data validation process with a good level of approximation even if the high value is higher than the range defined with the general literature data. Moreover, in the EEnvest technical risk assessment, each impact is referred to a specific probability that the event occurs, producing a probabilistic trend of the deviation following three levels of impacts (low, medium and high). In this specific case, a specific datasheet for the window element, including a range of probabilistic impact trend is developed, Figure 51. It will be stored in the EEnvest technical risks database, together with all other envelope and building system elements.

INDICATORS (INPUTS)		
Heating Demand		kWh/m2y
Windows cost		€/m2 window

			SOURCE	SOURCE	simulation based on a nZEB office in Sweden						Based on 350€/sqm								
WINDOW			**Probability**		**Heating demand**						**Costs**						**Specific corrective factors**		
			Interview	Literature	low		mid		high		low		mid		high		Blower Door Test	Thermography	Certification
			(as % of windows that could have these problems)		% Inv.	Prob.	% Inv.	Prob.	% Inv.	Prob.	% Inv.	Prob.	% Inv.	Prob.	% Inv.	Prob.	yes	yes	yes
					(% of impact /sqm window)						(% related to cost of a new window)								
Single window	AIR INFILTRATION			15%															
		Window frame	3,00%		0,066%	25%	0,130%	50%	0,200%	25%							0%		
			3,00%								15%	40%	35%	40%	70%	20%	0%		
		Components connection	3,50%		0,066%	25%	0,270%	50%	0,630%	25%							0%		
			3,50%								15%	40%	30%	40%	55%	20%	0%		
		Manufacturing	0,75%		0,020%	50%	0,030%	25%	0,066%	25%							0%		
			0,75%								15%	33%	15%	33%	15%	33%	0%		
		Blower Door Test	0%																
	THERMAL BRIDGE																		
		Window frame	7,50%		0,020%	25%	0,070%	50%	0,190%	25%								0%	
		Components connection	7,50%		0,020%	25%	0,040%	25%	0,070%	50%								0%	
		Thermography	0%																
	WATER INFILTRATION																		
		Window frame	6,00%								15%	30%	35%	55%	55%	15%			
	GLASS BREAKAGEs																		
		Glass	0,40%								25%	33%	25%	33%	25%	33%			
	ALERT	CHECK THE AIR CONDENSATION IN GLASSES																	
Automatic control opening system	AUTOMATIC CONTROL SYSTEM																		
		window sensors	0,00%										50€/finestra						
		window actuator	0,00%								100 €/finestra				150 €/finestra				
		meteo station	0,00%								150 €				5.000 €				

Figure 51. Windows datasheet of EEnvest technical risks database

In Figure 51 are reported the technical risks of windows. On the left side there are the problems (air infiltration, thermal bridge, water infiltration, glass breakages) and the respective possible independent causes (such as air infiltration, windows frame, components connections, manufacturing failures). The technical risk data identified with impacts and a respectively probability is reported for both indicators, energy gap (in pink colours) and damage (in violet color). Their amounts (in term of percentage of investment) and relative probability, have been populated with values coming from literature review, expert interviews, internal expertise, or calculated through parametric energy simulation.

Furthermore, in the datasheet of each building elements are reported alerts (in red) and the correction factors (in brown). These last, are specific for each occurrence, and they run the technical risk calculation process, modifying the impact-probability. As an example, in the window, the blower door test verification reduces to zero the air infiltration, that means no energy performance deviation at the planned energy performance is due to air infiltration. In addition, a particular attention to the window details in the construction and mounting phase through specific test (thermography) or specific procedures (compliance with certification guidelines) should help to minimize these energy and damage impacts.

Correction factors are also used to modify the probabilistic curve of technical risk impact of different energy renovation scenario and different combination of solution set.

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4.2 DISTRICT HEATING RISK INDICATOR

As stated for the building envelope components, for building services too there is a lack of detailed information on probability and cost impacts of components' faults. Scientific literature is mainly focused on fault detection methods, however in some case, such as the displayed district heating component, reliable data could be found. In this part it is presented the technical risk data acquisition process used for the district heating component, a building technical system.

4.2.1 Literature review

The literature review on district heating substations was performed following the general breakdown structure for building services faults illustrated in Figure 52.

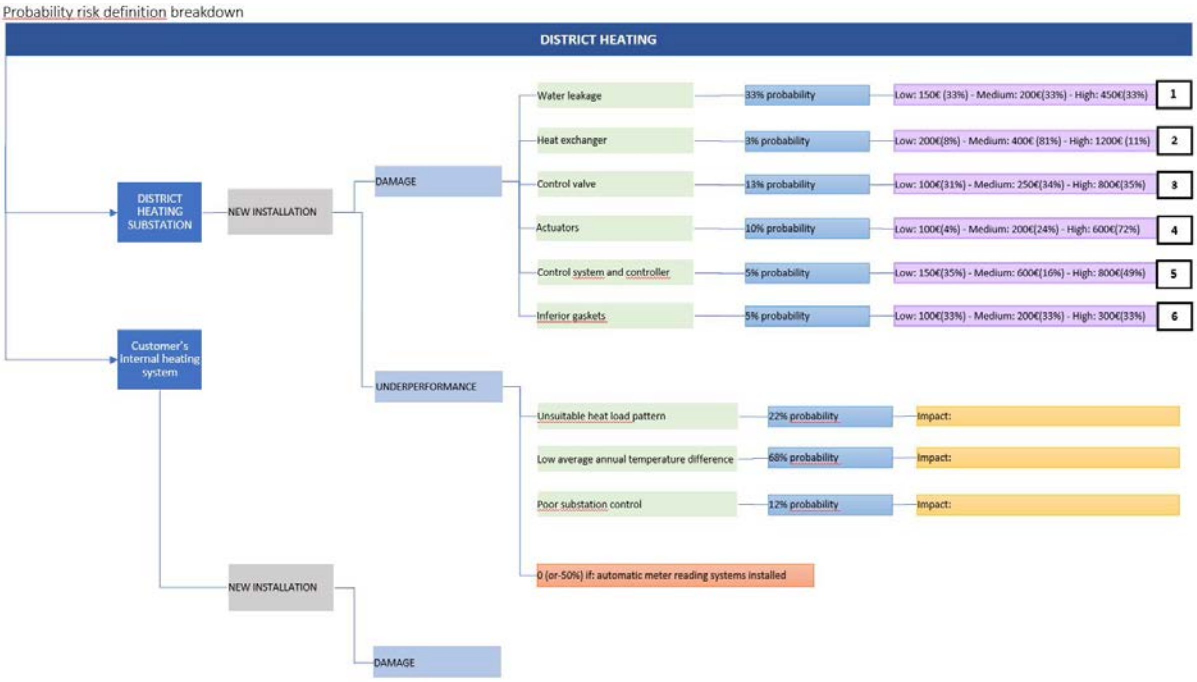

Figure 52. District heating breakdown technical risk structure template: probability and impact

Hyvärinen and Kohonen (1993) report that in district heating substation Fault Detection and Isolation methods (FDI) should consider the components. This statement confirms the selected approach, illustrated in this deliverable, which breaks down the renovation measure into its possible faults. Table 3 provides a breakdown of the most common faults found in components of a district heating substation.

Component	Fault

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Heat exchanger	Leakage, blockage, dirtiness
Valve	Stuck or binding, failure open or close, leakage
Controller	Drift, bias, hunting, faulty electronics, faulty computer program
Actuator	Shaft seizure or binding, failure open or close, bent or disconnected, linkage
Sensor	Bias, drift, poor location
Pipes	Clogging, leakage, faulty insulation

Table 3. District heating common faults (Pakanen, Hyvärinen, Kuismin, & Ahonen, 1996).

On the one hand, concerning damage probability, faults collected by Månsson et al. [25] which provided detailed data on faults in district heating customer installation in Swedish utilities, are in line with the data displayed in the previous table. According to this study many faults occur in the customers' internal heating systems or somewhere in the installation due to leakages.

Euroheat & Power[1], the international network for district energy, which promotes sustainable heating and cooling, provides information about district heating installation risk, reliability and durability. This data was used to define how many damaged district heating substations are to expect out of a sample of 100 substations investigated.

On the other hand, concerning energy performance gap probability, 135 district heating substations in Sweden were analysed in order to identify major faults through automatic meter reading systems. Three different fault groups were determined: unsuitable heat load pattern, low average annual temperature difference, and poor substation control [25]. These faults were present in 74% of the cases. In addition, the paper provided data concerning the occurrence of the single fault.

4.2.2 Damage determination

Månsson et al. [25] provided probability of a fault occurrence and its breakdown into the single fault type. Taking, for instance, the problem of faulty actuators, this occurs 3 times out of 100 faulty components reported. Among these, the study reports that 77% are broken actuators and 22% are seized actuators. This information has been used to determine the impact levels, replacing a broken actuator costs more (high impact) than the work required to repair a seized one (medium impact). Moreover, the percentage representing how many times this kind of faults have been found helps to give an indication on how the impact is distributed. In this example, the most probable case is the most relevant in terms of cost as well.

1 https://www.euroheat.org/

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Probability risk definition breakdown

DISTRICT HEATING -> probabilities and impacts definition

1

Probability: -> The largest fault category according to the survey was leakages (33%)
Impact: -> The faults that were included in the leakages category included leakages in all parts of the customer installation and substation.
low -> tech. call + 2h work to check and correct a small entity leakage -> **2%**
mid -> tech. call + 3h work to check and correct a medium entity leakage -> **3%**
high -> tech. call + 4h work to check and correct a large entity leakage -> **6%**

2

Probability: -> Problems in the heat exchanger (3%)
Impact: -> leakages were experienced to be the most common reason to faults in heat exchangers.
low -> tech. call + 3h work to tighten bolts/open and clean plates/change seals -> **3%** (fouling 4% + almost never an issue 4%)
mid -> tech. call + 6h work to weld broken parts -> **5%** (leakage 77% + 4% shell and tube heat exchanger)
high -> tech. call + 3h work to replace heat exchanger -> **16%** (cracking 7% + 4% broken heat exchanger plates)

3

Probability: -> Problems in the control valves (13%)
Impact: -> In this category, oversized control valves were reported as the most frequently occurring fault (35%). The two faults that were reported as second most common in the category were control valves leaking in a closed position (27%) and control valves seizing in a closed position (27%).
low -> tech. call + 1h work to unblock seized valve -> **1%** (seized in closed position 27%, seized in open position 4%)
mid -> tech. call + 4h work to dismantle, clean and correctly mount the valve -> **3%** (leaking gaskets 7%, leaks in closed position 27%)
high -> tech. call + 4h work to dismantle, change the valve -> **11%** (oversized 35%)

4

Probability: -> Problems in actuators (10%)
Impact: -> Due to wear and tear, the connection between the stem and the valve may become poor, or the actuator may break down.
low -> tech. call + 1h work to correct actuator stroke time-> **1%** (4%)
mid -> tech. call + 3h work to unblock seized actuator -> **3%** (22% + 2% poor connection actuator valve)
high -> tech. call + 4h work to replace defective actuator -> **8%** (70% + 2% do not close completely)

5

Probability: -> Problems in control system (5%)
Impact: -> 49% of the utilities answered that the most common fault was that the controller was broken. The second most common fault was broken temperature sensors (16%), and the third most common fault was temperature sensors giving the wrong signal (11%).
low -> tech. call + 2h work check and fix various sensor minor problems-> **2%** (35%)
mid -> tech. call + 4h work to replace temperature sensor -> **8%** (16%)
high -> tech. call + 4h work to replace controller -> **11%** (49%)

6

Probability: -> Problems in the gaskets (5%)
Impact: ->. **low ->** tech. call + 1h minor gasket problem -> **1%**
mid -> tech. call + 2h average gasket problem -> **3%**
high -> tech. call + 4h relevant gasket problem ->**4%**

Figure 53 Probability and impact definition for district heating

As a general consideration, the three damage levels were determined as follows:

- Low: company call fee, small intervention to repair a localized damage, reduced costs for the materials, replacement of minor components.
- Medium: company call fee, plus localized repair intervention with some parts substitution.
- High: company call fee and extensive repair or total component replacement, due to major damage.

Correction factors for the single components were identified. These factors act on the probability, changing its value if a condition is satisfied. The correction factors applied to the damage are:

- Certification: presence of a certification such as CE Directives/PED ensures a higher durability.
- Fouling detection: availability of a fouling detection system protects the heat exchanger from fouling related risks.

In addition to the specific correction factors, in commercial office buildings, the adoption of a maintenance program is a measure that prevents running costs from future increasing, achieves positive results due to a correct operation of the building system. Maintenance program can be considered a correction factor that reduces the technical risk indicators, decreasing the occurrences' probabilities to which it relates. Maintenance program is also considered a mitigation measure.

Building commissioning is a cost-effective measure, which ensures that buildings in the operation phase deliver the performance and energy savings defined in the design phase. When implemented, it reduces the technical risk both in terms of energy performance gap and damage indicators, because buildings tend to have a higher energy efficiency and lower

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maintenance costs. In this sense, commissioning is considered a systematic approach to quality assurance and performance risk management [26]. Therefore, in EEnvest framework, it is treated as a correction factor and a mitigation measure.

4.2.3 Energy performance gap

Thanks to the literature review, the probability related to the faults, which are responsible for an energy performance gap, could be determined [25]. However, no data for impact determination was available. Hence, a parametric study on 4 case studies which implement district heating system across Europe was conducted. The 'efficiency district heating net' parameter of the corresponding PHPP model was arbitrary varied between 100% and 85%, the resulting Primary Energy Renewable (PER) was observed (Figure 54). For instance, an efficiency degradation of 10% causes a corresponding primary energy increase of about 6%. These results permitted to estimate the impact in terms of kWh/m²a of the three faults.

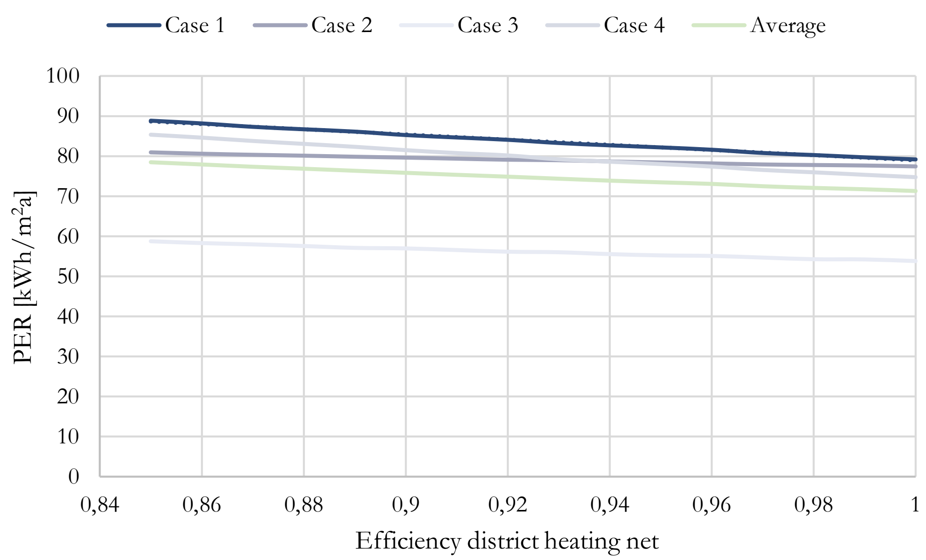

Figure 54. Parametric study efficiency impact on PER.

One of the most relevant outcomes of the above-mentioned study is that an automatic meter reading system can assure an effective fault detection, for this reason the presence of such system was inserted as a correction factor and therefore as a mitigation measure in EEnvest approach.

4.2.4 Conclusion

In conclusion, the data derived from literature sources was condensed in Figure 55. The column on the left reports the probability values; first a general value, which represents how many faulty district heating substations out of 100 installed substations are expected. Among these systems faults are distributed as indicated by the other percentages associated. Damage and energy performance gap impact have been divided in 3 levels (low, mid, high). For each level the impact is represented by a percentage of initial investment cost and a probability this event occurs. Finally, a column for components lifespan and correction factors were included

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MEASURE			DATABASE																		
DISTRICT HEATING			PROBABILITY		ENERGY PERFORMANCE GAP						DAMAGE						LIFESPAN	CORRECTION FACTORS		
			Literature	Interview	Heating demand						Investment cost									
					LOW		MID		HIGH		LOW		MID		HIGH			Automatic meter reading system	Certification (PED, F101/F103-	Fouling detection
					% Inv.	Prob.	% Inv.	Prob.	% Inv.	Prob.	% Inv.	Prob.	% Inv.	Prob.	% Inv.	Prob.				
																		Yes/No	Yes/No	Yes/No
DISTRICT HEATING SUBSTATION	DAMAGES		35%									20		40		40				
		Water leakage	33%								2%	33,3%	3%	33,3%	6%	33,3%	20		0,5	
		Heat exchanger	3%								3%	8,0%	5%	81,0%	16%	11,0%	15		0,5	1,0
		Control Valve	13%								1%	31,0%	3%	34,0%	11%	35,0%	15		0,5	
		Actuators	10%								1%	4,0%	3%	24,0%	8%	72,0%	10		0,5	
		Control system and controller	5%								2%	35,0%	8%	16,0%	11%	49,0%	20		0,5	
		Inferior gaskets	5%								1%	33,3%	3%	33,3%	4%	33,3%	10		0,5	
		Circulation pumps		1%							1%	33,3%	3%	33,3%	4%	33,3%	15		0,5	
	ENERGY PERFORMANCE GAP		74%																	
		Unsuitable heat load pattern	22%		1%	33%	2%	33%	5%	33%								1,0		
		Low average annual temperature difference	68%		1%	33%	2%	33%	5%	33%								1,0		
		Poor substation control	12%		3%	33%	5%	33%	10%	33%								1,0		

Figure 55. Conclusion: damages of district heating

In this section, the methodology for analysing damages was applied to one component of building services. In addition to the planned interviews, a simulation campaign, as done in the case of the window element, will be implemented here as well, to determine the risk associated to performance gap.

Eventually, risk data (probability and impact) of each component needs to be put together, assembling the risk for the district heating technology. The hypothesis of independence of the different problems has been assumed for two reasons: on the one hand because no data was found in literature which could help to describe a dependence of a problem from one other; on the other hand this level of detail outmatch the project purpose.

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5 DATA MANAGEMENT IN WP2

H2020 projects require consortiums to describe the plan for management of data retrieved, used and analyzed during the project. The full description of the data management is part of WP1 – Project Management, deliverable D1.3 - Data Management Plan.

In order to make it easier for the reader to consolidate the information about data management in the different WPs, this paragraph is meant to list and describe the data and information that were used for the development of Work package 2, this deliverable and EEnvest technical risk database.

The technical risk data collected in the WP2 comes from (i) literature, on several articles on different topics, in part reported in the Bibliography, (ii) interviews to building experts, building manager, Building and facility managers, Constructors, ESCO (iii) energy performance simulation.

Management of data – Technical Risk Database			
Source of data	Literature	Interviews Single and private interviews	Energy performance simulation
Use of data	Technical risk data will be collected to create the database: identification of the occurrences, cause-effects process, and impact-probability.	Interview's focus changes in relation to the stakeholders involved: • ESCO: building envelope elements and technical systems • Building and facility managers: building envelope elements and technical systems (maintenance issues) • Constructors: building envelope elements and technical systems • Building experts: as architects for building envelope elements, or mechanic engineers for technical systems Data and information collected are and will be used mainly to define the technical risks occurrences, impact and probability, and in the energy simulation. These data are no public. The data, one time analyzed and homogenized using a same unit of measurement, will be integrated in the EEnvest technical risk database, in the platform.	The results obtained from the energy simulation process will be collected in the EEnvest technical risk database, in the platform.
Storage Location	MS Sharepoint folder, shared with the EEnvest Consortium project partners and EURAC server	EURAC server – private data	MS Sharepoint folder, shared with the EEnvest Consortium project partners and EURAC server
Expected results	EEnvest technical risk database, in the platform.		
Relation with other WPs	EEnvest database and technical risk calculation process will be uploaded in the EEnvest web platform, WP5. The probabilistic trend of each occurrences (impact-probability) will be used in WP3.		

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6 CONCLUSION

This report presents the work done in WP2 on technical risks of energy renovation of commercial building, from the definition to the assessment.

Technical risk analysis in building sector is a complex and multi-faceted theme that depends on several cause-effect choices taken from different experts (design teams, constructors, investors, users…) at different staged of the building projects (design, construction or operation). Within EEnvest project, the indicators identified to carry out the technical risk analysis and the relative economic deviation from the investment are two: the *energy performance gap* indicator and the *damage indicator* he energy performance gap and the damage.

The report describes the analysis process used for the determination of technical risks indicators, which in turn are used to determine the economic deviation for a possible renovation investment of a commercial building, defined to estimate technical risk and therefore the probable economic losses connected. The first one estimates the energy performance deviation between predicted and real energy consumption; the second one takes into account economic losses due to malfunctioning, errors, failure or breakages of the installed components. Both indicators (D51) will be used independently in the evaluation of the business plan in the EEnvest web-platform (WP5).

Furthermore, in this report the technical risk calculation method developed for EEnvest web-platform is described, from the inputs (building features) to the outputs (economic indicators). Technical risk calculation flow is activated user, and through a statistic calculation method, permits to extract the final value of the two technical risk indicators, with a range of probability-impact, as percentage of investment. This calculation process takes place thanks to the EEnvest technical risk database, where several trend probabilistic impacts of energy performance gap and damage of each building element and technical system are collected. The top-down approach followed to establish the methodology started with a deep literature analysis. The technical risk data collected from literature was cross-checked with the real experiences of experts, through interviews. Missing data on risk impact on the investment was calculated through parametric simulations.

Currently, the data collection process is under development. The next deliverable in WP2 (D2.2) will contain the technical risk datasheet of building's elements and technical systems (EEnvest technical risk database), in term of numeric impact and completed with mitigation measures.

In D2.1 the technical risk calculation methodology developed in WP2 is reported, with the support of the other PPs: SINLOC and POLIMI for data set organization, calculation and managing of EEnvest technical risk database.

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Bibliography

[1] ISO, “ISO 31000:2009(en) Risk management — Principles and guidelines,” https://www.iso.org/obp/ui/#iso:std:iso:31000:ed-1:v1:en:term:2.17, International Organization for Standardization, 2009.

[2] “Wikipedia,” 2019. [Online]. Available: https://en.wikipedia.org/wiki/Risk. [Accessed 17 12 2019].

[3] Businessdictionary, 01 10 2019. [Online]. Available: http://www.businessdictionary.com/definition/technical-risk.html.

[4] ISO , “Risk management — Vocabulary — Guidelines for use in standards PD ISO/IEC Guide 73:2002,” British Standards, International Organization for Standardization, 2002.

[5] IPEEC, “Building Energy Performance Gap Issues. An International Review.,” International Partnership for Energy Efficiency Cooperation, Building Energy Efficiency Taskgroup, 2019.

[6] Chris van Dronkelaar, Mark Dowson, Catalina Spataru, Dejan Mumovic, “A Review of the Regulatory energy Performance Gap and its Underlying Causes in Non-domestic Buildings,” *Frontiers in Mechanical Engineeering,* vol. 1, no. Article 17, 13 January 2016.

[7] Yuting Qi, Queena K. Qian, Frits M. Meijer, Henk J. Visscher, “Identification of Quality Failures in Building Energy Renovation Projects in Northern China,” *MDPI ,* vol. 11, no. Sustainability, p. 4203, 3 August 2019.

[8] Saverio Mecca and Marco Masera, “TECHNICAL RISK ANALYSIS IN CONSTRUCTION BY MEANS OF FMEA METHODOLOGY,” in *Liverpool John Moores University*, 15th Annual ARCOM Conference, 1999.

[9] A. Maged, Composite FMEA for risk assessment in the construction projects, master of science in managment engineering ed., Politecnicao di Milano Como Campus School of industrial and infomration engineering, 2014.

[10] R. W. Saaty, “The Analytic Hierachy Process - What it is and how it is used,” *http://dx.doi.org/10.1016/0270-0255(87)90473-8.,* vol. 9, no. Math. model, pp. 161-176, 1987.

[11] Francesca Roberti, Ulrich Filippi Oberegger, Elena Lucchi, Alexandra Troi, “Energy retrofit and conservation of a historic building using multi-objective optimization and an analytic hierarchy process,” *Elsevier,* vol. 138, no. Energy and Buildings, pp. 1-10, 2017.

[12] Xing Shi, Binghui Si, Jiangshan Zhao, Zhichao Tian, Chao Wang, Xing Jin, Xin Zhou, “Magnitude, causes, and solutions of the performance gap of buildings: a review,” *MDPI,* vol. 11, no. Sustainability, p. 937, 2019.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement n° 833112

[13] Elena Cuerda, Olivia Guerra-Santin, Juan JoséSendra, Fco. Javier Neila, "Understanding the performance gap in energy retrofitting: Measured input data for adjusting building simulation models," *Elsevier - Energy & Buildings ,* p. 209, 2020.

[14] P. d. Wilde, "The gap between predicted and measured energy performance ofbuildings: A framework for investigation," *Elsevier,* vol. 41, no. Automation in Construction, p. 40–49, 2014.

[15] Christopher. M. Stoppel, Fernanda Leite, "Evaluating building energy model performance of LEED buildings: Identifying potential sources of error through aggregate analysis," *Elsevier,* vol. 65, no. Energy and Buildings, p. 185–196, 2013.

[16] Giulia Paoletti, Stefano Avesani,Dagmar Exner,Roberto Lollini, "Designing low energy buildings: application of a parametric tool and case studies," Louvain La Neuve, Belgium, PLEA 2011.

[17] Som Shrestha, Andre Desjarlais, Laverne Dalgleish, Lisa C. Ng, Diana Hun, Steven J. Emmerich, Gina Accawi, "Moisture Transfer in Commercial Buildings due to the Air Leakage: A New Feature in the Online Airtightness Savings Calculator," U.S. Department of Commerce , Clearwater, FL, 2019.

[18] Som Shrestha, Lisa Ng, Steven Emmerich, Diana Hun, Andre Desjarlais, Laverne Dalgleish, "Online Airtightness Savings Calculator forCommercial Buildings in the US, Canada and China," UT-Battelle, LLC, under Contract No. DE-AC05-00OR22725 with the U.S. Department of Energy., 2014.

[19] Steven J. Emmerich, Andrew K. Persily, Timothy P. McDowell, "Impact of Infiltration on Heating and Cooling Loads in U.S. Office Buildings," 2005.

[20] Steven J. Emmerich, Andrew K. Persily, "Analysis of U.S Commercial Building Envelope Air Leakage Database to Support Sustainable Building Design," *The International Journal of Ventilation,* vol. 14, no. 4, 2014.

[21] Chadi Younes, Caesar Abi Shdid, Gima Bitsuamlak, "Air infiltration through building envelopes: A review," *Editors Choice Collection ,* vol. 35, no. 3, pp. 267-302, 2012.

[22] Dickerhoff, DJ, Grimsrud, DT, Lipshutz, RD, "Component leakage testing in residential buildings," in *Proceedings of the American Council for an Energy-Efficient Economy*, Santa Cruz, CA,, 1982.

[23] Nathan Van Den Bossche,Arnold Janssens, "Airtightness and watertightness of window frames: Comparison of performance and requirements," *Elsevier,* vol. 110, no. building and Environment, pp. 129-139, 2016.

[24] Benjamin Barnes, Axy Pagán-Vázquez, Richard Liesen, Justine Yu, Nicholas Alexander, "Window Related Thermal Bridges," ASHRAE , 2013.

[25] H. Gadd and S. Werner, "Fault detection in district heating substations," *Applied Energy,* pp. 51-59, 2015.

[26] E. Mills, "Building commissioning: a golden opportunity for reducing energy costs and greenhouse gas emissions in the United States," *Energy Efficiency,* pp. 145-173, 2011.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement n° 833112

[27] Turner C, Frankel M, “Energy Performance of LEED ® for New Construction Buildings,” *Mendeley,* vol. New Buildings Institute, no. https://www.mendeley.com/catalogue/72444923-cd61-3c5a-a36d-1d1857521bff/, pp. 1-42, 2008.

[28] Carbon Trust 2011, “Closing the gap: Lessons learned on realizing the potential of low carbon buildings.,” Carbon Trust, Londoon, July 2011.

[29] Green Building Council Australia (GBCA), “Achieving the Green Dream: Predicted vs. Actual.,” GBCA, August 2013.

[30] Jouko Pakanen, Juhani Hyvärinen, Juha Kuismin & Markku Ahonen, Functional description of a district heating substation, VTT OFFSETPAINO, ESPOO 1996 ed., Vols. ISBN 951-38-4975-9, J. –. UTGIVARE, Ed., VTT Building Technology, 1996.

[31] Juhani Hyvärinen, Reijo Kohonen, “A system concept for real-time simulation of HVAC systems for building optimization, fault detection and diagnosis (BOFD),” *IEA Energy Conservation News,* no. 17, pp. 8-13, 1993.

[32] Sara Månssona, Per-Olof Johansson Kallioniemi, Marcus Therna Tijs Van Oevelen, Kerstin Sernhed, “Faults in district heating customer installations and ways to approach them: Experiences from Swedish utilities,” *ELSEVIER,* vol. 180, no. Energy, pp. 163-174, 2019.

[33] S. Månsson, P.-O. J. Kallioniemi, M. Thern and T. Van Oevelen, “Faults in district heating customer installations and ways to approach them: Experiences from Swedish utilities,” *Energy,* pp. 163-174, 2019.

[34] J. Pakanen, J. Hyvärinen, J. Kuismin and M. Ahonen, “Fault diagnosis methods for district heating substations,” *VTT Building Technology,* 1996.

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Annex A Combination method of technical risk

1 Document version

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2 Objective

The goal is to determine the probability of investment increase in percent related to a combination of issues or failures encountered during building design and operation (henceforth called a *risk* factor or simply a *factor*). This information is important, e.g., for investors.
To this aim, it is necessary to combine the investment increases and respective probabilities of occurrence caused by each single issue. This data is a required input to the calculation.
Note: the approach described in the following can be applied to determine the energy gap, i.e., the increase in building energy use intensity as quantified, e.g., in percentage of kWh/m2a. The only difference is that the investment increase has to be replaced by the energy gap.

3 Inputs

For each factor to be considered, a table specifying the investment increase and respective probability of occurrence is required. In the following, we consider the example of two factors (random variables) *X* and *Y* and assume the data summarized in Tables 1 and 2.

Investment increase	Probability of occurrence
0	0.97
0.066	0.0075
0.13	0.015
0.2	0.0075

Table 1: Data for factor *X*

Investment increase	Probability of occurrence
0	0.965
0.066	0.00875
0.27	0.0175
0.63	0.00875

Table 2: Data for factor *Y*

This data must be provided as input. We consider the investment increase in terms of a fixed monetary unit (e.g., 1000 Euro). If the base investment (total investment to construct the building) is the same for all factors, this amount can be easily translated into investment increase percentages.

Table 1 is to be interpreted as follows. If nothing goes wrong with factor *X*, there is no increase in investment. This happens in 97% of the cases, because the probability of occurrence of zero investment increase is 0.97. For instance, if factor *X* refers to the installation of 1 m2 of a transparent envelope construction element (a “window”), then we would expect about 3 m2 to be “faulty” on average for every 100 m2 of this element deployed. The remaining entries in Table 1 refer to the different severities in faulty installations. A low (less severe) investment increase of 0.066 occurs in 0.75% of deployed elements. A moderate investment increase of 0.13 occurs in 1.5% of deployed elements, and so on.

4 Calculation

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The *probability mass function* (pmf) for the combined influence of factors *X* and *Y* is given by a random variable $Z = X + Y$. The pmf of *Z* indicates the discrete probability distribution for all possible total investment increases caused by all possible combinations of outcomes for factors *X* and *Y*.
If factors *X* and *Y* are independent, it is calculated as follows.

$$P(Z = z) = \sum_x P(X = x)P(Y = z - x) \tag{1}$$

Expressed in words, the probability that the total investment increase is *z* is given as a sum over all possible investment increases *x* caused by factor *X*. Each such *x* gives a term in the sum, which is the probability that an investment increase of *x* is caused by factor *X* multiplied by the probability that an investment increase of $z - x$ is caused by factor *Y*.
In the following we assume that factors *X* and *Y* are independent, which means that Equation 1 holds.

5 Direct approach algorithm

To compute the *pmf* for *Z*, a basic algorithm goes as follows. We assume that a set *X* of tuples *(Ix, Px)* containing all possible investment increases *Ix* and associated probabilities *Px* related to factor *X* is given. Analogously, a set *Y* containing tuples *(Iy , Py)* is given.
Create an empty set *Z*, which will hold tuples *(Iz , Pz)* containing all possible total investments *Iz* and associated probabilities *Pz* .
For all possible investment increases *Ix* caused by *X* (loop over the set *X*):
    For all possible investment increases *Iy* caused by *Y* (loop over the set *Y*):
        Compute the total investment increase *Iz* = *Ix* + *Iy* .
        Compute *P* = *Px* + *Py* .
        If *Iz* appears in a tuple in *Z*:
            Add *P* to *Pz* in tuple *(Iz , Pz)*.
        Else:
            Add tuple *(Iz , P)* to set *Z*.

6 Exact result

The exact result for the overall investment increase probability distribution *Z* with inputs given in Tables 1 and 2 obtained by applying the algorithm in Section 5 is shown in Table 3.

Investment increase	Probability of occurrence
0	0.93605
0.066	0.015725
0.13	0.014475
0.132	6.5625e-5
0.196	0.00013125
0.2	0.0072375
0.266	6.5625e-5
0.27	0.016975
0.336	0.00013125
0.4	0.0002625
0.47	0.00013125
0.63	0.0084875
0.696	6.5625e-05
0.76	0.00013125
0.83	6.5625e-05

Table 3: Exact probability mass function for factor $Z = X + Y$

7 Scalability

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For more than two factors, the algorithm given in Section 5 can simply be applied multiple times, adding one factor at a time. For instance, the pmf of $Z = X1 + X2 + X3$ for three independent factors $X1$, $X2$, $X3$ is calculated by first calculating $Zt = X1 + X2$ and then calculating $Z = Zt + X3$.
While an exact calculation is preferable for a small number of factors, the algorithm given in Section 5 does not scale up well, because it requires two nested loops and a search in the innermost loop. Therefore, although applicable in principle for an arbitrary number of factors by simply repeating the process, it becomes computationally infeasible for a higher number of factors. For instance, if four potential investment increases are considered for each of two factors (e.g., no, low, medium, and high increase), there can be up to sixteen possible total investment increases. Each added factor may thus lead to a multiplication by four of the number of possible total investment increases. With ten factors, the number of possible total investment increases might therefore be close to one million (220) in the worst case. For an even larger number of factors, storage may also to be considered.
A possible solution could be to approximate the pmf for Z by one that again considers only four different risk levels. Then, the calculation in Section 5 scales up well to any number of factors.
Another possibility is to consider a Monte Carlo approach.

8 Monte Carlo approach

For a higher number of factors, rather than directly computing all possible total investment increases, we can perform a number N of computationally cheap simulations. In each simulation, a sample investment increase Ixi is drawn according to the *pmf* of each factor Xi. The total investment increase is the sum of all single investment increases:

$$I_x = \sum_i I_{x_i} \tag{2}$$

Where Ix denotes the investment increase of $X = \sum_i Xi$ To calculate the approximate probability for Ix, it is sufficient to count the number of times this investment is encountered and then divide by N at the end of the Monte Carlo simulation. In algorithmic form:
Choose a sufficiently large integer N (e.g., 100000). The higher N, the more also very low probabilities can be accounted for. If there is no need to capture very low probabilities, a smaller N can be chosen. If the installed surface of an element is very large (e.g., a transparent envelope element of a large office building or of multiple office buildings), low risks may occur.
Create an empty set Z, which will hold tuples (Iz , Pz) containing all possible total investments Iz and associated approximate probabilities Pz .
For i = 1 to N :

    Randomly choose Ix according to the *pmf* of X.
    Randomly choose Iy according to the *pmf* of Y .
    Compute $Iz = Ix + Iy$.
    If Iz appears in a tuple in Z:
        Increment Pz by 1 in tuple (Iz , Pz).
    Else:
        Add tuple $(Iz , 1)$ to set Z.
    Divide each element of Pz by N .

9 Approximated result

The approximated result for the overall investment increase probability distribution Z with inputs given in Tables 1 and 2 obtained by choosing N = 100000 applying the algorithm in Section 8 is shown in Table 4. This result depends on the pseudo-random number generator and seed used.

10 Scalability

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The Monte Carlo approach scales up well. A potential issue is that the probabilities for certain combinations of failures are very low and cannot be detected without choosing a very large N.
However, this also means that they will very rarely happen in practice.
For a very high number of factors, storage may also become important.

Investment increase	Probability of occurrence
0	0.93521
0.066	0.01569
0.13	0.01469
0.132	0.00012
0.196	0.00018
0.2	0.00743
0.266	0.00012
0.27	0.01728
0.336	0.00019
0.4	0.00029
0.47	0.00014
0.63	0.00837
0.696	0.00011
0.76	0.0001
0.83	8e-05
0	0.93521
0.066	0.01569
0.13	0.01469
0.132	0.00012
0.196	0.00018
0.2	0.00743
0.266	0.00012
0.27	0.01728
0.336	0.00019
0.4	0.00029
0.47	0.00014
0.63	0.00837
0.696	0.00011
0.76	0.0001
0.83	8e-05

Table 4: Approximated probability mass function for factor $Z = X + Y$

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