TALLINN UNIVERSITY OF TECHNOLOGY
DOCTORAL THESIS
12/2019

Modelling Construction Process Impact Factors on Degradation of Thin Rendered Facades

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TTÜ PRESS

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This dissertation was accepted for the defence of the degree 03/12/2018

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Defence of the thesis: 10/04/2019, Tallinn

Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology and Technical University of Berlin has not been submitted for doctoral or equivalent academic degree.

Virgo Sulakatko

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ISSN 2585-6898 (publication)
ISBN 978-9949-83-401-3 (publication)
ISSN 2585-6901 (PDF)
ISBN 978-9949-83-402-0 (PDF)

TALLINNA TEHNIKAÜLIKOOL
DOKTORITÖÖ
12/2019

Ehitusprotsessi mõjufaktorite modelleerimine õhekrohv fassaadide lagunemisel

VIRGO SULAKATKO

TTÜ KIRJASTUS

Methode zur Bewertung der Relevanz von beeinflussenden Faktoren im Bauprozess auf die Mängelfreiheit von Wärmedämmverbundsystemen

vorgelegt von
Virgo Sulakatko
geb. In Tallinn, Estland

von der Fakultät VI - Planen Bauen Umwelt
der Technischen Universität Berlin
zur Erlangung des akademischen Grades

Doktor der Ingenieurwissenschaften
- Dr.-Ing. –

genehmigte Dissertation

Promotionsausschuss:

Vorsitzender: Prof. Jarek Kurnitski
Gutachter: Dr. Bodo Buecher
Gutachter: Prof. Les Ruddock

Tag der wissenschaftlichen Aussprache: 10.04.2019

Tallinn 2019

Contents

List of publications

The list of author's publications, on the basis of which the thesis has been prepared:

I **Sulakatko, V**.; Vogdt, F. U. (2018). Construction Process Technical Impact Factors on Degradation of the External Thermal Insulation Composite System. Sustainability, 10 (11).10.3390/su10113900.
(journal paper: ETIS classification 1.1)

II **Sulakatko, V**.; Lill, I. (2019). The Economic Relevance of On-Site Construction Activities with the External Thermal Insulation Composite System (ETICS). International Journal of Strategic Property Management, 23 (4), 213−226. **(journal paper: ETIS classification 1.1)**

III **Sulakatko, V**. (2018). Modelling the Technical-Economic Relevance of the ETICS Construction Process. Buildings, 8 (11).10.3390/buildings8110155. **(journal paper: ETIS classification 1.1)**

Copies of these articles are included in Appendices 3 to 5.

Other published works:

IV **Sulakatko, V.**; Lill, I.; Witt, E. (2016). Methodological framework to assess the significance of External Thermal Insulation Composite System (ETICS) on-site activities. Energy Procedia: SBE16 Tallinn and Helsinki Conference; Build Green and Renovate Deep, 5-7 October 2016, Tallinn and Helsinki. Elsevier, 446−454.10.1016/j.egypro.2016.09.176.
(conference paper: ETIS classification 3.1)

V **Sulakatko, V.**; Lill, I.; Soekov, E.; Arhipova, R.; Witt, E.; Liisma, E. (2014). Towards Nearly Zero-energy Buildings through Analyzing Reasons for Degradation of Facades. In: D. Amaratunga; R. Haigh (Ed.). Procedia Economics and Finance (592−600). Elsevier.10.1016/S2212-5671(14)00980-0.
(conference paper: ETIS classification 3.1)

VI **Sulakatko, V.**; Lill, I.; Liisma, E. (2015). Analysis of On-site Construction Processes for Effective External Thermal Insulation Composite System (ETICS) Installation. In: Procedia Economics and Finance (297−305). 8th Nordic Conference on Construction Economics and Organization: Elsevier Science BV.10.1016/S2212-5671(15)00180-X.
(conference paper: ETIS classification 3.1)

VII **Sulakatko, V.**; Liisma, E.; Soekov, E. (2017). Increasing construction quality of External Thermal Insulation Composite System (ETICS) by revealing on-site Degradation Factors. Procedia Environmental Sciences, 38: International Conference on Sustainable Synergies from Buildings to the Urban Scale. Elsevier, 765−772.10.1016/j.proenv.2017.03.160.
(conference paper: ETIS classification 3.1)

Author's contribution to the publications

Contribution to the papers in this thesis are:

I The author of the thesis designed the study, collected and analysed the results, and wrote the paper. Prof. Vogdt supervised the research, reviewed the paper and contributed to the discussion.

II The author of the thesis designed the study, collected and analysed the results, and wrote the paper. Prof. Lill supervised the study, reviewed the paper and contributed to the discussions.

III The author of the thesis is the sole author of the article.

Introduction

The buildings, roads, parks, landmarks, and other constructed surroundings create the man-made environment around us. It affects our physical activities, travelling behaviours, safety, and even our health, as we spend the majority of our time in areas developed by humans – whether outdoors or indoors. Every single building in our cities plays a significant role in this multidimensional concept during its life-cycle. The quality of the building is determined during the physical creation or renovation of the building, and it builds the scene for the following decades. Yet, higher quality expects greater skills and awareness of the impact of construction activities in the long run.

Construction quality may be understood differently by the various stakeholders of the supply chain. The industry has multiple simultaneous inputs at the project level and involves a number of professional stakeholders who are clients to one another (Baden Hellard, 1991; Barrett, 2000). Under such conditions, firms develop their own practices and customs and build their network of partners. The quality depends on the requirements established for the group formed for a specific project. For each project, the main parties are the client, the designer, and the contractor. According to Yang et al. (2003), the client aims to gain value for money and is concerned about aesthetics, costs, functionality, quality, safety, and duration. The contractors are more concerned with buildability and optimised design to simplify the construction process and gain profit. The designers gather inputs from various parties and shape the ideas and requirements into buildings bearing the expected physical and technical characteristics. Therefore, the range of performance criteria that is seen as quality measure depends upon the point of strategic objective. Baden Hellard (1991) suggested four dimensions (time, cost, aesthetics, and function) as the variables, while the "iron triangle" focuses on time, cost, and scope as a function of quality (Atkinson, 1999; Albert P. C. Chan, Scott, & Lam, 2002). Since 1991, the range of influencers of the quality has been extended to include health, environment, safety, and impact on society in general. Another aligning research topic is the performance-based building concept, which integrates the perspectives of facility management, construction, and building design (Lee & Barrett, 2003) while assessing performance of technical, economic, and environmental aspects.

Cost has been suggested as a performance indicator for measuring construction quality by Love and Li (2000) and Chan et al. (2004). This relates to some extent with the energy-efficiency policies that direct the decisions of developers and the construction market in general. The reduction of energy consumption has been addressed by the European Commission during the past few decades in order to provide sustainable economic growth (European Parliament, 2002, 2012). Measures to improve energy efficiency for non-residential and residential buildings were introduced in 2002 (European Parliament, 2002) and were updated in 2010 (European Parliament, 2010). The Directive 2010/31/EU on the energy performance of buildings guides the member states of the European Union to develop and implement measures to improve energy efficiency in new buildings, existing buildings under major renovation, and the retrofit of their elements (i.e., walls, heating and cooling systems). In the European Union, 70% of the housing stock were built before 1980, 23% of which even pre-dates 1945 (Federcasa & Italian Housing Federation, 2006) due to the beginning of the industrialisation of the construction market at that time. This means that energy-efficiency measures concern the buildings in use to a large extent (Bertoldi, López Lorente, & Labanca, 2016). Industrialisation fostered the use of precast concrete panels for the erection of new apartment buildings in an accelerated manner, particularly in central and eastern Europe. As the lifespan of these apartment buildings is around 50 to 70 years, the structures themselves as well as the building services are, or will be, outdated in a short while and will require renovation to meet the requirements of the present day.

Increased number of energy efficiency requirements of the European Union have increased the renovation rate of apartment buildings having the External Thermal Insulation Composite System (ETICS) (Amaro, Saraiva, de Brito, & Flores-Colen, 2014; Helmut Künzel, Künzel, & Sedlbauer, 2006). For the inhabitants, the primary positive attributes include the external application of ETICS with a relatively short construction period. Due to the fast and optimised application process, a large degree of the quality assurance depends upon specific activities of the artisans involved. The systematic inadequacies, which occur during the construction phase, have a direct effect on the life-cycle considerations of the building and constructed environments in general.

The academic community has directed its efforts towards revealing the solutions to achieve the desired outcome and meet the set targets. They have simulated the energy performance that leads to minimum life-cycle costs, while considering the technical systems of the building (Kurnitski et al., 2011). Researches have estimated the thickness of the insulation for the achievement of the optimum condition for different climates, investigated the optimum for different energy sources (Dombayci, Gölcü, & Pancar, 2006), investigated the impact of wind direction (Axaopoulos, Axaopoulos, & Gelegenis, 2014), the most suitable type of insulation material (Ozel, 2011), and fenestration design solutions (Pikas, Thalfeldt, & Kurnitski, 2014). There are decision support tools to select optimal energy-efficient architectural solutions in the early design phase, including building performance simulations (Attia, Gratia, De Herde, & Hensen, 2012; Negendahl, 2015). Selection of optimal thermal insulation system has also been studied, with an emphasis on recycling potential, which considers environmental impact, primary energy consumption, and financial cost (Anastaselos, Oxizidis, & Papadopoulos, 2011). These and many other studies have focused on the design phase of the energy-efficient building. However, according to the study by Institute for Building research (2011), 66% of buildings with ETICS, which do not meet the required energy-efficiency level, have shortcomings during the construction phase, and 46% of them have defects caused during the application of the external shell. This percentage highlights the necessity to improve the construction process.

The history of ETICS dates back to 1950s (Cziesielski & Vogdt, 2007). Since then, the technical requirements set for the system have developed in alignment with new construction materials as well as construction technology. The multi-component system attributes highly differentiated expectations to the components as well as to the system in general. Besides mechanical stability, the system has a number of functions, such as energy efficiency, protection against fire outbreak, resistance against weather effects, and others, which are required to be fulfilled during its life-cycle. Neumann (2009) indicated that more than 80% of the defects of construction works reveal visible signs during the next five years, while two out of three are detectable during the first two years. Neumann also estimated that the majority of the shortcomings can be avoided if suitable measures are adopted.

The academic community has studied the façade system for decades and improved the production of construction materials, developed detailed guidelines for the construction process, and published numerous case studies to discover the causes for degradations (Cziesielski & Vogdt, 2007). Several studies, experiments, and destructive on-site case studies have improved the awareness of the effect of construction activities on the quality of the facade. Yet, the increasing amount of relevant activities have caused the necessity to drive the influencers to raise the awareness of priorities during the construction process.

These façade construction works are mostly by small or medium enterprises (SMEs) for the most part, while small-sized firms have low capital investment capability (Deutsche Bank Research, 2014; European Commission, 2017; Eurostat, 2011). This creates a clear section of decision-makers who have a great control over the outcome of the construction works but lack the capital, knowledge and training necessary to improve quality.

These considerations raise the question of how to support the decisions which enhance on-site construction process. Construction influences the resilience as well as the future deterioration of the ETICS in each layer. As each layer has a different purpose, their relevance to the system is diverse. The research conducted in the field of the quality of ETICS rationalises the specific reasons for degradation in silos. These silos have caused a situation wherein a large number of reasons for degradation have been identified, but it is impossible to prioritise their impact on the ETICS as a whole. Amaro et al. (2013) and Mendes Silva and Falorca (2009) approached the problem from the maintenance point of view and developed a predictive maintenance assessment model. Their top-down approach detects deterioration and connects multiple possible causes. In order to investigate the cause for visible deterioration with in-situ analysis, a destructive test is often required. A number of conducted destructive tests have been discussed (Cziesielski & Vogdt, 2007; Kussauer & Ruprecht, 2011; Neumann, 2009) as well as reconstructed in laboratory conditions (Arizzi, Viles, & Cultrone, 2012; Nilica & Harmuth, 2005; Zirkelbach, Künzel, & Slanina, 2008). Additionally, the deviant behaviour of specific components has been studied in isolation. The determined pathology routes include the alteration in mechanical properties through added kneading water to the mixture (Fernandes, Silva, Ferreira, & Labrincha, 2005b), freezing or drying of the mixture caused by weather effects while the façade is insufficiently covered (Fernandes, Silva, Ferreira, & Labrincha, 2005a; Fernandes et al., 2005b; Nilica & Harmuth, 2005), increased vapor resistance due to increased thickness of the mortar (Šadauskiene, Stankevičius, Bliudžius, & Gailius, 2009), or increased thermal conductivity through the gaps between insulation materials (Sedlbauer & Krus, 2002). These and many other technically relevant on-site degradation factors must be included in a single framework.

Besides technical relevance, in order to decide on quality control measures, cost considerations have a vital impact. Skitmore and Marston (1999) and Woodward (1997) have argued that construction quality is in correlation to its cost. On the one hand, increased quality control reduces the margins of the contractor during the construction process. On the other hand, future degradations cause financial risk for the owner or for the contractor, depending on the defect liability period. Determining the equilibrium between these costs would be beneficial for both the parties, as the elimination of inadequacies during the construction process requires fewer resources and effort in comparison with future repair activities.

In order to make better decisions that value the equilibrium, an assessment method is developed to set rational priorities during the construction process.

Purpose

The study contributes to the research work concerning the quality of ETICS. The thesis addresses the research gap that hinders the comparison of the relevance of degradation factors originating from various research works or the industry.

The objective of the dissertation is to develop a construction process assessment method that quantifies and prioritises the relevance of the on-site construction activities of ETICS. Based on the developed method an assessment model is to be introduced and verified through simulations. The simulations in this study focus on the systematic on-site degradation factors, which are influencing the quality of ETICS applied to existing buildings.

Focus and scope of the research

Although the developed assessment method is universal for the facades, the model for verification is focusing on the facade solutions that are most often applied in Estonia in order to provide benefits to a larger community. The degradation factors as well as the data collected concerns façades with the following characteristics, which are correspondingly the limitations of the simulations:

- the subject is an existing multi-apartment building;
- the external walls are made of masonry or prefabricated concrete panels;
- the fixing method for the ETICS is either purely bonded with adhesive or mechanically fixed with anchors and supplementary adhesive;
- the reinforcement consists of a mixture and glass-fibre mesh;
- the thermal insulation product is composed of mineral wool or expanded polystyrene with a thickness of 150–250 mm;
- the study concerns the region-specific aspects of Estonia, which lies in the snow climate, fully humid and warm summer (Dfb) zone according to the Köppen-Geiger Map.

The simulations reflect three different project-based cost scenarios with the characteristics shown in Table 1, which are referred to as simulation number or ETICS type throughout the study.

Table 1. Characteristics of the simulations.

Simulation number	ETICS type	Insulation type	Insulation thickness	Fixing method
Simulation 1	ETICS 1	Expanded polystyrene	200 mm	Purely bonded kit
Simulation 2	ETICS 2	Expanded polystyrene	200 mm	Mechanically fixed kit with supplementary adhesive
Simulation 3	ETICS 3	Mineral wool	200 mm	Mechanically fixed kit with supplementary adhesive

Research methods

The preparation of the dissertation was based on books, scientific and statistical publications, and legislative documents as well as on discussions with experts working in the field. The on-site degradation factors under assessment are following the guidelines developed by the European Organisation for Technical Approvals (2013a) on testing measures as well as the general international technical requirements outlined by Regulation (EU) Number 305/2011 (also Construction Products Regulation or CPR) (European Parliament, 2011).

The technical-economic relevance model is developed with the method of Failure Mode Effects Analysis in order to quantify the technical and economic relevance of construction process defects, which are refined by occurrence rate and detectability assumptions. The technical severity evaluations are collected bi-regionally and are based on experts' judgment. German and Estonian experts' evaluations of technical considerations are validated with the non-parametric Friedman's test. The predictable components (occurrence, detectability, and latency period) are based on experts' professional judgments from one region (Estonia) and are validated with the Delphi method. The project-specific economic simulation is constructed on the actual costs of three sample projects from an active façade construction company in Estonia. The long-term economic real interest rate considers the inflation rate and the 5- to 10-year loan interest rate for entrepreneurs in Estonia.

The research process is divided into eight phases that are marked as grey areas in Figure 1. The method can be followed by individual stakeholders in calculating firm-specific risks as economic aspects change during the seasonal influences as well as other alterations occur.

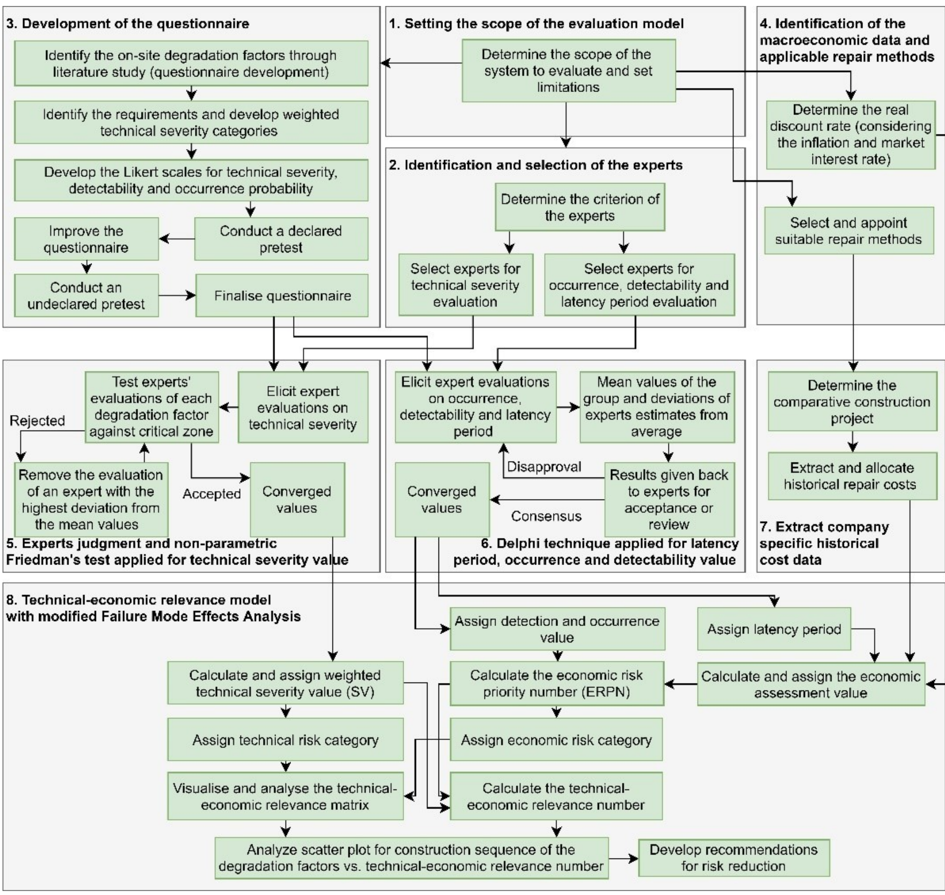


Figure 1. Research design.

The scope of the system as well as specific limitations are to be established in phase 1. Then the degradation factors are to be selected through literature review and described as a questionnaire (phase 2). It is to be followed by the selection of the experts (phase 3). In order to consider the economic aspects, it is necessary to extract the statistical data for the discounting of the costs and to specify repair methods (phase 4). The data collection and the data analysis is divided into two evaluations due to the difference in the nature of the data. The evaluation of technical aspects requires an in-depth knowledge and understanding of the façade system (phase 5). The occurrence ratio, detectability, and the latency period of the shortcoming is more region, company, and craftsmen specific and concerns the forecasting as well as practical observations (phase 6). Historical cost data is company specific, and it is extracted from similar construction projects described in the system's scope (phase 7). As all the data is acquired (phase 8), the weighted technical severity value and economic assessment value is calculated. The results position each degradation factor into a risk category and provides the technical-economic risk priority number for prioritisation. This enables the analysis of the results and the development of recommendations.

Outline of the dissertation

The dissertation consists of an introduction, six sections, conclusions, annexes, references, and Curriculum Vitae of the author.

The introduction sets the scene for the research by providing an overview of the topic. This outlines the focus, scope, and significance of the study. Chapter 1 rationalises the selected design approach for the developed quality assessment method. The data collection and analysis process is introduced in Chapter 2. Chapter 3 describes the essentials of ETICS and identifies the on-site degradation factors for further analysis. Chapter 4 discusses the individual components of the developed method as well as their results. Chapter 5 simulates the technical and economic relevance individually as well as the unified technical-economic relevance. It is followed by the discussion in Chapter 6 and conclusions from the study.

Abbreviations

DF	Degradation factor
DV	Detectability value
EAV	Economic assessment value
ERPN	Economic risk priority number
ERPN-C	Economic risk priority category
ETICS	External Thermal Insulation Composite System
ETICS 1	ETICS: purely bonded system, polystyrene
ETICS 2	ETICS: adhesive with mechanical anchors, polystyrene
ETICS 3	ETICS: adhesive with mechanical anchors, mineral wool
FMEA	Failure mode and effects analysis
LP	Latency period
OV	Occurrence value
SC	Severity category
Sim1	Simulation 1
Sim2	Simulation 2
Sim3	Simulation 3
SV	Severity value
SV-C	Severity value category
TER	Technical-economic relevance
TER-C	Technical-economic relevance category
TRPN	Technical risk priority number

1 On-site construction activity risk assessment framework

The liability of construction works can be addressed by the negligence law. According to the law (Stamatis, 2003), construction engineers are responsible for designing and building a safe building. They act in a reasonable manner, avoid actions that cause damages, and understand the causes of their actions that can affect the injured party. In negligence, there is a necessity to prove unreasonable action that causes the defect. The manufacturer and construction workers need to avoid defects and unwanted outcomes. If the priorities are not set, the actions of the construction process is focused on the largest problem at the current moment, overshadowing the global optimum. To shift the focus on the global optimum, the vital few activities must be recognised. This can be done with appropriate risk assessment.

The risk analysis asks what can go wrong, what the probability of the occurrence is, and how severe the consequence is (Stamatis, 2003). If this is known, the priorities of the preventive actions can be decided. Risk elimination can be addressed with the failure mode and effects analysis (FMEA), which is a bottom-up approach, enabling the focus on initial causes. The method of FMEA was initially developed in the 1950s as a military procedure in the USA (Carbone & Tippett, 2004). Severity stands for the significance of the failure, occurrence is the frequency of the failure, and detection is the level of difficulty to detect the failure during the process. The result of the method is the quantified priority of the failure, articulated with the risk priority number. The knowledge enables the prioritisation and elimination of highly relevant failures through preventive actions (Rhee & Ishii, 2002).

Although FMEA widely used in production, the method has shown practical results in the construction industry in several studies (Abdelgawad & Fayek, 2010; Layzell & Ledbetter, 1998; Mecca & Masera, 1999). Mecca and Masera (1999) pointed out the necessity to make non-quantitative evaluations in the construction industry in order to identify judgment parameters and found the FMEA-type tool applicable, as did Stamatis (2003). The method has also shown flexibility to include relevant parameters by the user and is suitable for use by small and medium enterprises (SME) who are the main performers in this industry and for this particular study.

1.1 Process of the failure mode and effects analysis

The current study aims to focus on the on-site application process and is therefore the best described with the “process FMEA”, which addresses failures associated with the assembly process rather than design. The design of the FMEA follows the procedure described by Ostrom and Wilhelmsen (2012), which is compliant with the work by Teng and Ho (1996) and the quality standards QS 9000 and ISO 9000 (Hoyle, 1997). The process is visualised in Figure 2. The general procedures are into three main phases.

The first phase determines the scope of the system and the possible failure modes. Each failure has an effect that must be determined, and is represented as severity value. In the second phase it is essential to determine an occurrence ratio and evaluate the detectability difficulty of the failure during the process. The third phase calculates the risk priority number, sets focus on the most relevant defects, develops corrective actions, and re-evaluates the impact of the implemented corrective actions.

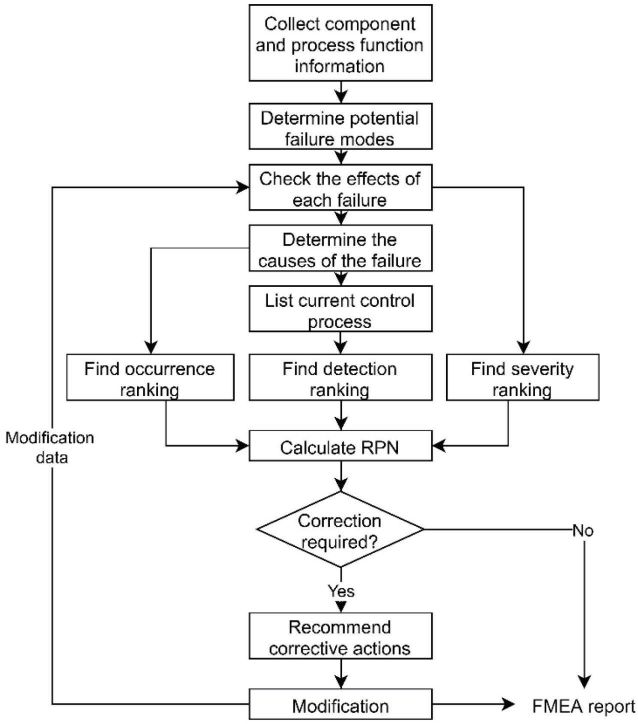


Figure 2. The FMEA procedure visualised by the author according to Teng and Ho (1996).

The traditional FMEA process constitutes quantifying the risk of technical aspects, but the decision making has additional relevant parameters to consider. The FMEA approach has been proven to be a flexible model that can be adapted according to specific needs of the user. It is neither standardised and needs to reflect the specific problem to be solved (Stamatis, 2003). Researchers have included various other factors in the model to provide more specific results according to their research goals (Carmignani, 2009; Shafiee & Dinmohammadi, 2014; Vazdani et al., 2017). As the need to evaluate technical impact is unambiguous, there is a necessity to include additional aspects into the developed relevance assessment method. The following sub-chapters discuss the additional components required for the relevance assessment and discusses the methods.

1.2 Economic input value for enhanced decision-making

Traditionally, the defect severity consideration with FMEA focuses on the impact of the technical aspects. Bowles (2003) has argued that the financial aspect is undervalued to provide recommendations on risk reduction. Similar research using financial aspects as severity input for FMEA has been conducted by Shafiee and Dinmohammadi (2014) for the production and erection of wind turbines. He pointed out that there is a relevant difference in the future cash flows on the turbines, if offshore or onshore placement is observed. In his research, he focused on the cost of consequences of failures that support managers during the investment decision-making process. The economic risk assessment concluded that the financial relevance is beneficial, as more detailed considerations are required from the operational phase to evaluate the ultimate effects of the shortcomings. Rhee and Ishii (2003) pointed out the need to include costs into the risk calculation approach and developed a “Life Cost-Based FMEA” that includes traditional FMEA, Life Cycle Costs, and the Service Mode Analysis. Carmignani (2009) included into the developed FMECA model the cost of preventive action that enables to calculate the estimated profitability if measures are taken. These FMEA modifications highlight the relevance of cost in risk management, as it is the expected benefit for reducing systematic failure during the process.

Woodward (1997) and Skitmore and Marston (1999) stated that construction technology and quality are considered in correlation to cost. Quality cost is a measure that provides the management additional information to prevent unwanted outcomes (Love & Li, 2000). Love and Li (2000) defined the quality costs as “the total cost derived from problems occurring before and after a product or service is delivered”. The quality related costs can be divided into prevention, appraisal, and failure, which are described as the PAF concept (Rosenfeld, 2009). Prevention costs concern the action taken during the construction process, and appraisal costs are related to the measurement of quality (Schiffauerova & Thomson, 2006). The quality costs of a failure include the activities for correcting the defect that has occurred. The costs of failure are characterised as internal or external, which depend upon whether the measures are adopted before or after delivery to the client. The PAF concept has declared that direct control can only be exerted over prevention and appraisal, as failures show visible signs later and already form a consequence. The elimination of the shortcomings of the construction process after completion requires more effort and resources in comparison with their avoidance during the initial construction phase. These corrective prevention costs have significantly lower costs in general in comparison with the costs of failure in the future and are in correlation to appraisal costs and low prevention (Rosenfeld, 2009). It is expected that spending more time and money on prevention can bring a reduction in total construction costs (Love & Li, 2000). Due to this effect, it is significant to realise which activities have a high impact, enabling to conduct the trade-off between the future repair costs and quality assurance in the early construction phase. This outlines the relevance of the economic aspects in the assessment method, as it enables setting the focus on corrective actions already during the construction process.

1.3 Criticism against FMEA

The FMEA model has been criticised due to the multiplication of variables on the equal scale by Pillay and Wang (2003), Bowles (2003), and Carmignani (2009). The researchers argued that the occurrence and detectability values should not be linear. Puente et al. (2002) and Pillay et al. (2003) opined that the weighting of occurrence, severity, and detectability, considered as the simple multiplication of ordinal scales, might be misleading, as different combinations might reflect the same output value. The change in one variable has a relatively large impact on the risk number, on which the final recommendations are based. In the earlier work or Bowles and Peláez (1995), a disadvantage is also detected in the occasion as multiple effects on severity occur. In order to diminish the impact of this disadvantage in this research, the weight factor has been applied to the technical severity component and the analysis concerns several technical categories. However, the outcomes of detectability and occurrence remain linear.

The criticism of economic variable is focused towards the difficulty of predicting the corrective action cost. Carmignani (2009) and Bowles (2003) pointed out the inaccuracy of predicted future costs as the costs may change due to economic, political, as well as technological alterations. This risk remains also in the developed method, but the influence can be reduced as the economic parameters are reapplied as relevant alterations occur.

1.4 Construction process multi-criteria assessment method

The main aim of this research work was to develop an assessment method of the shortcomings that quantify the on-site degradation factors of ETICS that is suitable for the stakeholders. To achieve this, the complex method considers the technical as well as the economic impact. The framework of the components included in the model are shown in Figure 3, while the research process is shown in Figure 1.

The degradation factors (DFs) of the on-site construction process, which are the failure modes in the concept of the FMEA, have been identified. Their relevance is influenced by four sets of components. In order to reveal and adjust the technical significance, a severity weighting system according to the essential requirements set for the façade system has been developed. To include the economic impact, the repair methods along with their future costs have been appointed to the DFs and represented as economic assessment values.

The analysis of the study show the results of the individual components in prior to the application of FMEA method on technical and economic models separately. Finally, a technical-economic model is developed which unifies the components and provides the relevance categories and relevance numbers for focus setting.

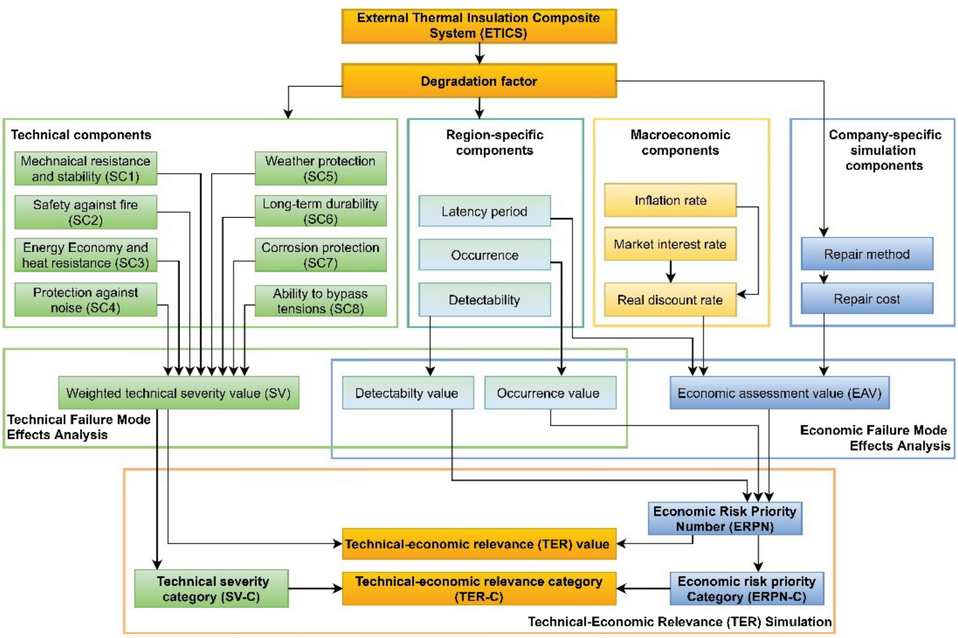


Figure 3. The framework of the technical–economic relevance (TER) method.

2 Data collection and validation of the components

The developed multi-criteria assessment method requires the collection of different sets of data. As there is no quantified data available on many components, the experts' judgment method is chosen to evaluate the relevance of the technical- and region-specific components. For both data sets the experts were identified, panelists selected and validation methods appointed. In order to test the method with company-specific historic cost information, an active façade construction company was identified and selected. The following sub-chapters provide rationalisations for data collection.

2.1 Selection of experts in the panel

It is relevant to consider that there is no quantified data available on the subject of the research. Hence, expert judgement was suitable for use in this study. The selection of experts considerably affects the quality of the data (A. P. C. Chan, Yung, Lam, Tam, & Cheung, 2001). The terms for the selection of experts was their in-depth knowledge and understanding of technical considerations of ETICS as well as their practical on-site experience. According to Olson (2010), variations in experts backgrounds can be allowed. Hallowell and Gambatese (2010) suggested that in the construction industry, expert identification could be conducted through the membership of nationally recognised committees or by participation in similar studies. The expert should meet at least four of the following eight requirements:

(1) at least five years of professional experience in the construction industry;
(2) tertiary education degree in the field of civil engineering or other related fields;
(3) professional registration in the field of construction;
(4) member or chair of a nationally recognized committee for ETICS;
(5) writer or editor of a book or book chapter on the topic;
(6) faculty member at an accredited institution of higher learning;
(7) presenter at a conference on the topic; and
(8) primary or secondary writer of at least three peer-reviewed journal articles.

The most suitable number of panellists has not been exactly determined in the literature for quantifying expert evaluations. The size of the group depends on the availability of the experts, available resources, and the research topic (Ameyaw, Hu, Shan, Chan, & Le, 2016). In other studies of the construction industry, a small number of experts has often been used. Chan et al. (2001) involved eight panellists to study the selection process of a procurement system in the construction industry. Chau (1995) included seven experts to evaluate the estimated probability of unit costs. Six experts were identified and selected for a risk assessment of road projects (Thomas, Kalidindi, & Ganesh, 2006), and five experts evaluated construction business risks (Dikmen, Birgonul, Ozorhon, & Sapci, 2010). Studies have included 3 to 144 experts in the studies of various industries (Skulmoski & Hartman, 2007) and 3 to 93 panellists in the construction industry (Ameyaw et al., 2016). Hallowell et al. (2010) proposed a panel size between 8 and 12, whereas Rowe and Wright (2001) suggested including five or more experts in the panel and pointed out that there are "no clear distinctions in panel accuracy" when the panel size varied from 5 to 11 experts. Hence, for the data collection for this model, five experts should at least be included.

Due to the difference in the nature of data the technical and region-specific components were approached separately.

2.2 Technical severity data

In order to collect the data for the technical severity evaluation model, 14 experts with the required characteristics were identified through nationally recognised ETICS committees in Estonia and Germany. The experts agreed to participate in various phases of the study. The panel included seven experts each from Germany and Estonia. Of them, seven were consultants/supervisors, two were managers/project managers in façade construction companies, and five were technical specialists working with ETICS manufacturers. Two of the experts pre-tested the questionnaire and twelve out of the fourteen were involved in judging the technical severity in 2016. The demographics of the experts participating in the technical severity evaluation are provided in Figure 4.

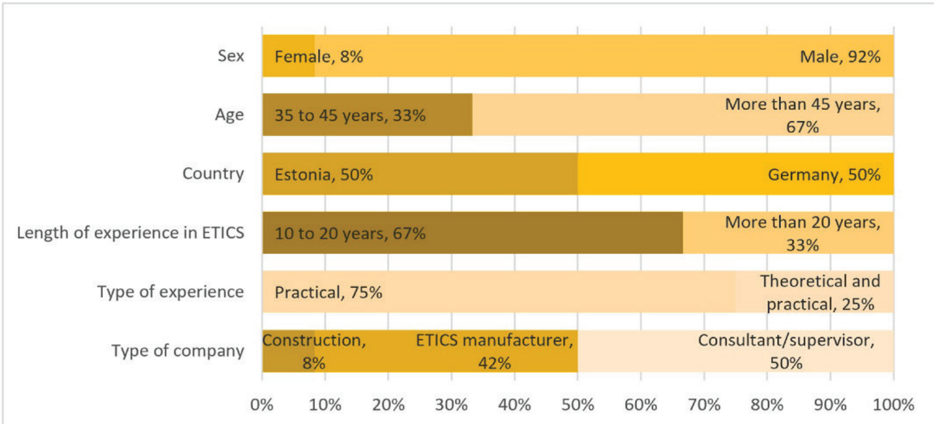


Figure 4. Demographics of the experts participating in the technical severity evaluation.

In order to test the validity and the difference between experts' estimations, a non-parametric Friedman's test is applied (Levine, Berenson, Hrehbiel, & Stephan, 2011) as it increases the credibility of quantification of subjective evaluations (McCrum-Gardner, 2008; O'Gorman, 2001). Non-parametric Friedman's test assesses the difference between a number of related samples. The test is used as an alternative for analysing variances for repeated measures, as the same parameters have been measured in terms of the same subjects, but under different conditions. It supports the comparison of more than two related groups and is suitable for ordinal data.

The procedure ranks the blocks (rows) and considers the values by columns. The blocks are the categories that are to be evaluated and ranked, and the columns are the evaluations of experts that are compared. If the calculated Friedman rank is in the rejection region, the experts' ratings with the most extreme column values are eliminated (Sulakatko, Lill, & Witt, 2016).

Friedman's test has shown the same quality for more than 10 experimental units in comparison with the aligned rank test. If the experimental units were fewer in number than 6, the difference that lies between aligned rank test is below 5% (O'Gorman, 2001). After Friedman's test was applied, the data sets concerned 4 to 12 experimental units in this study. As there were enough different components in the calculation, the inaccuracy of 5% did not have a major impact on the final results. The results of the Friedman test are described in sub-section 4.1.

2.3 Region-specific data

The data collection for determining the detectability and occurrence values was developed using the Delphi technique, where independent and anonymous expert judgements are combined through mathematical aggregation (Skulmoski & Hartman, 2007). The Delphi is applicable if there is no quantifiable data available and predictions are required (Ortega Madrigal, Serrano Lanzarote, & Fran Bretones, 2015).

As the study aims to address the situation in Estonia, the Estonian experts were asked to participate in the region-specific data collection. Five of the seven Estonian experts agreed to participate in the survey conducted in 2018. All of them had 10 to 20 years of practical experience in the field. Figure 5 presents the demographics of the experts. All the data were collected during face-to-face meetings due to the requirement of a high response rate. Due to the small panel size of the region-specific data collection, it can be argued that the full capacity of the Delphi technique was not fully utilized. However, as the quality of the expert panel is more significant than the size (Powell, 2003) and since the aim of the study was to verify the developed method, the small panel size was satisfactory.

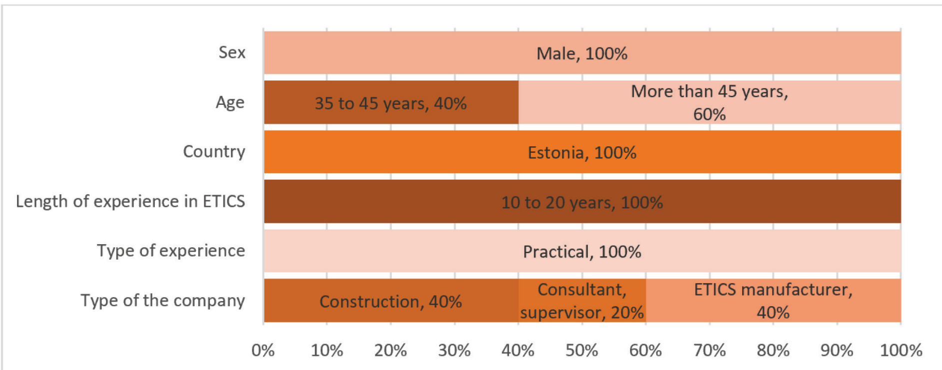


Figure 5. Demographics of the experts participating in the occurrence, detectability and latency period evaluation.

The expected outcome was a consensus between the experts. The Delphi technique requires the circulation of a questionnaire amongst the selected experts. There is no specific guideline for determining when a consensus has been achieved. In this study, consensus was achieved when the experts agreed upon the mean values of the group.

The experts were asked to individually and anonymously provide their evaluations. According to the questionnaire, each expert had to provide evaluations for occurrence and detectability. In order to obtain a high response rate, a meeting time with each expert was individually organized. During the face-to-face meeting, the questionnaire was completed by the expert. The responses from all the experts were summarized and mean values were calculated. The collective mean results were sent to each expert, and they were asked to revise their evaluation or agree/disagree with the collective result. During the next two weeks, three participants agreed with the collective results. Two experts reviewed the group results after a reminding phone call and stated their agreement with consensus. Hallowell et al. (2010) described the “bandwagon effect”, where decision makers could feel pressurised to agree with the opinion of a group. Due to the fast agreement with the consensus, there was a need to investigate whether there was this described effect. So, the team of experts was brought physically together and the highest and the lowest evaluations were discussed with the group in order to check if there were any hidden assumptions. The consensus remained unchanged after the meeting. The primary reason was that individual evaluations depend highly on the skills and experience of the expert and the results may vary.

2.4 Development of Likert scales

In order to evaluate the severity of the system's performance, the likelihood of occurrence, and detectability, a Likert scale is recommended and used by several researchers (Chew, 2005; McCrum-Gardner, 2008; Preston & Coleman, 2000; Toor & Ogunlana, 2010; Vazdani et al., 2017; Zeng, Tam, & Tam, 2010). According to Preston and Coleman (2000), Likert scales with a range from 2 to 11 points have been used are used most often and those below or equal to 4 points should be avoided. For the severity evaluation, a 6-point Likert scale was used to include the value of zero, which simplifies the interpretation of the cases in which no influence is expected. Detectability and occurrence were evaluated on a 5-point Likert scale.

The developed Likert scale for the technical severity evaluation is shown in Table 2. The highest rating was assigned if the failure had a very high effect on the requirement and a score of zero was given when the failure had no impact on the requirement. These experts' ratings were the input data for the calculation of weighted technical severity value.

Table 2. Likert scale for the evaluation of technical severity.

Risk level	Characteristic	Severity rating
Very high	Total failure of the requirement	5
High	Requirement is highly influenced	4
Moderate	Requirement is moderately influenced	3
Low	Requirement is slightly influenced	2
Very low	Requirement is minimally influenced	1
No effect	No effect on the requirement	0

The probability of occurrence rates the incident frequency during the construction process. It is a subjective evaluation by the experts and is dependent on personal experience. The pre-test questionnaire revealed that it is impossible to quantify the occurrences in a specific range, and a quantification of subjective evaluation was required. The developed rating scale is shown in Table 3. The highest value was given to often-occurring failures and the lowest value was attributed to unlikely failures.

Table 3. Likert scale for the evaluation of occurrence probability.

Risk level	Characteristic	Occurrence value
Very high	Failure is almost certain	5
High	Often repeated failures	4
Moderate	Occasional failures	3
Low	Relatively few failures	2
Very low	Failure is unlikely	1

The detectability value rates the difficulty level of on-site detection of the shortcoming, which is also dependant on the experience of the expert to some extent. The characteristics are presented in Table 4.

Table 4. Likert scale for the evaluation of detectability.

Risk level	Characteristic	Detectability value
Very high	A potential cause of failure cannot be detected visually. Additional tests need to be performed. High experience is required.	5
High	In-between very high and moderate conditions.	4
Moderate	Potential failure can be detected visually before completion of the layer, during the application process or through markings on the material packages. Medium level of experience required.	3
Low	In-between very low and moderate conditions.	2
Very low	Cause of the failure can be detected after completion of the layer with a less experienced observer.	1

2.5 Repair techniques and company-specific cost data

Repair technique is the set of construction activities required to remove the defect and restore the functionality of ETICS. Professionals in the field (Amaro et al., 2014; Cziesielski & Vogdt, 2007; Fraunhofer IRB Verlag, 2016; Krus & Künzel, 2003; Kussauer & Ruprecht, 2011; Neumann, 2009) have thoroughly described repair methods for ETICS, which are reliable to use. Maintenance techniques such as cleaning, disinfecting and coating the external layer, or crack filling, which is required due to externally applied forces or ageing, were not considered. The defects caused by shortcomings in the sealants of additionally fixed details and roof edges were handled as a requirement to remove the insulation due to the causation of moisture-induced problems. The possibility to cover degraded ETICS with second ETICS was not observed, and the repair technique was replaced by dismantling and reapplication of the whole system. As the current simulation model was explicitly developed for the systematic on-site shortcomings of ETICS, the scope of works was specified by the affected layers (Sulakatko, Lill, & Liisma, 2015) – replacement of the finishing layer, reinforcement layer, or the whole system.

As the economy is undergoing continuous change, the recent cost data from the industry is the most exact for risk analysis. The usage of industry data has provided valuable and more relevant in other studies (Love & Li, 2000; Serpell, 2004). Serpell (2004) recommended to include more experienced estimator who has an industry background as more exact results are expected. The location of the project, economic situation, and cost of artisans and materials may change for each project. Therefore, the cost data should consider projects with comparable characteristics. In this study, the total costs of façade construction projects were observed.

In order to collect industry cost data, the author established contact with a senior manager of a façade construction company located in Tallinn, Estonia. The nature of the research was described, and the costs of initial construction of the façade was gathered from actual construction projects of the company in the year 2017. The estimator who provided the cost data has worked in the field of ETICS for more than 15 years and was a participant in the panel of experts. Three selected sample projects were located in Tallinn and had similar characteristics in order to enable comparison, while corresponding to the aims of the study (Table 1). Due to the scope of the study, the selected sample projects were dwellings under renovation and varied in fixing method and insulation type. For the cost comparison, all the cost components of the model were adjusted to the unit €/m^2 without value-added taxes.

3 Selection of the on-site degradation factors of ETICS

The list of degradation factors was developed through two stages – literature study and verification with two experts. The list of degradation factors was collected through the literature review. The litertature was surveyed with the keywords and search terms "ETICS", "External Thermal Insulation Composite System", "WDVS", "Wärmedämmverbundsystem", "SILS", and "Soojusisolatsiooni liitsüsteem". Relevant papers in English, German, and Estonian were considered, as they are languages comprehensible to the author. The list of shortcomings is based on:

a) descriptive instructions, recommendations, harmonized standards, set requirements (European Committee for Standardization (CEN), 2003, 2004, European Organisation for Technical Approvals, 2002, 2013; Fraunhofer IRB Verlag, 2016);
b) studies regarding simulations or material studies performed in laboratory conditions (Annila, Pakkala, Suonketo, & Lahdensivu, 2014; Arizzi et al., 2012; Balayssac, Nicot, Ruot, Devs, & Détriché, 2011; Barberousse, Ruot, Yéprémian, & Boulon, 2007; Barreira & de Freitas, 2013; Bochen, 2009; Bochen & Gil, 2009; Bochen, Gil, & Szwabowski, 2005; Collina & Lignola, 2010; D'Orazio et al., 2014; Daniotti & Paolini, 2008; Fernandes et al., 2005b; Holm & Künzel, 1999; H. M. Künzel & Gertis, 1996; H Künzel & Wieleba, 2012; Nilica & Harmuth, 2005; Norvaišiene, Burlingis, & Stankevičius, 2007; Norvaišienė, Griciutė, & Bliūdžius, 2013; Pakkala & Suonketo, 2011; Pikkuvirta, Annila, & Suonketo, 2014; Schrepfer, 2008; Silva, Flores-Colen, & Gaspar, 2013; Simões, Simões, Serra, & Tadeu, 2015; Topcu & Merkel, 2008; Vallee, Blanchard, Rubaud, & Gandini, 1999; Yin, Li, Haitao, & Ke, 2010; Zirkelbach, Holm, & Künzel, 2005; Zirkelbach et al., 2008);
c) field researches (Amaro et al., 2014, 2013; Barreira & de Freitas, 2014; Barreira & De Freitas, 2014; Barreira, Delgado, & Freitas, 2013; Breuer et al., 2012; Edis & Türkeri, 2012; Flores-Colen, Brito, & Branco, 2009; Gaspar & de Brito, 2011; Institute for Building Research (Institut für Bauforschung) e. V., 2011; Johansson, Wadsö, & Sandin, 2010; Korjenic, Steuer, Šť'Astník, Vala, & Bednar, 2009; H. M. Künzel, 1998, 2010; H Künzel & Wieleba, 2012; Hartwig M. Künzel & Fitz, 2004; Helmut Künzel et al., 2006; Zillig, Lenz, Sedlbauer, & Krus, 2003);
d) and books on the topic (Cziesielski & Vogdt, 2007; Kussauer & Ruprecht, 2011; Neumann, 2009).

Based on these 54 references published between 1996 and 2015 (Figure 6), a list of 114 identified on-site degradation factors was created.

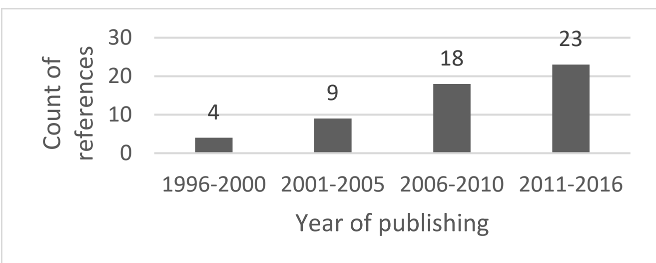


Figure 6. Yearly distribution of references.

The degradation factors were distributed according to the seven layers of the system. The construction works in the substrate layer mainly concern the preparation of the existing external wall. Adhesive, reinforcement, and finishing layers include work practices with mixtures and mesh application. Insulation and mechanical anchors specify the activities for the application of insulation panels and the mechanically fixed anchors. The additional details generalise the defects of the installations of auxiliary products, such as windowsills and plinth areas. Table 5 categorises the sources of literature according to the layers to which the degradation factor is related.

Table 5. Categorisation of the literature sources according to the layers of ETICS.

Layer	Literature Source
Substrate (S)	(Balayssac et al., 2011; Cziesielski & Vogdt, 2007; Flores-Colen et al., 2009; H. M. Künzel, 2010; Kussauer & Ruprecht, 2011; Neumann, 2009; Silva et al., 2013)
Adhesive (D)	(Amaro et al., 2013; Arizzi et al., 2012; Barreira & De Freitas, 2014; Collina & Lignola, 2010; Cziesielski & Vogdt, 2007; Fernandes et al., 2005a, 2005b; Gaspar & de Brito, 2011; H. M. Künzel, 2010; Kussauer & Ruprecht, 2011; Neumann, 2009; Nilica & Harmuth, 2005; Silva et al., 2013)
Insulation (I)	(Cziesielski & Vogdt, 2007; Holm & Künzel, 1999; H. M. Künzel, 1998, 2010; H. M. Künzel & Gertis, 1996; Kussauer & Ruprecht, 2011; Neumann, 2009; Zirkelbach et al., 2005, 2008)
Mechanical anchors (A)	(Cziesielski & Vogdt, 2007; European Organisation for Technical Approvals, 2002, 2013; Kussauer & Ruprecht, 2011; Neumann, 2009)
Reinforcement (R)	(Amaro et al., 2014; Cziesielski & Vogdt, 2007; Kussauer & Ruprecht, 2011; Neumann, 2009; Schrepfer, 2008)
Finishing layer (F)	(Arizzi et al., 2012; Cziesielski & Vogdt, 2007; Fernandes et al., 2005b; Gaspar & de Brito, 2011; Kussauer & Ruprecht, 2011; Neumann, 2009)
Additional details (X)	(Annila et al., 2014; Cziesielski & Vogdt, 2007; Kussauer & Ruprecht, 2011; Neumann, 2009; Norvaišienė et al., 2013)

In order to reveal errors in the questionnaire, one declared and one undeclared pre-test were conducted. Individual pre-testing has been used by other researchers similarly (Rothge, Willis, & Forsyth, 2001) and has shown good results in identifying misinterpretations (Presser et al., 2004). The reviews were conducted individually and independently, and the results of the other evaluations were not revealed. One expert was located in Germany, had a doctoral degree, and had more than 20 years of experience with the ETICS as a consultant and supervisor. The second was located in Estonia, had a master's degree in civil engineering, and more than 15 years of experience as project manager in ETICS construction. Both experts were participating in the National ETICS Standards Committee. During the pre-tests the wording of 16 degradation factors was rephrased to improve the legibility and suitability for selected ETICS systems.

The entire list of revealed on-site shortcomings for further evaluation is presented and discussed in the following sub-sections by layers. Due to the scope of the research, the shortcomings eligibility is set by the type of the system's fixing method, adhesive with mechanical anchors or purely bonded system. For the indexing of the DFs according to the fixation types ”a” or ”b” is added to the identification code (ID). Additionally, the distinction by the type of insulation material, expanded polystyrene or mineral wool, was made which is represented with “ETICS type” as was shown in Table 1.

3.1 Substrate

The first layer is the external layer of the existing structure - the layer of substrate (S). The DFs concern the pre-treatment of the surface and the properties of the substrate. The existing exterior wall of the building is required to resist the additional load caused by ETICS and is responsible for the stability and the adhesion characteristics of the attached system to a large extent. Adhesive creates mechanical bonds due to the infiltration of mortar fluids into the cavities and pores of the substrate, caused by capillary suction. Crystallisation of the fluids creates a mechanical connection between the layers. Factors that influence the process in the layer of substrate are summarised in Table 6.

Table 6. Degradation factors for the substrate preparation.

ID	ETICS type	Description of the degradation factor
S1 (a,b)	1,2,3	Substrate is covered with grease or oil
S2 (a,b)	1,2,3	Substrate is covered with dust or dirt
S3 (a,b)	1,2,3	Substrate is covered with biological growth
S4 (a,b)	1,2,3	Substrate is covered with paint or other material that can chemically react with adhesive
S5 (a,b)	1,2,3	Substrate is under required load-bearing capacity
S6 (a,b)	1,2,3	Substrate has large unevenness or has detached areas
S7 (a,b)	1,2,3	Unsuitable surface (too smooth), which reduces adhesion properties
S8 (a,b)	1,2,3	Substrate has very low humidity (inorganic adhesive)
S9 (a,b)	1,2,3	Substrate is very wet (raining prior to application of adhesive)
S10 (a,b)	1,2,3	Substrate is frozen during the application (inorganic adhesive)

The DFs S1, S2, S3, and S4 concern the cleanliness of the surface. Surfaces with biological growth (S3), dirt (S2), or oil (S1) create an adhesion-prohibiting layer (H. M. Künzel, 2010). The adhesion-prohibiting layer influences the penetration rate of adhesive fluids and are a subject of construction process factors (Flores-Colen et al., 2009). It depends on preparation works that aim to increase the access to pores, such as cleaning dust, grease, and oil (Silva et al., 2013). Old paint on the substrate (S4) can create a chemical reaction between the old paint and the adhesive. This might cause the reduction of bond strength and the loss of stability of insulation plates (Cziesielski & Vogdt, 2007, pp. 194–195). It can be avoided if a test with the adhesive is conducted before application of the next layer. The loss of adhesion can be diagnosed with slight pressing afterwards. As a solution for failures, additional anchoring can be done if polystyrene insulation plates are used.

During surface pre-treatment, the removal of large unevenness of the substrate is foreseen (S6) to enable equal curing process in the layer and reduce the risk of airflow in the system. Unevenness of up to 2 cm/m is allowed to be levelled with adhesive, while unevenness above 2 cm/m should be levelled with mortar (Cziesielski & Vogdt, 2007).

Adhesive bond with another layer is dependable according to the layers' surface conditions. Layer with rough surfaces enable higher penetration into the pores, which has a positive influence (Silva et al., 2013). In contrary, surfaces that are too smooth disable penetration into the pores (S7), thereby posing a risk to the system.

The minimum bond strength requirement to be fulfilled is 0.08 N/mm2 (S5), which enables bearing wind suction load, intrinsic weight, hygrothermal loads, and internal movements of structure (Cziesielski & Vogdt, 2007, pp. 192–193). The pre-treatment of the irregularities enables the bearing of additional load as calculated.

Beside the surface properties, unfavourable climate conditions during the construction process influence the properties of the adhesive (Flores-Colen et al., 2009). Frozen substrate (S10) affects the curing process of the inorganic mortar. Dry substrates (S8) affect the cracking sensitivity, decrease flexural strength, and bending modulus of the mortar (Balayssac et al., 2011). Wet substrate (S9) or condensation, on the other hand, causes the filling of pores on the top layer of the substrate (Kussauer & Ruprecht, 2011, p. 146; Neumann, 2009, p. 169). If the pores are filled, the adhesion cannot penetrate the substrate to provide the calculated adhesion properties. Therefore, wet substrates need to be dried beforehand.

3.2 Adhesive

The DFs in the layer of the adhesive concern the activities after the pre-treatment of the substrate. Correctly applied adhesive layer reduces stability concerns of the whole system (Collina & Lignola, 2010). The DFs for the layer of adhesive are summarized in Table 7.

The adhesive must be compatible with the substrate's characteristics to provide the required adhesive properties. For insulation with polystyrene, the adhesive should cover at least 40% of the insulation plate's surface area, applied with the bead-point technique (in case of bonded and fixed ETICS) (Cziesielski & Vogdt, 2007, p. 156). As an advantage of the application technique, the unevenness of the substrate will be settled if the plate is installed with enough pressure. In case the area is reduced, the stability of the system is reduced. Other types of ETICS may require full area coverage, such as insulation materials made out of mineral wool.

The bead-point technique foresees that the insulation plate boarder areas (D1), and the two dots in the middle (D2) are covered with adhesive (Kussauer & Ruprecht, 2011, p. 183; Neumann, 2009, p. 202). This ensures the necessary bond strength and the bowing out of the insulation plate.

The leading temperature gradient is located in the insulation panel that increases stresses in the adhesive layer. During winter seasons, peeling stresses in the adhesive layer are higher than that in summer. Thermal effects increase tensions near the edges. During the laboratory test, it is revealed that the stresses reached maximum on a distance of 57 mm from the centre on the longer side of the panel (1200 mm). Therefore, the presence of adhesion is important on the outlines of the insulation panel (D1), as the inner area is practically unloaded. Correct application prevents the bending out of the sides, which causes vertical or horizontal crack formation directly on the edge of the plate.

Table 7. Degradation factors of the adhesive layer.

ID	ETICS type	Description of the degradation factor
D1(a,b)	1, 2	Missing adhesive on the edges of insulation (polystyrene)
D2(a,b)	1, 2	Missing adhesive in the centre of insulation (polystyrene)
D3(a,b)	1, 2, 3	Insufficient adhesive surface area
D4	3	Adhesive is not rubbed into insulation plate (mineral wool)
D5	3	Adhesive is not treated with notch towel (mineral wool)
D6	1, 2	Increased area covered with adhesive
D7(a,b)	1, 2, 3	Working time of the adhesive is exceeded
D8(a,b)	1, 2, 3	Low pressure during the application of insulation plates
D9(a,b)	1, 2, 3	Large unevenness of the adhesive layer
M1(a,b)	1, 2, 3	Unsuitable mixture storage conditions
M2(a,b)	1, 2, 3	Failure of mixing procedures to remove clots
M3(a,b)	1, 2, 3	High share of kneading water
M4(a,b)	1, 2, 3	Low share of kneading water
M8	1, 2, 3	Addition of ingredients that are not recommended to the mixture
M9(a,b)	1, 2, 3	Low temperature (freezing) during the application and/or the curing process
M10(a,b)	1, 2, 3	High temperature (hot) during the curing process
M11(a,b)	1, 2, 3	Low humidity (dry) during the curing process
M12(a,b)	1, 2, 3	Usage of winter mixtures if weather conditions are not suitable

Summer season increases linear thermal expansions and affects the aspect of stability. Failure risk increases with thinner insulation panels due to the effect caused by the simultaneous effect of compression stress to high slenderness. The adhesive in continuous areas in the centre reduces stability concerns (Collina & Lignola, 2010). Arching out of insulation plates is caused by missing adhesive in the centre area (D2). It is identifiable visually as the upper area of the plates enables the attachment of more dust. This results with the growth of microorganisms in these areas. Furthermore, if the light is falling parallel to the façade, arching can be seen. Additionally, correct adhesive installation prevents airflow behind insulation, improving safety in case of fire (H. M. Künzel, 2010).

The area size of the adhesive (D3) should be between 40% to 100%, depending on the type of selected system. Mineral wool insulation plates must be covered fully with adhesive and treated with notch towel (D5). Without the treatment, there is no possibility to level the substrate ground in case of unlevelled areas, disabling the possibility to level the edges of neighbouring plates (Cziesielski & Vogdt, 2007, p. 207). A similar effect occurs when the thickness of adhesive differs to a large extent (D9). Increased coverage area also has a negative effect, as large contact area decreases the soundproof properties up to 3dB (Cziesielski & Vogdt, 2007, p. 37). It is also important to rub the adhesive into the mineral plate in order to provide sufficient adhesive property (D4) (Cziesielski & Vogdt, 2007, pp. 85–87). At this phase, the top fibres must not break. After this preparation phase, the whole amount of adhesive can be applied. It is allowed to apply the adhesive mix directly to the substrate. The application of the prepared mixture (D7) must occur shortly in order to prevent curing and exceeded working time before actual application.

The pressure during application (D8) ensures the needed bond strength and prevents the bowing out of the insulation plate. Without the pressure, the adhesion strength between adhesive and substrate will be too weak due to hollow areas (Cziesielski & Vogdt, 2007, p. 207). At the same time, the adhesive cannot penetrate into the joints between insulation plates. During application, the plates should be pushed to the sides slightly with a minor pressure to level the adhesive. If an insufficient amount of adhesive is applied (D3) during the construction process, the stability of the system is reduced while increased adhesive area (D6) can decrease the soundproof properties up to 3dB (Cziesielski & Vogdt, 2007).

The curing process influences relevant characteristics of the mortar (Gaspar & de Brito, 2011). As the value of cohesive rupture is greater than adhesive in the early phases of curing, moist conditions prevent cracking and micro cracking (Barreira & De Freitas, 2014; Silva et al., 2013). During the construction works, it is essential to follow the appropriate storage conditions (M1) and weather conditions during the application of the materials (Nilica & Harmuth, 2005). High temperatures during the curing of the mixture (M10) and low relative humidity (M11) lead to fast dehydration and cracking due to tensions caused by rapid shrinkage. Low temperatures (M9) cause frost damage, which can be seen if snowflake shaped minor cracks occur shortly after application.

Only laboratory-tested specific ingredients are allowed to be added (M8) if the product manufacturer foresees it. The adhesives must have a specific amount of ingredients. For example, sand can be added to the mixture, but the adhesive properties will decrease (Arizzi et al., 2012; Cziesielski & Vogdt, 2007, p. 207). Prefabricated mixtures are not authorised to be altered on site, and it is necessary for preparation works to hold the right dosage of kneading water (M3, M4) to meet the expectations of the mixture properties and sufficient mixing process (M2) to remove clots (Amaro et al., 2013; Fernandes et al., 2005a, 2005b; Silva et al., 2013).

3.3 Insulation material

The adhesive application is followed by the application of the insulation plates. The primary expectation of the insulation material is to reduce the thermal conductivity of the façade. The shortcomings in the construction technology are collectively presented in Table 8.

The polystyrene-based insulation products are not protected against UV-radiation (I1). Insulation plates being exposed to UV radiation alters the material structure on the exposed side. The adhesion will decrease. In case of UV related degradation, the plates must be cleaned before adding the next layer (Cziesielski & Vogdt, 2007, pp. 207–208). After the first months of the production of the insulation plate made out of polystyrene, moisture diffusion initiates the shrinking process (I2). In order to avoid cracking, the insulation plates must have finished the diffusion process (Cziesielski & Vogdt, 2007, pp. 137–140).

Insulation plates made of mineral wool have altered properties in wet conditions (I3). The wetting causes a decrease in tensile strength, which disables the ability to hold anchor plates pulling through. The wetting problem occurs often during installation, when the end of the plate is opened to rain, leading to decreased adhesion between insulation plate and adhesive (Cziesielski & Vogdt, 2007, pp. 208–211). In case of trapped moisture in the façade system, the highest relative humidity rises at the interface between the external rendering and insulation material (Holm & Künzel, 1999). Pull-off strength reduction occurs during the first four months after the construction, and humidity and moisture as factors are not relevant during the aging process in that sense (Zirkelbach et al., 2005). However, the laboratory tests show that the drying-out period might reach up to 12 years (H. M. Künzel, 1998). The walls that have better thermal resistance cause the lowering of vapour pressure as temperature falls. The lower vapour transmission through capillaries reduces the drying out capability to the exterior side and internal moisture is retained in the wall construction for a longer period. This causes a reduction in the thermal resistance of the wall and reduces corrosion protection of the existing structural elements (H. M. Künzel & Gertis, 1996; Zirkelbach et al., 2008). The argument must be considered during the reconstruction of existing buildings as the moisture content on the exterior side is higher in comparison to internal areas.

Table 8. Degradation factors of the insulation layer.

ID	ETICS type	Description of the degradation factor
I1	1, 2	Polystyrene is exposed to UV-radiation for a extended period
I2	1, 2	Insulation plates are installed shortly after manufacture (unfinished diffusion process)
I3(a,b)	3	Insulation plates with very high relative humidity (wet)
I4	1, 2, 3	Continuous gaps between substrate and insulation material
I5	1, 2, 3	Corners of neighbouring insulation plates are crossed or too close
I6	1, 2, 3	Corners of the openings have crossed joints
I7	1, 2, 3	The joint width of neighbouring insulation plates is too wide
I8	1, 2, 3	Large height difference between neighbouring insulation plates
I9	1, 2, 3	Broken areas of the insulation plates are not filled with the same material
I10	1, 2, 3	Missing or narrow fire-reluctant areas

As a result of the application process of the insulation plates, the airflow between insulation and substrate must be avoided (I4). Continuous airflow alters the thermal conductivity properties and has a high impact on fire protection capacity. For the system with insulation made of polystyrene, fire-reluctant areas are foreseen in many countries (I10) and must be followed (Cziesielski & Vogdt, 2007, p. 157). ETICS with polystyrene insulation are flame-retardant systems (Euroclass B1), while system with mineral wool are inflammable (Euroclass A).

During the installation process, the crossed joints between insulation plates in the continuous areas (I5) and the corners of openings (I6) hold risks. As the mixture in this area undergoes thickness changes, cracks can easily occur. The insulation plates on the corners of the openings should be cut into the required shape, in order to avoid joint crossing on the corner (Cziesielski & Vogdt, 2007, p. 211). Wide gaps between insulation plate joints (I7) can be avoided by installing the plates tightly next to each other (Kussauer & Ruprecht, 2011, pp. 186–189). If gaps are present, the mixture fills the areas to some extent, causing the formation of a thicker layer in the specific area, resulting in cracks due to shrinking of materials (Cziesielski & Vogdt, 2007, p. 212) or decrease in airtightness (H. M. Künzel, 2010). Height difference between insulation plates (I8) leads to cracks in the thinner layer. In case of uneven areas of polystyrene-based insulation, the insulation plates must be polished off or filled with suitable material (I9) (Neumann, 2009, p. 210). In case of mineral wool insulation, the substrate needs to be levelled or the difference reduced by adhesive thickness (Cziesielski & Vogdt, 2007, pp. 213–214).

3.4 Mechanical anchors

After the application of the insulation material, anchorage is attached, if required. The DFs that influence the performance of mechanical anchors are presented in Table 9.

Table 9. Degradation factors of the mechanical anchors.

ID	ETICS type	Description of the degradation factor
A1	2, 3	Increased diameter of drilled anchor hole
A2	2, 3	Decreased diameter of anchor plate
A3	2, 3	Decreased number of anchors in the continuous areas
A4	2, 3	Increased number of anchors
A5	2, 3	Location of anchors is not as foreseen
A6	2, 3	Anchor plate is installed too deeply into insulation material
A7	2, 3	Anchor plate is placed too high on the surface of insulation material
A8	2, 3	Decreased number of anchors in the corner areas
A9	2, 3	Usage of unsuitable anchor type
A10	2, 3	Hole of the anchor is not cleaned

Two types of mechanical anchors are mainly used, plastic anchors having a screw or a nail as the expansion element. The plate covering the anchor is usually 60 mm wide (140mm for additional anchors in mineral wool), and the anchor needs to bear wind suction loads (Cziesielski & Vogdt, 2007, pp. 141–146). In order to bear wind suction load, the minimal amount of mechanically fixed anchors should be used, with specified type (A9), length and load bearing class (Cziesielski & Vogdt, 2007, p. 157). The increased number of mechanical anchors (A4) decrease the soundproofing of the system to some extent (Cziesielski & Vogdt, 2007).

The anchorage system has the exact amount of anchors in the continuous areas and in the corners of the building (A3, A8), with the specified diameter of anchor plate (A2) and location (A5) (European Organisation for Technical Approvals, 2002, 2013). If the anchor plates are failing, the system fails to bear the necessary wind suction loads (Cziesielski & Vogdt, 2007, p. 201; Neumann, 2009, pp. 195–202). The calculated number of anchors are responsible for frictional strength that occurs between the cavity wall and the anchor.

The anchors must have the specified length and anchor plate. In installing the anchors, the hole diameter (A1) and the depth should follow the specifications (Kussauer & Ruprecht, 2011, pp. 156–159). To ensure a faultless installation, the hole should be cleaned and dust-free (A10), as the dust will reduce the frictional strength between the cavity wall and the anchor. The exterior side of the plates should be at the same level and they should be placed lower than insulation plate (A6) in order to avoid visibility after the render is attached (Neumann, 2009, p. 193). In case the plate lies on the higher level (A7), decreased render thickness will dry out faster in comparison with other areas. During repeated wetting and drying out periods, the tone of the areas will be lighter.

The durability will decrease to 10 years as the hygrothermal tests have shown (Cziesielski & Vogdt, 2007, pp. 214–215).

3.5 Reinforcement layer

The stresses caused in the system are transmitted to the mesh applied in the reinforcement layer. The ability to transfer stress evolves during mesh or mortar application. The DFs in the reinforcement layer are summarised in Table 10.

Table 10. Degradation factors of the reinforcement layer.

ID	ETICS type	Description of the degradation factor
R1	1, 2, 3	External layer of the insulation plate is too smooth; reduced adhesion
R2	1, 2, 3	Decreased overlap of the mesh
R3	1, 2, 3	Folded mesh
R4	1, 2, 3	Missing diagonal mesh
R5	1, 2, 3	Mesh not filled with mortar; placed on the edge of the layer
R6	1, 2, 3	Thin mortar layer
R7	1, 2, 3	Layer is not applied in wet to wet conditions
R8	1, 2, 3	Usage of incompatible mesh
M1c	1, 2, 3	Unsuitable material storage conditions
M2c	1, 2, 3	The mixing procedures do not remove clots
M3c	1, 2, 3	High share of kneading water
M4c	1, 2, 3	Low share of kneading water
M5	1, 2, 3	High purity of kneading water in mortar
M6	1, 2, 3	Increased aggregate (sand) share
M7	1, 2, 3	Increased binder content
M9c	1, 2, 3	Low temperature (freezing) during application and/or curing process
M10c	1, 2, 3	High temperature (hot) curing conditions
M11c	1, 2, 3	Low humidity (dry) curing conditions
M12c	1, 2, 3	Usage of winter mixtures during unsuitable weather conditions

The DFs can be classified as mortar-related or mesh application shortcomings. During the application of the mortar, the weather conditions should be considered (Amaro et al., 2013). The factors M1c to M12c shown in Table 10 are the same as in sub-chapter 3.2, but these are applicable for the reinforcement mixture.

The stresses caused in the render and in the insulation layer are transmitted to the reinforcement layer and the mesh (Schrepfer, 2008). The stresses can be directed successfully only if there is adhesion between the surface of the insulation plate and the reinforcement mixture (R1), compatible mesh type is used (R8), and mortar fills the inner areas of the mesh (R5) (Neumann, 2009, p. 211). If the layer of mixture is too thin (R6), the tensile strengths cannot be transmitted (Kussauer & Ruprecht, 2011, pp. 202–203). In case of a shortcoming in an area, cracks occur. During the installation process, the first layer of mixture should be applied on the insulation plates and the mesh should be pressed into the mixture. The covering layer should be applied shortly in wet to wet condition (R7), as the mixture is not cured (Cziesielski & Vogdt, 2007, p. 220). Otherwise, a separating layer forms. The fast installation of the covering layer reduces the risk of curing of the mixture and separation of layers.

Folds in the mesh (R3) disable the ability to resist tensile forces. They should be cut out before the covering layer is applied and replaced with additional mesh (Cziesielski & Vogdt, 2007, p. 220). The overlapping should be equal or more than 10 cm (R2). Otherwise, the tensile forced cannot be transmitted to the neighbouring mesh and cracking may occur. The effect can occur easily with even a slight misalignment in angle, as the mesh is applied vertically. The transmittance of forces can also occur if different meshes that are incompatible with each other are used (Cziesielski & Vogdt, 2007, pp. 216–217).

Near the openings, the diagonally placed additional mesh should be 30 to 40 cm in length and 20 cm in width. Diagonally placed additional mesh should be applied on the corners of openings as notch stresses occur (R4). The additional mesh should be applied together with the main mesh and covered as usually in not cured conditions (wet to wet) (Cziesielski & Vogdt, 2007, pp. 117–124). In case of missed mesh, diagonal cracks occur.

3.6 Finishing layer

The external layer, besides the aesthetic function, is responsible for weather protection to some extent. Natural conditions lead to a combination of effects: the wind, rain, pollutants, relative humidity, temperature, and solar radiation (Arizzi et al., 2012). Possible construction technology related DFs are summarised in Table 11.

Table 11. Degradation factors of the finishing layer.

ID	ETICS type	Description of the degradation factor
F1	1, 2, 3	Missing primer if required
F2	1, 2, 3	Reinforcement mixture or primary coat is not cured
F3	1, 2, 3	Thick render layer/differences in thickness
F4	1, 2, 3	Thin render layer
F5	1, 2, 3	Render is not applied in one continuous workflow
M1d	1, 2, 3	Unsuitable material storage conditions
M2d	1, 2, 3	Failure of mixing procedures to remove clots
M3d	1, 2, 3	High share of kneading water
M4d	1, 2, 3	Low kneading water share in mixture
M9d	1, 2, 3	Low temperature (freezing) during the application and/or the curing process
M10d	1, 2, 3	High temperature (hot) curing conditions
M11d	1, 2, 3	Low humidity (dry) curing conditions
M12d	1 ,2, 3	Usage of winter mixtures when weather conditions are not suitable

The factors M1d, M2d, M3d, M9d, M10d, and M11d have the same description as in sub-chapter 3.2, but are applicable for render (Fernandes et al., 2005b).

Crack formation is prevented when a primer is applied (F1) in accordance with the system producer (Neumann, 2009, p. 212). It ensures the required adhesive properties between render and reinforcement mixture. Although it is essential that the reinforcement mixture is cured (F2). The primer is especially necessary if the time gap between the application of the layers is longer (Cziesielski & Vogdt, 2007, p. 220). If the adhesive properties are reduced, the capillary water will get between layers and the amount of water will increase in this area over time, resulting in detaching (Gaspar & de Brito, 2011). That is, the render arches out and is filled with water. If the technology is not followed, the render should be reapplied.

The application process is essential to follow the required climatic conditions and thickness of the layer. Increased thickness (F3) and high temperatures lead to fast dehydration and cracking due to tensions caused by rapid shrinkage. Decreased thickness (F4) reduces the resistance to weather effects, and the anchor plates will be visible, as they will dry out faster (Cziesielski & Vogdt, 2007, p. 220; Kussauer & Ruprecht, 2011, p. 213).

3.7 Additional details

Specific technical solutions for particular areas of ETICS are developed rapidly by product manufacturers, and an increased amount of technological installation may be suggested. In order to reveal a comparative overview of problematic areas the construction technology related problems of additional details are approached more generally. The DFs are presented in Table 12 in a more holistic manner.

Table 12. Degradation factors of the external details.

ID	ETICS type	Description of the degradation factor
X1	1, 2, 3	Structural expansion joint is not installed/finished properly
X2	1, 2, 3	Windowsill is not appropriately finished (i.e., curved upwards, proper sealants)
X3	1, 2, 3	Unsolved rainwater drainage (i.e., drainpipe or drip profiles are not used)
X4	1, 2, 3	Fixed frame connection is not finished accurately (i.e., missing sealants)
X5	1, 2, 3	Roof edge covers are not installed correctly (i.e., vertical detail too short)
X6	1, 2, 3	Shock resistance solution is not used (i.e. no double reinforcement mesh, corner details with metal, or additional protective plate installed)
X7	1, 2, 3	Unfinished penetrations through the system (i.e., fixed without sealants)
X8	1, 2, 3	Unsuitable plinth detail solutions (i.e., incorrect fixing, overlapping of details)

The DFs consist of the most problematic areas of the façade (Institute for Building Research (Institut für Bauforschung) e. V., 2011) that have an impact on the performance. The areas to be evaluated are structural expansion joints, windowsills, rainwater drainage, fixed frames, roof edge covers, plinth details, penetration through the system, and solutions for shock resistance. The external details should be planned and applied in a way that water does not penetrate into the system and internal tensions do not harm the layers.

Usually the width of the expansion joint (X1) should be at least 15 mm and the length of the joint details should not exceed 2,50 m. The correct expansion joints enable the protection against rainwater penetration during hot and cold cycles (Neumann, 2009, pp. 229–232). In order to protect the joint from rainwater, the detail on the upper area should overlap the detail below. For the expansion joints completion, four possibilities are mainly used: (i) specific expansion joint details, (ii) detail to end render with sealant tape, (iii) detail to end render covered with sealant tape and applied sealant, or (iv) creation of a gap between two section and using sealant tape (Cziesielski & Vogdt, 2007, pp. 167–170). Horizontal or vertical joints might be necessary to prevent degradation caused by structure movements. If the endings of render are not finished properly, water will penetrate into the joint and cause damage. There is a need to end render properly by covering the area with a sealant such that the water has no access to the edge. Alternatively, corner and short areas of the horizontal side can be covered with continuous reinforcement and render and the joint filled with sealant (Cziesielski & Vogdt, 2007, pp. 241–244).

In the lower area of the plinth (X8), where a connection to earth is possible, extruder polystyrene should be used (Kussauer & Ruprecht, 2011, p. 179). As the plinth details are mounted on the substrate, the fixing should be less than 30 cm apart as expansion stresses occur. Unevenness of substrates should be evened with distance disks. The details should be placed tightly together horizontally, not overlapped, and mounted together with a clamping detail (Neumann, 2009, p. 240). The length of plinth profile should be between 2,5 and 3,0 m. It should not be exceeded, as fixing details will be loaded with high stresses. The detail covering the lower area of the façade – (base profile) exterior side of the detail (in the render) must be perforated to assure the fixation in render. The thermal conductivity can be reduced by using the thermally decoupled system. It consists of a detail mounted on the substrate, but it remains in the insulation layer. The base of the plinth is covered with a plastic detail, which enables the protection of the area from rainwater splashes.

Roof edge covers and soffit corners (X5) are mainly made with aluminium or zinc details (Cziesielski & Vogdt, 2007, pp. 174–176). The details must be able to stand loads created by wind and be watertight. The fixing details should be as near as possible on the exterior side. The top area of the detail should be inwardly directed (rainwater) at a minor angle (2%). Otherwise, the water might flow into the façade. The vertical side of the detail on the outer perimeter should cover the façade up to 10 cm when the height of the building is more than 20 m. If the height is less than 8 m, the coverage of 5 cm is allowed. In case the height is between 8 and 20 m, then 8 cm are expected. The ETICS vertical area needs to be protected from rainwater directed by wind (Neumann, 2009, pp. 234–237). If due to construction process the details are mounted before rendering, then it is preferred to unmount the details to apply the render. An additional sealant can be used, but it is not preferred, as the gap between vertical detail and ETICS might be too wide. The upper area of the façade should be designed with an additional vertical detail to prevent the access of wind-driven rain penetration to the edge of ETICS, enabling access between the layers. The fault leads to a detachment of render or loss of stability for mineral wool insulation (Cziesielski & Vogdt, 2007, pp. 248–249).

The connection between openings (X4) and the façade should be built in a way that stresses and moisture do not cause any harm. Therefore, after the window frame is mounted, the joint between the frame and the wall is filled with mineral wool (Neumann, 2009, pp. 218–222). The usage of PU foam is not recommended, as it has reduced soundproofing properties. In the internal side of the window, the joint should be vapour proof such that no condensation can occur. Between ETICS and the window, a sealant with a compression rate below 1:3 should be installed in order to provide protection against external effects. The compressed sealant should also be installed between vertically raised edge of the window sill and the insulation material to avoid cracks caused by thermal expansion. Additionally, the reinforcement mesh (300 mm x 200 mm) should be placed diagonally on the corners of the window to avoid cracks caused by stress concertation (Cziesielski & Vogdt, 2007, pp. 177–178). Frames of the openings placed in window and door areas need special sealants to prevent uncontrolled cracking (Cziesielski & Vogdt, 2007, p. 247).

Below window ledge (X2), the insulation needs to be covered with a reinforcement layer to protect water penetration from wind-driven rain, which might penetrate into the system (Cziesielski & Vogdt, 2007, pp. 245–246). The window areas should be considered with care. The thermal changes create shrinkage and expansion of materials. Therefore, the windowsill must be curved upwards and sealants between materials to be used. If it is not possible the joint should be covered with special elastic sealant band (Neumann, 2009, pp. 222–226).

On the edges, where vertical surface turns into horizontal surface, a corner profile with drip should be used. It enables to lead rainwater (X3) in a safe dripping area. Without the drip area the wind directs the drops into other areas of the façade. It can be done with various profiles similar to plinths. If no edge for dripping is built, the water creates a dripping damage in the length of 40 mm inward, eroding the render (Cziesielski & Vogdt, 2007, pp. 179–181).

Additionally fixed details that require fixation through the system (X7) need protection from water with sealants to prevent moisture access (Cziesielski & Vogdt, 2007, pp. 181–183,251–255; Neumann, 2009, pp. 242–248). The fixed details can also cause increased thermal conductivity. Shock resistance of the façade (X6) should be raised on the lower areas, where pedestrians have access. One of the possibility is to use double reinforcement mesh and the corners could be protected with corner details made of metal (Annila et al., 2014; Norvaišienė et al., 2013). Alternatively, an additional plate can be installed in the ETICS. The thickness change can be compensated with thinner insulation (Cziesielski & Vogdt, 2007, pp. 251–255).

4 Relevance of the components

The developed relevance assessment method mathematically aggregates a number of individual components. In this section, the components are presented and their results in isolation are discussed.

4.1 Technical severity categories

For the building products used in the European Union, the general international technical requirements are outlined by Regulation (EU) Number 305/2011 (European Parliament, 2011) (also Construction Products Regulation or CPR), which is the basis for the "Guideline for European technical approval of External Thermal Composite System (ETICS) with rendering" (also ETAG 004) (European Organisation for Technical Approvals, 2013). The Construction Products Regulation presumes that buildings and construction products meet the performance requirements during their economically reasonable working life and describes seven essential requirements for construction products. "Mechanical resistance and stability" (SC1), "safety in case of fire" (SC2), "energy economy and heat retention" (SC3), and "protection against noise" (SC4) are considered in this study as described in the CPR. "Sustainable use of natural resources" is explained in ETAG 004 as measures for the "aspects of durability and serviceability", which concern durability from several aspects that are differentiated in this study. The system must provide protection against short-term weather effects such as "humidity and weather protection" (SC5), deliver its functions during the whole service life ("long-term durability", SC6), and be resistant to corrosion ("corrosion protection", SC7). "Safety in use" considers the resistance to combined stresses caused by normal loads. For clarity in this research, the label "ability to bypass tensions" (SC8) is used. "Hygiene, health, and environment" considers the effect on the indoor and outdoor environments as well as pollution due to the release of dangerous substances, which is not seen as a separate severity category in this façade construction technology-related study.

The impact of the degradation factors on the severity categories were evaluated by the experts. In case the expert was not confident regarding the technical effect, an option to not rate a specific factor was enabled. 11 degradation factors received severity evaluations from less than two experts and were removed from further analysis. The factors were the following: increased number of anchors (A4), adhesive not rubbed into isolation plane made out of polystyrene (D4b), increased area covered with adhesive (D6), usage of winter mixtures in adhesive and finishing layer (M12a, M12b, M12d), low share of kneading water in the mixture in the finishing layer (M4d), render not applied in one continuous workflow (F5), high purity of kneading water in the reinforcement mortar (M5), increased aggregate share in the reinforcement mortar (M6) and increased binder content in reinforcement (M7).

Friedman's test was used for each degradation factor separately to detect expert values that are in the critical zone. After each negative outcome of the Friedman's test, the most aberrant evaluation from the mean value was removed. In case of a number of factors with the same difference from the mean value, the lowest scoring rating was chosen. The remaining 103 degradation factors included 991 individual evaluations; 53 degradation factors received positive Friedman's test results with the first analysis. 82 individual evaluations were in the critical zone, and a maximum of four rounds were applied. 33 of the DFs that had the value of Friedman's test over the critical value required the elimination of one expert rating, 6 DF required the removal of two ratings, 7 DF required the removal of 3 ratings, and 4 required the removal of 4 ratings. 909 evaluations remained in the analysis. After the Friedman's test, the data sets included 4 to 12 experimental units. As there were enough different components in the calculation, the inaccuracy of the evaluations did not have a major impact on the final results. Figure 7 shows the number of evaluations that were removed by the experts.

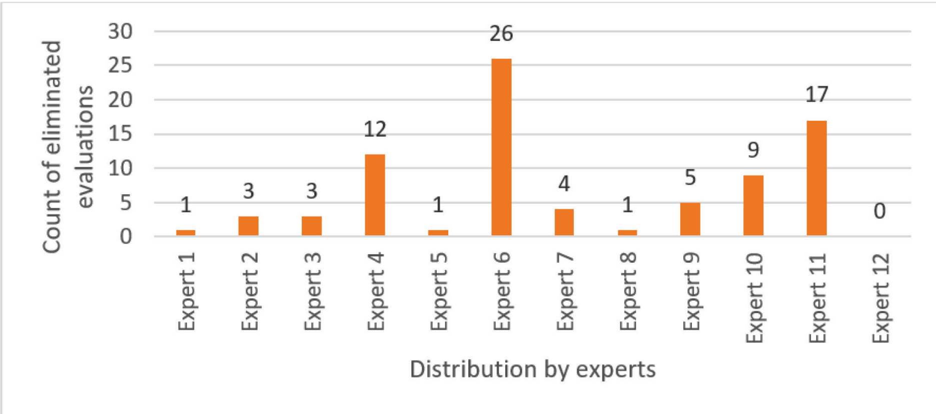


Figure 7. Count of eliminated evaluations by the experts.

The mean value or the severity ratings by severity category of a degradation factor ($SR_{SC,DF}$) is calculated with Equation 1,

$$SR_{SC,DF} = \frac{\sum SR_{DF,SC,e}}{n_e}, \text{ where} \quad (1)$$

$SR_{SC,DF}$ – severity rating of a degradation factor for a specific severity category;
$SF_{DF,SC,e}$ – experts' severity rating for a severity category;
n_e – number of experts.

The comparison of the average evaluations of the severity categories is shown in Figure 8. The mechanical resistance and stability as well as the long-term durability have the highest impact, they are followed by humidity and weather protection and the ability to bypass tensions. The lowest values are those for safety in case of fire, energy economy, corrosion protection, and protection against noise.

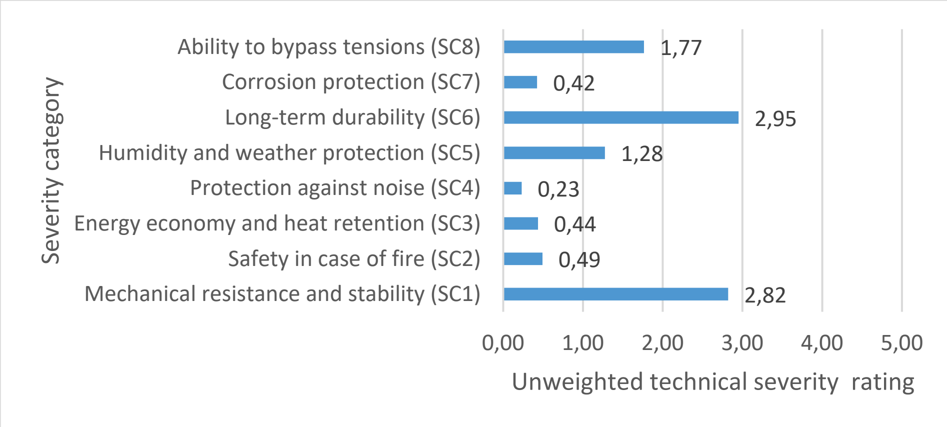


Figure 8. Average unweighted technical severity ratings by severity category.

4.1.1 Comparison of the severity categories' relevance and their correlation

The comparison of unweighted severity ratings of singular severity categories with each other showed that the severity categories of mechanical resistance and stability and long-term durability were affected the most. The standard deviations were 1.02 and 0.81 respectively.

In order to test the relationships of the variables between severity categories, the Pearson correlation coefficient *r* is calculated. It quantifies the degree of relationship between two variables, as shown in Table 13. The correlation analysis of the severity categories revealed correlations within the groups of high-ranking severity categories (SC1, SC5, SC6, and SC8) and within low-ranking categories (SC2, SC3, SC4, and SC7).

Table 13. Correlation analysis between severity evaluation values.

Severity category	SC1	SC2	SC3	SC4	SC5	SC6	SC7	SC8
SC1	1,00							
SC2	–0,17	1,00						
SC3	–0,40	0,40	1,00					
SC4	–0,24	0,58	0,78	1,00				
SC5	–0,08	0,04	0,31	0,23	1,00			
SC6	0,54	–0,07	0,05	0,10	0,62	1,00		
SC7	–0,06	0,29	0,54	0,44	0,49	0,34	1,00	
SC8	0,49	–0,07	–0,13	–0,05	0,52	0,77	0,12	1,00

The degradation factors of the low-ranking categories included a large number of variables that received the value of zero as they have no relevant impact on the severity category. The count of 909 experts' evaluations in each category are presented by their value in Table 14. Fire protection (SC2), thermal resistance (SC3), protection against noise (SC4), and corrosion protection (SC7) have received the rating zero for 753 (83%), 752 (83%), 790 (87%), and 779 (86%) occasions respectively. This is also the reason for the high correlation between these categories, and the correlation within the low-ranking group can be interpreted as irrelevant.

Table 14. The count of ratings by severity category.

Severity category	0	1	2	3	4	5	Sum of the counted evaluations
SC1	101	101	158	209	180	160	909
SC2	753	37	22	46	27	24	909
SC3	752	36	47	39	25	10	909
SC4	790	59	39	13	6	2	909
SC5	538	53	49	113	111	45	909
SC6	99	71	131	242	207	159	909
SC7	779	12	37	31	43	7	909
SC8	410	71	84	126	102	116	909

The correlation in the high-ranking group enables the interpretation of the interaction between the severity categories in the context of defect pathology. The correlation analysis results show that if the shortcoming is reducing the mechanical resistance and stability (SC1), then the long-term durability (SC6) is reduced as well as the ability to bypass tensions (SC8) with moderate correlation (0,54 and 0,49 respectively). Second, the results confirm that if the ability to bypass tensions (SC8) is reduced, then the long-term durability (SC6) is decreased with strong correlation (r = 0,77), and humidity and weather protection (SC5) is decreased with moderate correlation (r = 0,52). Third, the interaction of the corrosion protection (SC7) and humidity and weather protection (SC5) has caught attention, although there is a large number of zero values that strengthen the correlation. It can be said that, to some extent, the reduction of the ability to protect against humidity and weather (SC5) reduces the corrosion protection (SC7), as moderate correlation (0,49) is obtained.

In the context of pathology, it can be said that the defects within mechanical resistance and stability (SC1), together with the ability to bypass the tensions (SC8), are the causes for degradation, and long-term durability (SC6), humidity and weather resistance (SC5), and corrosion protection (SC7) are the effects. Figure 9 presents the interaction of severity categories.

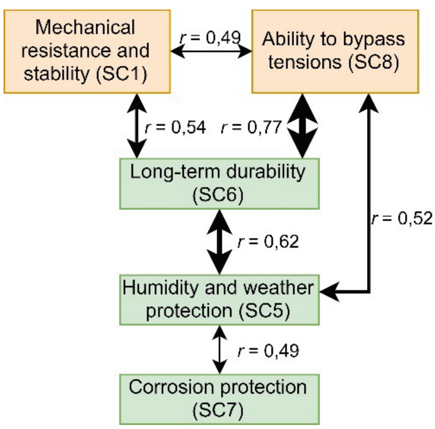


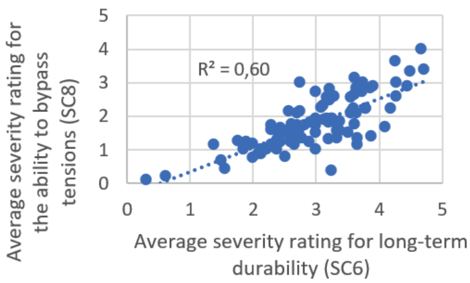
Figure 9. Correlation coefficients of the severity categories.

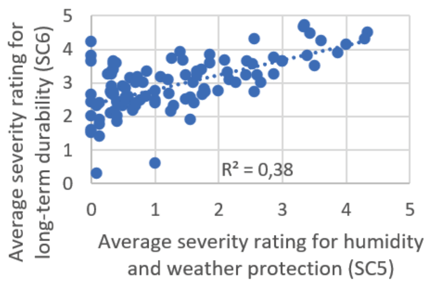
The average values of the severity categories in the high-ranking group is additionally analysed with the help of regression analysis. The pair of ability to bypass tensions (SC8) and long-term durability (SC6) received the R^2 value of 0,60 ((a)

(b)

Figure 10a). By 60% of the cases, the degradation factors that reduce the ability to bypass tensions reduce also the humidity and weather protection of the system. The linear regression analysis for the pair of weather protection (SC5) and long term-durability (SC6), as shown in (a) (b)

Figure 10b, had the R^2 value of 0.38, which implies that the failure in weather protection (SC5) reduced the long-term durability of the system (SC6) for 38% of the cases. The other three pairs (SC1-SC8, SC1-SC6, and SC5-SC8) had R^2 values between 0,28 and 0,29, providing a modest explanation of the model.





(a) (b)

Figure 10. (a) Linear regression for long-term durability (SC6) and ability to bypass tensions (SC8), and (b) humidity and weather protection (SC5) and long-term durability (SC6).

Before the results within each severity category and their impact on various layers can be presented, a technical severity weighting system for the categories must be developed.

4.1.2 Weighting system for technical severity

The described eight severity categories influence the total performance of the façade system. However, as their relevance is not equal, a weighting system has been developed to calculate the weighted severity values of the layers. The weighting of the technical severity categories is following the weighted impact method developed by Aurnhammer (1978), which estimates the diminished value for the users. The method was developed specifically for buildings and concerned the direct technical influence as well as the overall performance. Following Aurnhammer (1978), the total value of 100% is divided into a number of sub-values, each having a specific share from the total value. In the case of a shortcoming in any segment, the final resulting value decreases.

The method enables outlining the criteria and their impact according to the requirements of the research. The degradation severity in all categories sum up to 100%, which describes the total failure in each category. By using this model, it is possible to re-evaluate the weights if new circumstances arise.

In this study, the highest share of 35% has the severity category that is responsible for stability and mechanical resistance (SC1) of the system, as this is the primary essential requirement. The ability to bypass the tensions (SC8) has a share of 10%, as it is relevant for the pathology but has no severe effect on health. The aspects that influence the sustainable use of natural resources and are the results of defects have the overall share of 25%, including long-term durability (SC6) with a share of 15%, humidity and weather protection (SC5) as well as corrosion protection (SC7) with 5% equally. A share of 20% is set for safety in case of fire (SC2) due to its severe impact on the health of the inhabitants. Protection against noise (SC4) and energy economy and heat retention (SC3) are the expected performance requirements without any effect on health and, therefore, have a share of 5% each. The distribution is visualised in Figure 11.

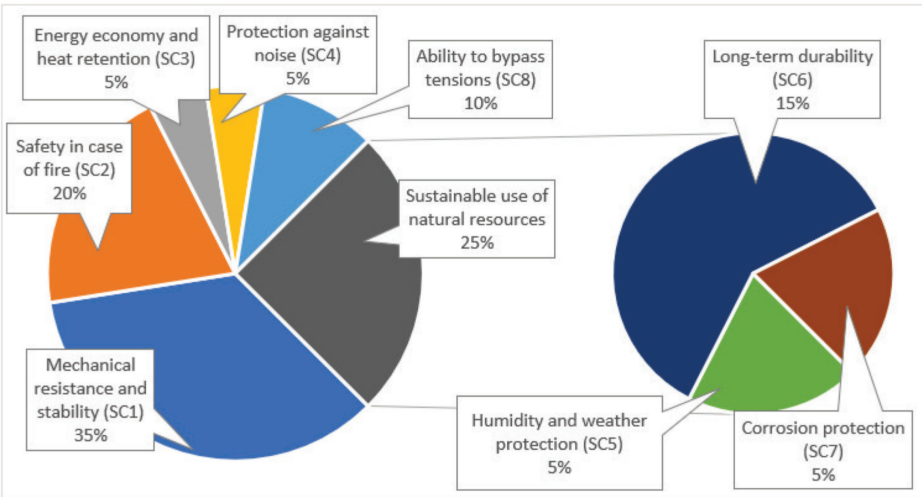


Figure 11. The weight distribution of the severity categories.

The adjusted distribution of the weights facilitates the calculation of the weighted technical severity value of each expert for each degradation factor with Equation (2).

$$SV_{DF,e} = \sum \left(\frac{SR_{DF,SC,e}}{SR_{SC,max}} \times T_{SC} \right) \text{ ,where} \quad (2)$$

$SV_{DF,e}$ – the weighted severity value of an expert;
$SR_{DF,SC,e}$ – the individual rating of an expert for a severity category;
SR_{SC},max – the maximum rating value for the severity category;
T_{SC} – the weight of the severity category according to Figure 11.

The following sub-subsections visualise and highlight the impact of the highly relevant degradation factors in specific layers within each severity category.

4.1.3 Mechanical resistance and stability

Mechanical resistance and stability (SC1) is one of the most essential functions of the building. Although ETICS is a non-load bearing element, this severity category includes the fixation with the exterior wall. The load-bearing structure must tolerate the dead load of the system and be resistant to wind suction and pressure.

The mean severity rating values by layer are shown in Figure 12. Mechanical resistance and stability is relatively highly influenced by the activities in all layers. Slightly higher influence can be noticed from layers' substrate (3,31), reinforcement (3,16), adhesive (3,09), and mechanical anchorage (2,98). Lower impact is caused by additional details and insulation, with the scores of 1,75 and 1,39 accordingly.

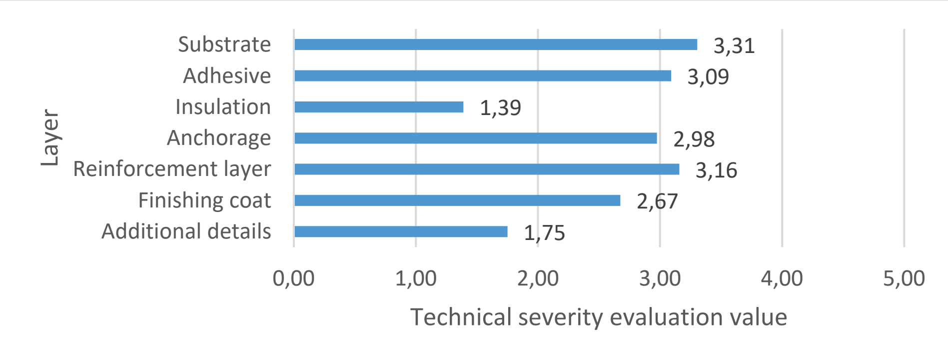


Figure 12. The mean severity rating values of severity category SC1.

The average evaluation value above or equal to 4,0 is caused by 16 degradation factors. The highest impact is caused by low temperatures of the substrate (S10b, S10a) as well as freezing of the mixtures of adhesive, reinforcement, and render (M9c, M9b, M9d). They are followed by preparation activities of the substrate. High risk is caused due to coverage with oil (S1b), dust (S2b), or existing paint (S4b). Additionally, the cases when the substrate is under the required load-bearing capacity (S5b), has very low humidity (S8b), or has exceeded the working time of the adhesive mixture (D7b) are relevant. For the fixation of insulation, the relevant anchorage application related factors are the usage of unsuitable anchor type (A9) and the increased diameter of drilled anchor hole (A1). The list of the highest relevance in this category is completed with the wrong material storage conditions of adhesive (M1b), reinforcement (M1c), or finishing coat (M1d).

4.1.4 Safety in case of fire

Safety in case of fire (SC2) is impacted by material properties as well as airflow within the system that can increase or decrease the threat. In the case of an outbreak of fire, the façade is required to hold load-bearing capacity for a determined period of time and limit the spread of fire and smoke. Material properties are specified with flammability, smoke emission, and dripping of burning material. The detailed performance levels are defined in national regulations and laws. Construction areas should be separated into sections to stop the spread of fire with non-flammable materials (i.e., mineral wool). The shortcomings in this severity category pose a threat to the human life and also have a fatal effect on the system.

This severity category has relatively low overall influence. The main shortcomings are in the insulation layer (1,04), following adhesive (0,49) and reinforcement (4,83), as seen in Figure 13.

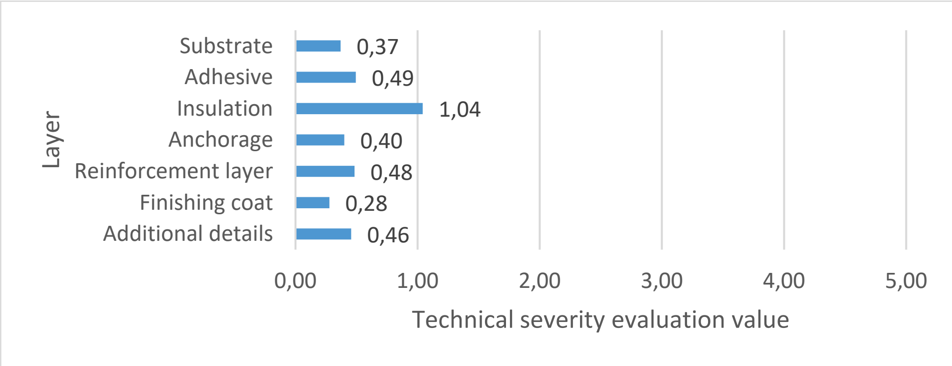


Figure 13. The mean severity rating values of severity category SC2.

The most relevant degradation factors are in the insulation layer when missing or too small fire reluctant areas are installed (I10) and the application process defects that enable the airflow through the system – continious gaps (I4), insufficient amount of adhesive (D3a, D3b), or missing adhesive on the border areas of the insulation plates (D1a, D1b). The thin reinforcement layer (R6) has some effect, as resistance to fire is decreased.

4.1.5 Energy economy and heat retention

Energy economy and heat retention (SC3) can be described through thermal conductivity of the external wall and is affected by the properties of the structure and the construction materials. Although thermal conductivity is influenced mainly by insulation (1,43) and additional details (1,04), the shortcomings of the construction process are less relevant in this layer (see Figure 14).

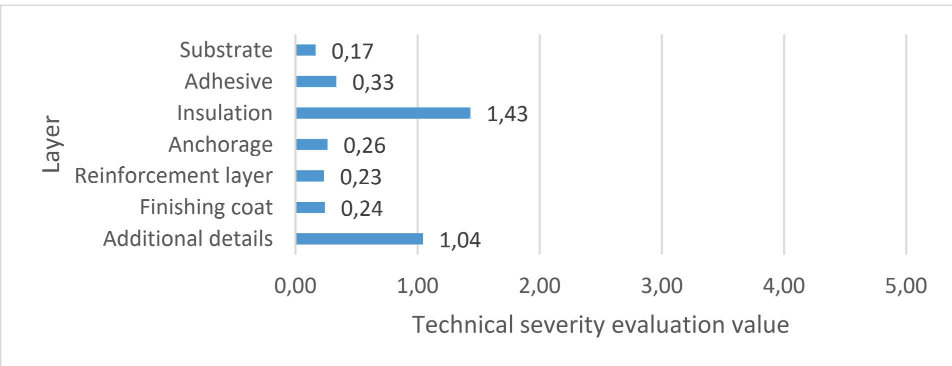


Figure 14. The mean severity rating values of severity category SC3.

The top influencers of thermal insulation are the continuous gaps between substrate and insulation material layer when external air entry is possible (I4) and increased width between insulation plates (I7). A similar effect is caused when adhesive is missing in border areas of the insulation plate (D1a, D1b). The high internal moisture of the insulation plates (I3a, I3b) and the application of additional details, where moisture can penetrate the system due to unsolved rainwater drainage (X3), problematic usage of sealants for the fixed frames (X4), and windowsills (X2) are also relevant. In case of broken insulation plates (I9), the thickness of the layer reduces thermal resistance.

4.1.6 Protection against noise

Although protection against noise (SC4) is not regulated with ETAG 004 (European Organisation for Technical Approvals, 2013), it might be relevant for the inhabitants. The load-bearing construction and ETICS influence the noise resistance of the outer wall, and more exact calculations consider the influence of anchors, area of adhesive, material properties, and resonance frequency.

The severity category has the least effect caused by the shortcomings. The highest influencers are in the layer of insulation (Figure 15), followed by the additional details (X). The majority of the degradation factors have a value below 1 (out of 5).

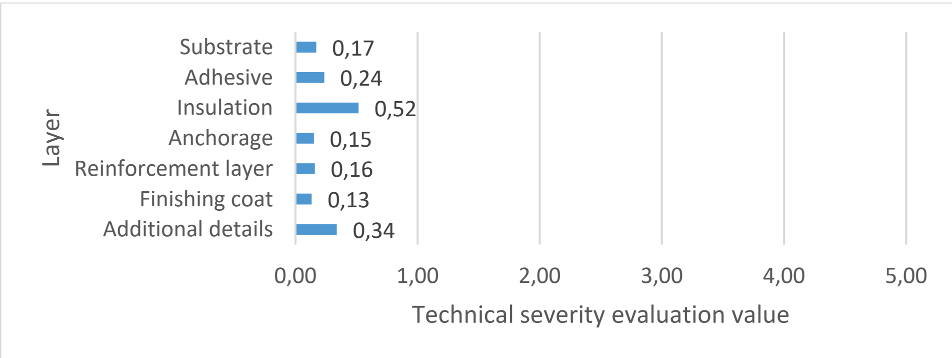


Figure 15. The mean severity rating values of severity category SC4.

During the installation of adhesive, continious gaps between insulation and substrate (I4) hold the highest risk in this category but remain low in value. The other shortcomings concern the decreased areas of adhesive on the border areas of insulation plates (D1a) and in the central areas (D1b) and thin reinforcement layer (R6). Slight impact on the noise transformation is also caused due to broken insulation plates, which are filled with dense material (i.e. mixture) (I9).

4.1.7 Humidity and weather protection

Aspects of durability and serviceability concern durability in several aspects. The system is required to provide protection against short-term weather effects such as solar radiation and wind-driven rain, be resistant to corrosion, and deliver its functions during the whole service life. Humidity and weather protection (SC5) is one of the primary functions of the external shell of the building. Resilience to the condensation, wind-driven rain, and splashing water among water absorption and water vapour permeability is outlined for the façade.

The severity category is most influenced by additional details added to the system, along with finishing coat and reinforcement layer, as seen in Figure 16.

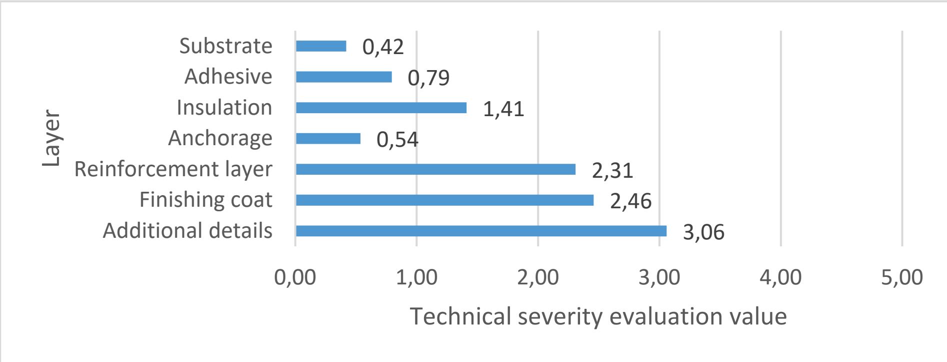


Figure 16. The mean severity rating values of severity category SC5.

The additional details are the most problematic category due to the high risk of leakages and moisture penetration. The riskiest shortcomings is the unsolved rainwater drainage (X3), inappropriately conducted windowsills (X2), and mechanically fixed details that are penetrating the system (X7). They are followed by problematic sealants of fixed frames (X4) and incorrect application of roof edge covers (X5).

In the reinforcement and finishing layer, the leading influencers are the factors that influence the mixture properties. In the reinforcement layer, the highest relevance is held by thin mortar application (R6), the risk of freezing (M9c), and low humidity during curing process (M11c). The problematic storage conditions of the mixture (M1c) and a high share of kneading water (M3c) are also highly relevant.

The finishing layer holds the same inadequacies in the top list, with slight changes in the order. The high share of kneading water (M3d), unsuitable storage conditions (M1d), problematic mixing process (M2d), and risk of freezing (M9d) are followed by dry curing conditions (M11d).

4.1.8 Long-term durability

Within the severity category of long-term durability (SC6), it is expected that the installed façade system lasts during its service life and is resistant to ageing. For example, the ageing of glass fibre mesh causes reduction of bond strength, which is increased due to the movements of dowel heads of anchors due to hygrothermal stresses. This causes degradations as well as reduces the impact to freeze-thaw cycles (Schrepfer, 2008).

SC6 is profoundly influenced by all layers (Figure 17). The highest influence is caused by the reinforcement layer (3,61), additional details (3,54), and finishing coat (3,25). The other layers have slightly less influence but are still relevant.

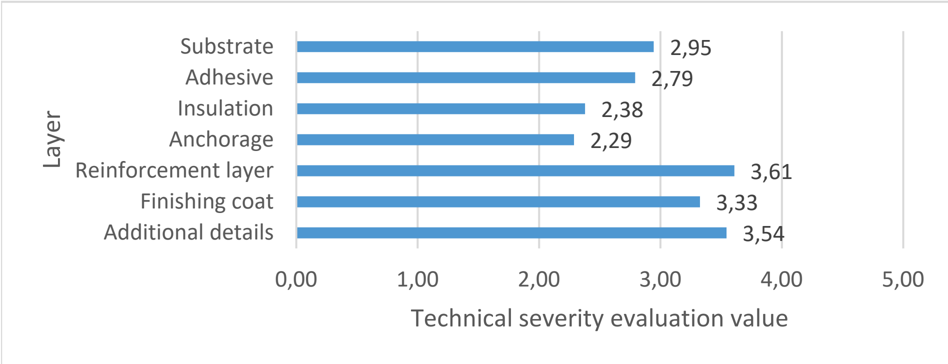


Figure 17. The mean severity rating values of severity category SC6.

Long-term durability is one of the most relevant categories in comparison (see Figure 8). If the results are compared to mechanical resistance and stability (SC1), it is noted that the internal layers (substrate, adhesive) remain relevant. However, the focus is shifted to external layers (reinforcement, additional details, and finishing coat). The category of long-term durability includes nine degradation factors with a value equal to or above 4,0 and 42 DFs equal to or above 3,0 and lower than 4,0. None of the factors from mechanical anchors has received a value above 3, 0.

The reinforcement layer has the highest relevance. The weather conditions having a significant impact are freezing during the application process (M9c) and unsuitable material storage conditions (M1c). The application process aspects that need to be considered are the thickness of the applied layer (R6) and the usage of improper mesh type (R8). High kneading water share (M3c) with hot (M10c) and dry (M11c) curing conditions are among the top influencers during the application process.

Next relevant are the external details, where increased risks with unsolved rainwater drainage (X3) and inappropriately finished windowsills (X2) are top influencers.

The finishing layer is the third-most relevant layer. The weather conditions and mixture-related problems compose the top factors. Low (M9d) and high temperatures (M10d) with low humidity levels (M11d) have a significant impact. During the application process, the high share of kneading water (M3d), wrong material storage conditions (M1d), and clots in the mixture (M2d) are problematic factors.

The layer of the substrate has the most influence on the ETICS, which is applied only with adhesive, concerning eight degradation factors out of the top ten. The risks are increased with frozen substrate (S10b, S10a) and problematic load-bearing capacities (S5b, S5a). The other factors concern the adhesion between adhesive and substrate, whether it is decreased regarding chemical reaction with existing paint (S4b) or due to coverage of biological growth (S3b), oil (S1b), or dust (S2b).

During the application process of adhesive, it is relevant to avoid the usage of unsuitable ingredients in the mixture (M8). High risk is caused in the curing process due to low temperatures (M9b, M9a) and unsuitable material storage conditions (M1b). Insufficient amount of adhesive on border areas (D1b, D1a) and in the centre (D2b) and the application of the mixture during suitable working time (D7b) remain relevant.

During the insulation application process the continuous gaps between substrate and insulation material (I4), extended period of UV-radiation (I1), and crossed joints in the corners of the opening (I6) are the top influencers.

4.1.9 Corrosion protection

Corrosion protection (SC7) of the load-bearing structures is the protective function that is relevant when the upgrading of existing buildings is considered. The primary factor is the internal humidity level in the system. The drying out period of the construction materials has a significant influence, as the moisture can remain in the system for years after ETICS is installed. The corrosion process is stopped if the relative humidity is below the critical level of 80% (Cziesielski & Vogdt, 2007).

This severity category is one of the least influencing categories. Highest scores are received from the shortcomings among additional details (0,85) and insulation (0,54), but they have a very low value in general. The visualization by layers is seen in Figure 18.

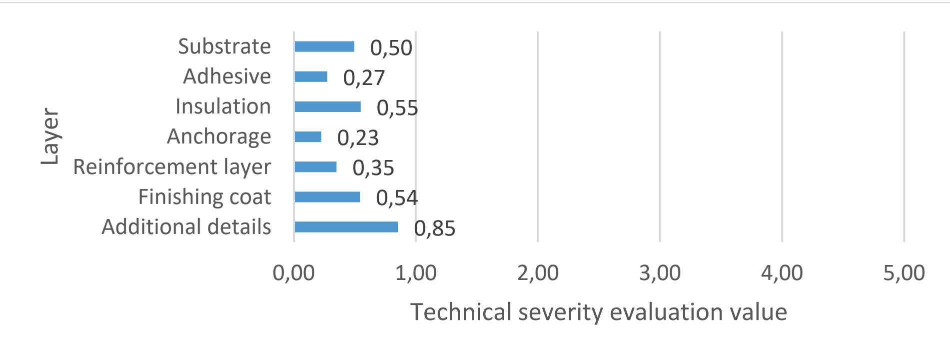


Figure 18. The mean severity rating values of severity category SC7.

The highest risk is caused by unsolved rainwater drainage (X3), penetrations through the system (X7), and inappropriately installed windowsills (X2).

4.1.10 Ability to bypass tensions

The ability to bypass tensions considers the resistance to combined stresses caused by normal loads. Intrinsic weights, wind suction, movements of the structures cause tension. The forces must be absorbed by the combination of materials that withstand the occurring stress.

A significant influence is caused by the reinforcement layer (2,78) and finishing layer (2,05). At the same time, the other layers remain less relevant with scores ranging from 1,31 to 1,69 (Figure 19).

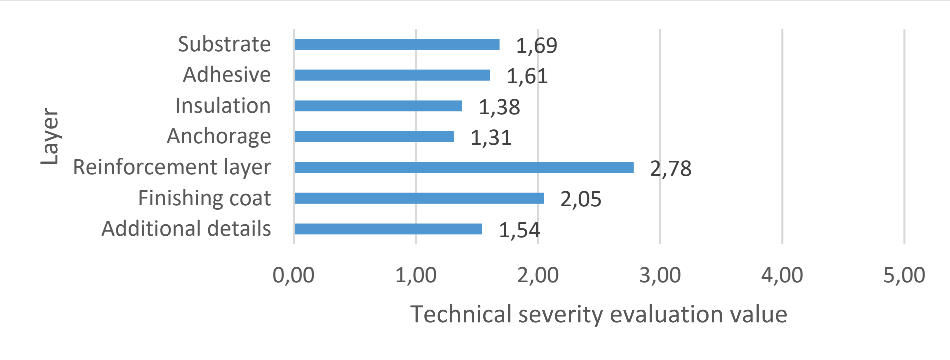


Figure 19. The mean severity rating values of severity category SC8.

Eight degradation factors have received an evaluation value above or equal to 3,00, while 25 received a value equal or over 2,00 and below 3,00. The highest ranked DFs are in the reinforcement layer.

Freezing risk (M9c) has the highest influence in the reinforcement layer, along with the drying out due to low humidity (M11c), high temperatures (M10c), or wrong material storage conditions (M1c). During the mixture preparation process, high (M3c) or low (M4c) shares of kneading water or clots (M2c) in the mixture have received relatively higher scores. During the application of reinforcement mixture, thin mortar layer (R6) or reduced adhesive properties due to fast curing of the layers (R7) are noted. Additionally the decreased overlap (R2), missing diagonal (R4) or folded (R3) mesh cause degradations.

In the finishing layer, the freezing (M9d) with a high share of kneading water (M3d) influence the ability to bear stress.

The highest degradation factors in the layer of substrate concern freezing risk (S10a, S10b), coverage with materials that may cause chemical reaction (S4b), biological growth (S3b), or decreased load-bearing capacity of the structure (S5b).

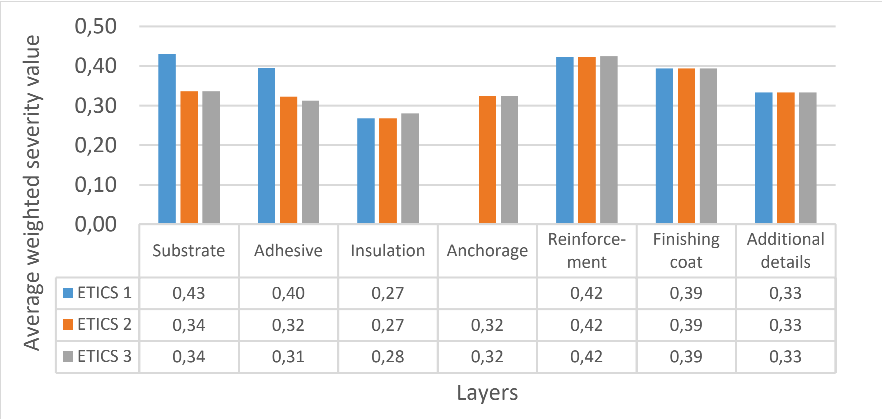
In the adhesive layer, the evaluation revealed that adding ingredients that are not recommended (M8) to the mixture and application with low temperature (M9b, M9a) hold the highest risks. Additionally, the exceeded working time of the mixture remains relevant (D7b).

During the application of the insulation plates, the crossed joints in the corners (I6) and in the continuous areas (I5) are relevant along with the occasion that the plates have not finished their diffusion process (I2).

Within additional details, the problems with the sealants in structural expansion joints (X1) and unsolved rainwater drainage (X3) decreases the ability to bypass tensions due to moisture penetration into the system.

4.2 Weighted technical severity value

The average weighted technical severity value considers the technical significance of the degradation factors in the eight severity categories (see Figure 11). The average weighted severity values by layers are shown in Figure 20, where higher values denote higher significance. In the figure, the results are distributed by the type of ETICSs that are applicable for the characteristics described in Table 1. The degradation factors in the substrate and adhesive layers have significantly different severity values when ETICS types are compared. The purely bonded system, ETICS 1, is highly dependant on the characteristics of adhesion and has a higher severity value, whereas ETICS 2 and 3 share the fixation risk with mechanical anchors and have lower values. In other layers, the ETICS types have comparable values.



	Substrate	Adhesive	Insulation	Anchorage	Reinforce-ment	Finishing coat	Additional details
ETICS 1	0,43	0,40	0,27		0,42	0,39	0,33
ETICS 2	0,34	0,32	0,27	0,32	0,42	0,39	0,33
ETICS 3	0,34	0,31	0,28	0,32	0,42	0,39	0,33

Figure 20. The average weighted severity value by the layer of the system.

The severity values of the degradation factors were placed in the order of the construction, as shown in Figure 21. The coloured horisontal lines visualise the average values of the weighted technical relevance for each ETICS type by layer. The standard deviations were the smallest in the substrate (0,04 to 0,06) and adhesive (0,07 to 0,08) layers. The coloured areas represent the range of a specific layer. The groups of degradation factors discussed more specifically are identified with green lines.

The SV1 group includes the degradation factors of the purely bonded system in the substrate layer, which involves the preparation of the surface. Substrate coverage with oil (S1b), dust (S2b), biological growth (S3b), old paint (S4b), as well as decreased load-bearing capacity (S5b) have high technical severity.

The second highly relevant group SV2 describes the missing adhesive on the edges of insulation (D1b), freezing of the mixture (M9b), exceeded working time of the adhesive (D7b), and adding of unsuitable ingredients (M8). The high technical severity of the substrate and adhesive layers is caused by the construction activities that are responsible for the fixation of the system to the existing external shell of the building. The degradation factors in the substrate layer include the pre-treatment of the surface and the properties of the substrate that affect the characteristics of adhesion. The existing exterior wall of the building must resist the additional load imposed by the ETICS and is responsible, to a large extent, for the stability and adhesion characteristics of the attached system – regardless of whether the fixation relies on mechanical anchors or adhesive. The factors in the substrate and adhesive layers have a relatively high impact on the mechanical stability of the system and a mediocre influence on long-term durability.

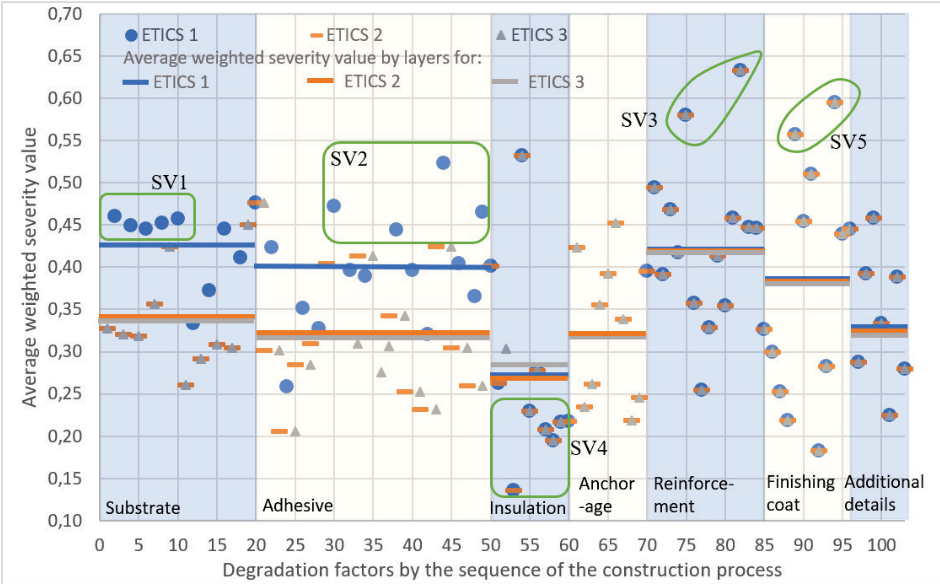


Figure 21. Severity value (SV) of the degradation factors by the sequence of the construction process.

The highest technical impact was caused by the shortcomings in the reinforcement layer, which is responsible for the essential task of stress transmission within the system. In a correctly applied layer, the stresses are transmitted to the mesh applied. These factors not only impact mechanical stability to a considerable extent, but also the ability to bypass tensions, long-term durability, and weather protection. The relatively high impact of these severity categories can be explained by the requirement to bear stresses caused by the external environment, such as hygrothermal changes during different seasons and the freeze-thaw cycles. The two degradation factors with high severity were in the SV3 group: a thin layer of reinforcement mixture (R6) and the freezing of the reinforcement mixture (M9c).

Similar to the adhesive layer, mechanical anchors fix the system to the existing external shell and bear wind suction loads. Their technical effect mainly concerns the mechanical stability of the system, whereas all the other severity categories remain rather irrelevant.

The degradation factors in the additional details layer were technically equally relevant. In this study, the layer includes more generally described shortcomings that reflect the installation of additional products in contact with the system (i.e., application of windowsills, fixations that require penetration through the system, installation of roof edge details). The additional details have high ratings on the severity categories of energy efficiency and, to some extent, on protection against noise, weather protection, long-term durability, and corrosion protection. In comparison with the internal layers of the system, the shortcomings in this layer mostly affect the moisture-induced problems, as sealants fail and enable external moisture to penetrate the system.

An unexpectedly high severity value was assigned to the finishing coat and the degradation factors in group SV5. The external layer, in addition to its aesthetic function, is responsible for weather protection to some extent, although ETICS is designed to function without the finishing layer. The natural conditions include a combination of effects from which the external layer provides protection: wind, rain, pollutants, relative humidity, temperature, and solar radiation. The results show a higher influence on the severity categories that consider the external effects: weather protection, long-term durability, and the ability to bypass tensions. The shortcomings in the finishing layer had the highest standard deviation of 0,15. The degradation factors with high severity value include the risks of the mixture: freezing of the mixture (M9d), unsuitable storage conditions (M1d), and increased amount of kneading water (M3d). The lesser risks concern the adhesion with the previous layer, including missing primer (F1) and not cured reinforcement layer (F2).

The insulation layer received the lowest average technical severity value. Although the primary function of the insulation is to reduce thermal conductivity, defects also affect noise protection. All other shortcomings have extremely low influence (group SV4). The broken insulation plates (I9) and airflow on the surface of the substrate (I4) have an increased effect on noise protection as well as on safety in the case of fire. To some extent, the shortcomings influence the ability of corrosion protection due to moisture-induced problems in the system. Otherwise, the shortcomings concerning the application of the insulation layer have minimal influence.

4.3 Probability of the occurrence

The second relevant component in the prioritisation of the shortcomings with FMEA is the probability of occurrence, as it rates the frequency of an incident during the construction process. The higher value emphasises the shortcomings that occur more often. The average values of the likelihood of the occurrence in the seven layers ranged from 1,43 to 2,80 out of 5,0, as shown in Figure 22.

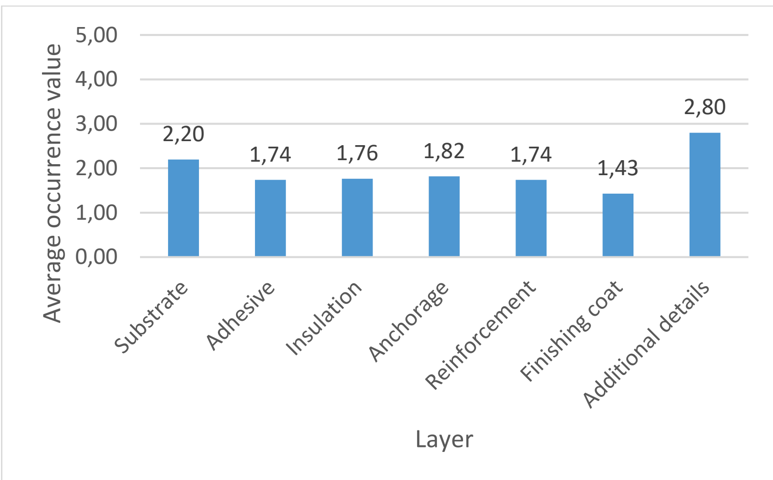


Figure 22. Average occurrence value by layers.

The average occurrence values of the degradation factors were placed in the order of the construction process in Figure 23. The average values by layer are indicated with coloured lines. The comparison between the three ETICS systems showed no significant effect, and the difference is not highlighted separately.

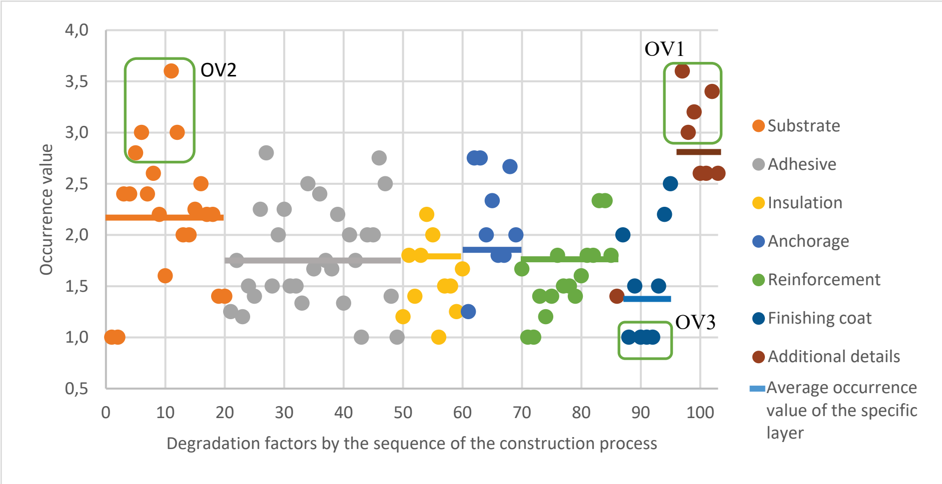


Figure 23. Occurrence value of the degradation factors by the sequence of the construction process.

The degradation factors including the additional details received the highest average rating (2,80), followed by the substrate layer (2,12). The shortcomings in the additional details layer are described in a more general manner and, therefore, include an increased variety of risks, which probably increase the occurrence rate in comparison with other layers, to some extent, that are more specifically described. In the group OV1, the highest occurrence values included problematic structural expansion joints (X1) and penetrations through the system due to fixation (X7).

The substrate layer included activities that are often intentionally not conducted, and they do not cause a visible problem unless other failures occur (group OV2). Such degradation factors included cleaning the surface of biological growth (S3a, S3b) and levelling the surface (S6a, S7b). An increased amount of adhesive is sufficient to decrease the risk. A slightly lower occurrence value was detected for the finishing layer (1,43), which is pointed out in group OV3.

4.4 Detectability

The third component of the TRPN calculation is the detectability of degradation factors during construction. The average detectability value ranged from 1.20 to 2.82, as shown in Figure 24, where higher values indicate increased risk and lower detectability.

The degradation factors with the highest detectability values were in the adhesive layer, as this layer is covered immediately with the insulation plate, making it impossible to detect shortcomings after the application without a destructive test. The second highest rating was for the reinforcement layer, where the mesh is covered during the application. The detectability remained slightly better, as the surface stays open and visible defects can be detected. The layers that are accessible for quality control for a longer period had lower detectability values. These layers included mechanical anchors, insulation, additional details, and the finishing layer.

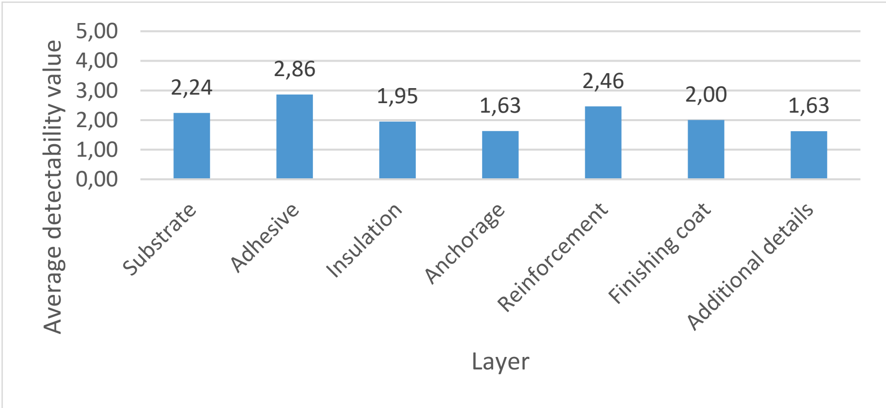


Figure 24. Average detectability value by layer.

The detectability values of the degradation factors are visualized in the order of the construction process in Figure 25, where the average values are depicted with coloured lines. The shortcomings in the substrate layer are visible for quality control for a longer period. However, the defects are often hard to detect and require additional measures to be adopted in some cases (group DV1), which is the reason for the high standard deviation (0,76). These degradation factors included the low load-bearing capacity (S5b, S5a), unsuitable type of adhesive (S7a, S7b), and chemical reaction between the remaining paint and applied adhesive (S4a, S4b). Additional measures should be adopted to check the adhesion properties of the external surface and to test the pull-through strength of the structure. The variance between the different ETICS systems was very low.

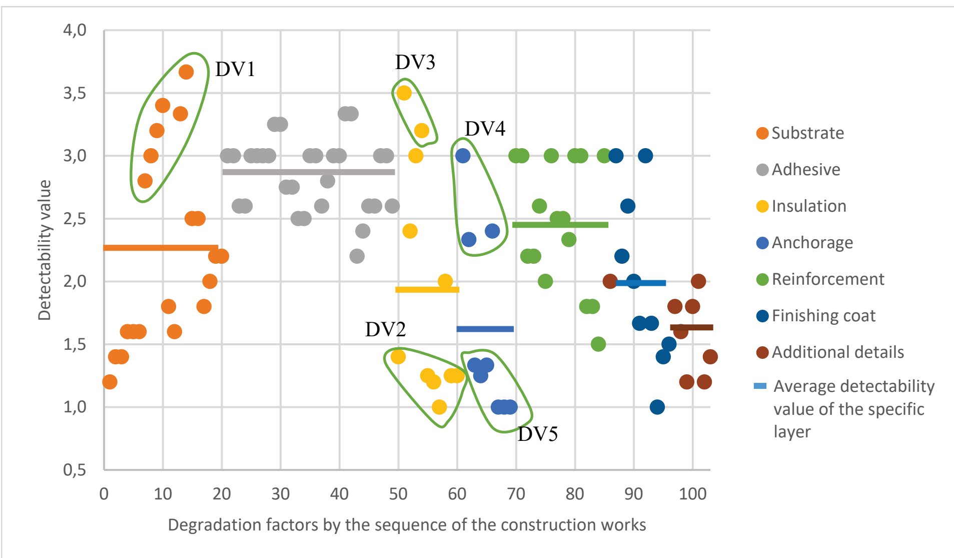


Figure 25. Detectability value of the degradation factors by the sequence of the construction process.

The insulation layer had a high standard deviation (0.92) due to the group DV2, which had a low detectability value, and the group DV3, which had a high value. High detectability values in group DV3 included two shortcomings: continuous gaps between the insulation layer and substrate (I4) and unfinished diffusion process of the polystyrene insulation plates (I2). On an average, the mechanical anchors had good detectability (group DV5), except for the three factors in group DV4: cleaning of the anchor hole (A10), application of unsuitable anchor type (A9), and increased diameter of drilled anchor hole (A1).

4.5 Economic components

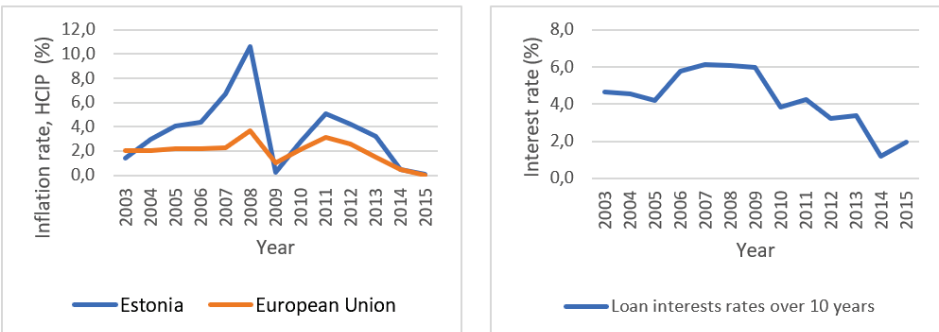
4.5.1 Real interest rate

Discounting technique compares costs that occur in different time periods, and the discount rate represents the time value of money. Although it is recommended to use the real discount rate of 2% for the LCC calculation by several researchers (Eisenberger I., Rener D.S, & Lorden G., 1977; Langdon, 2007), the inflation rate and the market interest rate provide a more specific outcome. The real interest rate is calculated as follows:

$$R_r = R_m - R_i \text{ , where} \quad (3)$$

R_r – real discount rate;
R_i – inflation rate;
R_m – market interest rate.

The economic relevance model focuses on the features of the Estonian market, and for the inflation rate, the value of harmonised consumer price index (HCPI) is used. The average of 12 months' harmonised inflation rate of a calendar year is shown in Figure 26a (Eurostat, 2017). In the case of Estonia, the inflation rate of 3,73% is applied. In comparison, the average HCIP in European Union is 1,96%. The selected long-term market interest rate base on the national average interest reported by the national statistics of the central bank of Estonia. The average 5- to 10-year loan interest rate for entrepreneurs is 4,25% as shown in Figure 26b (Bank of Estonia, 2017). The real interest rate in the NPV calculation is 0,52%.



(a) (b)

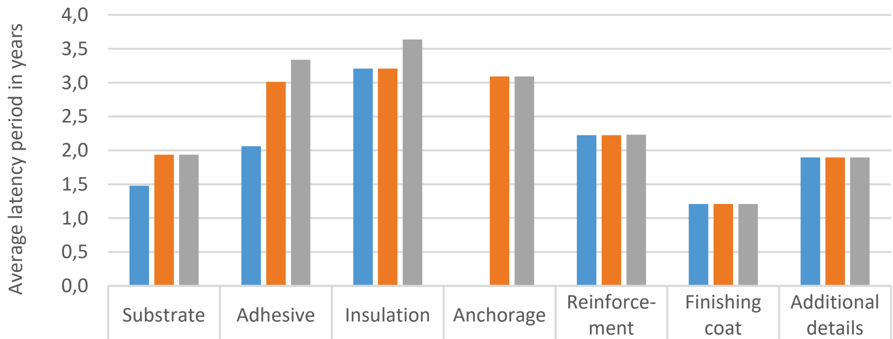
Figure 26. a – Annual HCIP in Estonia and EU (Eurostat, 2017)*; b – Interest rates in Estonia* (Bank of Estonia, 2017).

4.5.2 Latency period

The average latency period of the 103 degradation factors is 2,32 years, with the standard deviation of 1,5 years. The distribution by layers is shown in Figure 27. The correlation and linear regression analysis between the latency period, occurrence, and detectability did not reveal relevant results.

The degradation factors in the layers of reinforcement, finishing coat, and additional details do not depend on the system (simulation) and have an equal latency period.

The layers of substrate, adhesive, and insulation have a noticeable difference in comparison with the ETICS types under observation. The degradation factors that concern ETICS 3 have the longest latency period. In the layer on insulation, the difference is caused by two shortcomings – insulation material opened to UV radiation for a longer period (I1) and continuing diffusion process of the insulation material (I2). Both are relevant for the polystyrene-based insulation and decrease the average value of the systems. The difference in the layer of adhesive is due to the fixing mechanism. ETICS 1 highly depends on the properties of adherence, while ETICS 2 and ETICS 3 are primarily mechanically fixed and the relevance of adhesive is significantly lower, as is the latency period. The layer of substrate is the most homogenous layer and shows the lowest standard deviation of 0,50 years.



	Substrate	Adhesive	Insulation	Anchorage	Reinforce-ment	Finishing coat	Additional details
ETICS 1	1,48	2,06	3,21		2,22	1,21	1,90
ETICS 2	1,94	3,01	3,21	3,09	2,22	1,21	1,90
ETICS 3	1,94	3,34	3,64	3,09	2,23	1,21	1,90

Figure 27. The average latency period by layer.

Figure 28 presents the latency periods of the degradation factors in the sequence of the construction process and highlights the average values for different ETICS types by layers. The degradation factors in the layer of substrate appear rather fast. The latency period rises in the layers of adhesive insulation and begins to fall after the installation of mechanical anchors. The shortcomings in the layer of reinforcement and finishing layer appear within the shortest period. The trend is similar for all three ETICS types.

The groups LP1 and LP2 shown in Figure 28 have the longest latency period – above five years – and are relevant for the long-term durability. The layer of adhesive has a group of five degradation factors (LP1), which depend on the appearance of natural disasters as well as ageing, according to the discussion in the expert panel. The shortcomings in the group LP1 are insufficient adhesive (D3a, D3b), adhesive not rubbed into mineral wool (D4a) or treated with notch towel (D5), and exceeded working time of the mixture (D7a). The group LP2 concerns five factors from several layers – decreased diameter of anchor plate (A2), increased diameter of anchor hole (A1), crossed joints of insulation plates (I5), broken and not properly filled insulation plates (I9), and usage of incompatible mesh (R8). The glass fibre mesh in the base coat is required to be resistant to the alkaline environment. In the case of non-resistant mesh application, the required residual strength properties will reduce until a critical level is achieved and the failure of the system occurs.

The group LP3 diverges with a very low latency period. The majority in this group belong to the finishing layer. Eight degradation factors out of ten in the finishing layer reveal problems during the first year after application. The two factors with high values are the thin render layer (F4) and high kneading water share (M3d) with a latency period of 3,2 and 3,3 years accordingly. However, both degradation factors have low occurrence and detectability values, as shown in the next sub-chapter. Low values imply that the shortcomings are rare to happen and have good visibility.

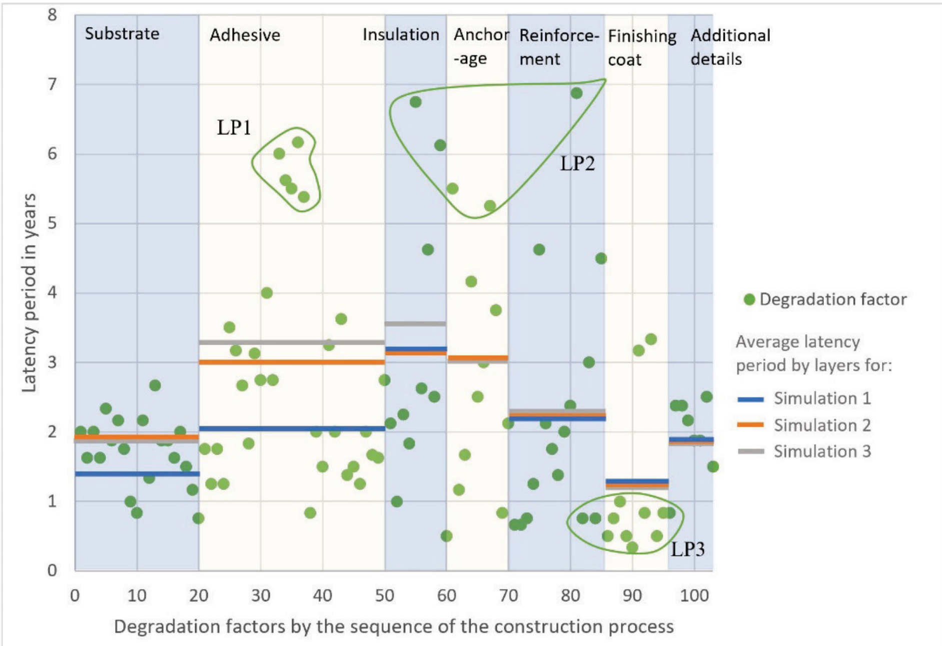


Figure 28. Latency period of the degradation factors by the sequence of the construction process.

4.5.3 Economic assessment value

The life-cycle costing method reflects the expenses in each phase of the building (Li, Zhu, & Zhu, 2012). In order to simplify the economic considerations, the current model concerns only the future repair cost, which is the result of the specific shortcoming of a construction process activity and is calculated (4) as follows:

$$EAV_{DF} = \frac{NPV_{DF}}{CCI}\text{, where} \qquad (4)$$

EAV_{DF} – economic assessment value;
NPV_{DF} – discounted repair costs of a degradation factor;
CCI – construction cost index.

The discounted repair costs of a degradation factor is leveraged with the construction cost index for new residential buildings provided by the Eurostat in order to maintain the comparability during economic fluctuations. As the simulations in this research are based on the situation of Estonia, the value of quarter 4 in 2017 is used (116,6%) (Eurostat, 2018). The comparative ratio of the construction and the repair costs for the initial construction costs of simulation 1 is presented in Table 15.

Table 15. The comparative ratio of construction and repair costs to the initial construction costs.

Description of construction work	Simulation 1	Simulation 2	Simulation 3
The initial construction of ETICS	1,00	1,08	1,30
Replacement of insulation and reapplication of mechanical anchors, reinforcement layer, and finishing coat	1,74	1,80	2,01
Replacement of reinforcement layer and reapplication of finishing coat	1,11	1,11	1,11
Replacement of the finishing coat	0,50	0,50	0,50

The lowest initial construction costs are for the system with polystyrene as insulation material and the highest for the system with mineral wool as insulation material. The repair techniques dismantle the existing system till the required layer and replace them with reapplied layers. The dismantling of the insulation layer is the most expensive, as it is there that the utilisation of insulation materials is responsible on average for 50% of the dismantling costs, artisans costs cover 21%, and lifting mechanisms, covers, and other minor accessories make up for 29%. The dismantling and utilisation of reinforcement the layer and the finishing layer concerns 30% of the expenses of the applicable repair technique.

The repair costs are the time-relevant components in the life-cycle consideration. Hence, a repair technique is appointed to each degradation factor, and the discounted repair costs are calculated with (5):

$$NPV_{DF} = \frac{C_R}{(1+R_r)^{LP_{DF}}} \text{, where} \quad (5)$$

NPV_{DF} – net present value of the repair costs for a degradation factor;
R_r – real discount rate per annum;
LP_{DF} – latency period of a degradation factor;
C_R – repair cost of selected repair method.

The net present value calculations are considering the latency period of the shortcoming. The maximum change of economic assessment value through NPV calculation was 3,5% due to the short latency periods. Therefore, the major impact of the economic assessment value is caused by the costs of repair techniques. In comparison between layers, the degradation factors in the layers of anchorage and reinforcement have lower repair costs, while the finishing layer has the lowest values in general. Visualisation of average economic assessment values by layers is shown in Figure 29.

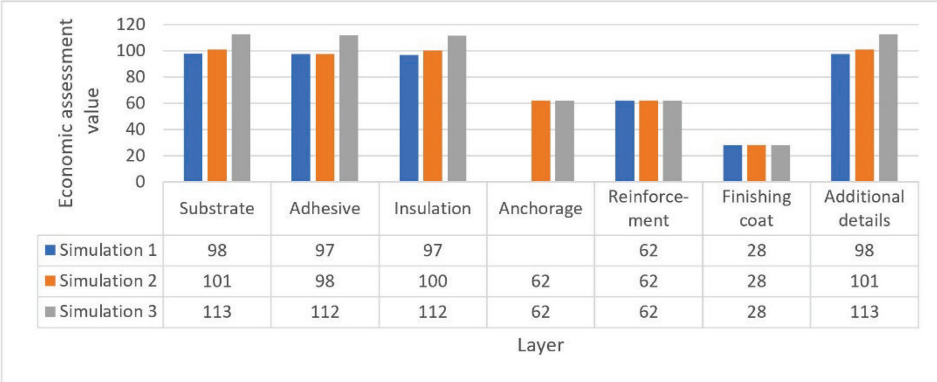


Figure 29. The average economic assessment value by layers.

The latency period has a relatively low effect on the results, as it varies in a relatively small range. A similar observation is made by Neumann (2009), who stated that 80% of the shortcomings occur during the first five years and two to three occur in the first two years, which is in alignment with this study. According to our results, 56% occur during the two-year period and 90% during the five-year period.

Due to the short period, the interest rate has a relatively low impact on the discounted costs. However, the results of the latency period of the degradation factors can be interesting to various stakeholders of the project, depending on their contractual agreement. If the contractual defect liability period is two years, then the financial risk is relatively equally divided between the contractor and the owner. However, if the liability period is up to five years, then the contractor holds the majority of the risks with only a small number of exemptions. These considerations enable the decision of quality issues and responsibilities of the parties on the contractual level.

4.6 Conclusions on the impact of individual components

The results of the individual components discussed in this section are summarized. In order to evaluate the degradation factors, the method selected the technical severity categories according to the essential technical requirements outlined for buildings and developed an appropriate weighting system. A probability of occurrence and detectability value has been assigned to each degradation factor. The costs of repair techniques have been obtained and discounted according to the time period estimated for visible signs to appear.

The technical severity assesses the technical significance of the degradation factor. The severity evaluation is divided into eight severity categories, which are considered as the potential technical severity effect in the FMEA approach. The highest technical impact is present in categories with mechanical resistance and stability (SC1) and ability to bypass tensions (SC8), which influence the humidity and weather protection (SC5) and long-term durability (SC6). The results of the weighted technical severity emphasise the relevance of the construction process activities in the layer of reinforcement and finishing coat for all three ETICS types. In the layers of substrate and adhesive, the construction works that influence the adhesion properties have high technical effect for the purely bonded system.

The probability and detectability values assess how often the shortcoming is appearing and how difficult the detection is during the application process. Defects during the installation of additional details and substrate preparation have shown the highest occurrence in comparison to other layers. The most difficult detectability is within the layer of adhesive due to the fast coverage with insulation plates, which is followed by the activities of reinforcement application.

The economic aspect is introduced due to the future costs caused by the shortcomings of the construction phase. The discounted cost of repair is the highest for shortcomings in the internal layers, as they require the removal and reapplication of the entire system. The data concerning the latency period shows that 56% of the shortcomings show visible degradation signs during two years after the construction is finished, and 90% are revealed during the next five years.

5 Priority setting of the degradation factors

5.1 Technical failure mode and effects analysis

The evaluation system focused on the essential technical performance requirements outlined for ETICS. The study assumes that if the performance of the system does not meet the desired characteristics, a failure occurs. In order to classify and rate the significance of each failure, the risk assessment methodology Failure Mode Effects Analysis (FMEA) was used, as it enables the quantification and prioritisation of risk (Abdelgawad & Fayek, 2010; Layzell & Ledbetter, 1998; Mecca & Masera, 1999). The technical risk priority number of a degradation factor was calculated with the following formula:

$$TRPN_{DF} = \overline{SV_{DF}} \times \overline{OV_{DF}} \times \overline{DV_{DF}} \text{ , where} \quad (6)$$

$TRPN_{DF}$ – the technical risk priority number of a DF;
SV_{DF} – the average technical severity value of a DF;
OV_{DF} – the average occurrence value of a DF;
DV_{DF} – the average detectability value of a DF.

The simulation data were divided into technical and region-specific components. The framework of the model is visualized in Figure 30, where occurrence and detectability are individual components, and the weighted technical severity value is a combination of eight severity categories.

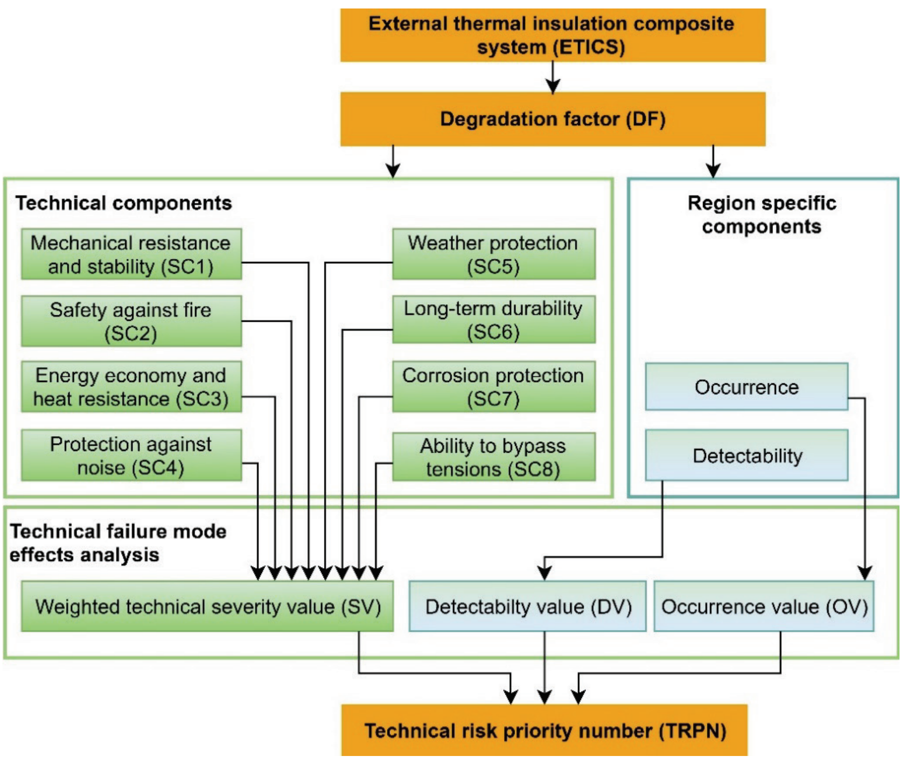


Figure 30. The framework of the technical relevance model.

The technical risk priority number (TRPN) is a combination of the weighted technical severity value, the detectability value, and the occurrence value. The results by layer and ETICS type are shown in Figure 31, whereas Figure 32 positions the degradation factors according to the TRPN in the order of the construction process.

	Substrate	Adhesive	Insulation	Anchorage	Reinforce-ment	Finishing coat	Additional details
ETICS 1	2,09	1,90	0,90		1,77	1,00	1,49
ETICS 2	1,61	1,50	0,90	1,00	1,77	1,00	1,49
ETICS 3	1,62	1,55	0,93	1,00	1,73	1,00	1,49

Figure 31. Average value of technical risk priority number by layer and ETICS type.

The correlation and regression analysis between the pairs of severity value and occurrence value and severity value and detectability value showed no relevant correlation. Between the variables of occurrence value and detectability value, there was a weak negative correlation ($r = -0{,}24$), even though R^2 in the linear regression was 0,059, which does not explain the relationship between the variables. In comparison to the average weighted severity values shown in Figure 21, the reinforcement, substrate, and adhesive layers retained their high average relevance rating. The deviation in all layers was relatively high. In the substrate and adhesive layers, ETICS 1 increased TRPN values due to the differences in severity values between the systems. Occurrence and detectability values had no significant difference in comparison with the ETICS types observed.

The highly relevant degradation factors in the substrate layer are shown in group TR1 (Figure 32). The incidence when the substrate is covered with chemically reacting remaining paint (S4b), usage of unsuitable adhesive type (S7b), and low humidity of the substrate as inorganic adhesion is applied (S8b) were highly relevant for ETICS 1. The systems with mechanical anchors and supplementary adhesive (ETICS 2 and ETICS 3) were highly influenced by the low load-bearing capacity of the substrate (S5a). In the low relevance group TR2 (substrate covered with oil; S1a, S1b) the relevance decreased due to very low values of occurrence and detectability.

The adhesive layer had the most relevant shortcomings in the group TR3. Insufficient adhesive (S3a, S3b) had very high occurrence and detectability values, increasing its relevance. Three degradation factors with relatively high detectability values also belong to this group: dry curing conditions (M11b), lack of pressure during application of insulation plates (D8b), and adhesive not rubbed into mineral wool insulation plate (D4a). The low relevance group TR4 included the mixture-related factors that reduced their relevance due to their low occurrence value. The factors include only the mixture preparation process: wrong material storage conditions (M1a, M2b), clots remaining in the mixture during mixing process (M2a, M2b), and high share of kneading water (M3a).

The insulation layer and mechanical anchors included the majority of the degradation factors in the low relevance group TR6. Although the occurrence value of the shortcomings for mechanical anchors was relatively high (Figure 23), the good detectability and below average technical severity reduced the TRPN relevance. However, there were three degradation factors with a high TRPN in group TR5. Although continuous gaps that enable an internal airflow (S4) had high relevance in all three components, increased diameter of drilled anchor hole (A1) and unsuitable anchor type (A9) had increased relevance due to difficult detectability. The detection is more problematic in this layer, as the quality check must occur during the application process.

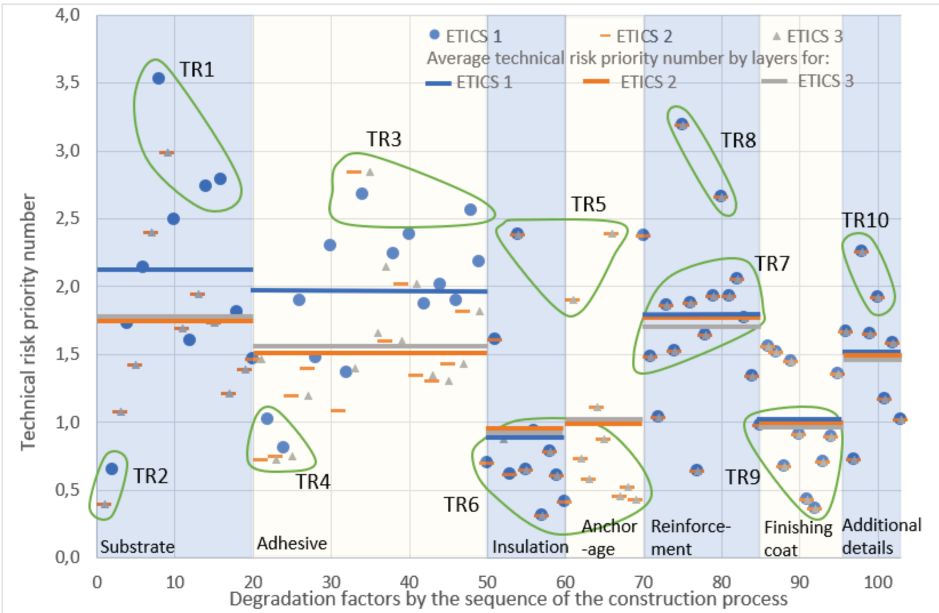


Figure 32. Technical risk priority number of the degradation factors by the sequence of the construction process.

The reinforcement layer had the highest average TRPN and the majority of the degradation factors were positioned near the average value (group TR7). The degradation factors of the thin reinforcement layer (R6) and layers not applied in wet to wet condition (R7) in the group TR8 reduced the ability to bypass tensions into the mesh and were the most relevant. Thin reinforcement layer (R6) had, in comparison, a higher severity value due to the impact on the long-term durability, but it is easier to detect, as the pattern of the mesh is visible after the completion of the layer. Layers that are not applied in wet to wet condition (R7) can be detected only during the application process.

The risks in the finishing layer, mostly assembled in group TR9, decreased its relevance due to the low occurrence value. The layer has no degradation factors that are considered highly relevant to the system's performance.

The shortcomings in the additional details layer decreased the relevance due to their low detectability value but remained relatively high, as the failures occur rather often.

Most problematic was the penetration of moisture into the system due to problematic solutions windowsills (X2) and other fixed frame connections (X4) in group TR10.

5.1.1 Conclusions of the technical failure mode and effects analysis

The objective of this chapter was to prioritise on-site construction process activities in order to enable better resource allocation to technical aspects of quality control. The developed technical severity model combines the effect of weighted technical severity, the probability of occurrence, and the detectability of the on-site construction work. The output values were divided into layers of the applied system and ETICS types for analysis. ETICS 1 concerns the purely bonded system with polystyrene. Polystyrene with mechanically fixed anchors and supplementary adhesive are categorised as ETICS 2. ETICS 3 represents the mineral wool system of the same fixation type as ETICS 2. The benefit of the differentiation by ETICS type is to provide the ability to assign only relevant degradation factors to the simulation under evaluation. The differentiation by layers of the system allows for the comparison between the sequences of the construction process.

The technical severity evaluation revealed that the ETICS construction process significantly alters the resilience of the system with regards to mechanical stability, long-term durability, ability to bypass tension, and weather protection. The preparation of substrate and application of adhesive are important factors, as are the activities that involve the reinforcement and the finishing layer. The occurrence probability component reduced the relevance of the finishing layer but added value to additionally added details (i.e., windowsills, plinth details). The detectability component was more relevant for the application of mixtures in the adhesive and reinforcement layers. The output, technical risk priority number (TRPN), emphasised that the most relevant is the reinforcement layer for all ETICS types, and the significance of adhesion for the purely bonded system.

Based on the results, the following general aspects should be considered during resource allocation for quality control:

(1) The adhesion to the exterior façade of the building is highly relevant for the purely bonded ETICS. During the application process, the degradation factors that influence the adhesion characteristics have a tremendous impact on the technical severity of the system. These shortcomings are hard to detect, as they are covered for further inspection shortly.

(2) The preparation process of the reinforcement mixture and the application of the mesh have a high technical risk, as shortcomings occur often. The layer is responsible for distributing internal and external stress. If a failure occurs, the anomalies evolve and enable moisture to penetrate the system.

(3) The failures during the application of additional details (windowsills, fixed frames, plinth areas, and other fixings) often occur and have severe technical consequences.

(4) The failures that occur during construction in the insulation, anchorage, and finishing layers have reduced risk, as they occur rather rarely and are visually detectable. Nevertheless, the technical severity remains high for mechanical anchors.

5.2 Economic failure mode and effects analysis

The outcome of the economic relevance calculation for each degradation factor is the Economic Risk Priority Number ($ERPN_{DF}$), which is calculated (7) as follows:

$$ERPN_{DF} = EAV_{DF} \times OV_{DF} \times DV_{DF} \text{, where} \tag{7}$$

$ERPN_{DF}$ – Economic Risk Priority Number;
EAV_{DF} – economic assessment value;
OV_{DF} – detectability value;
OV_{DF} – likelihood of occurrence.

The development procedure of the model defines the components required for the calculation of the economic impact, as shown in Figure 33. The economic model is influenced by regional, macroeconomic, and company-specific components, which are the input values in the calculation of ERPN. The following chapters describe the method for the selection of degradation factors, data collection and calculation steps, as well as the characteristics of the sample simulations.

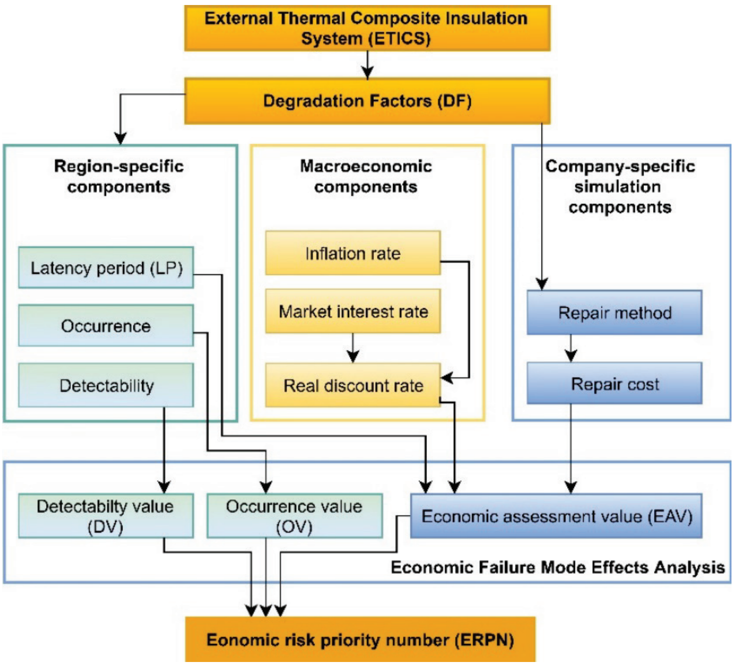
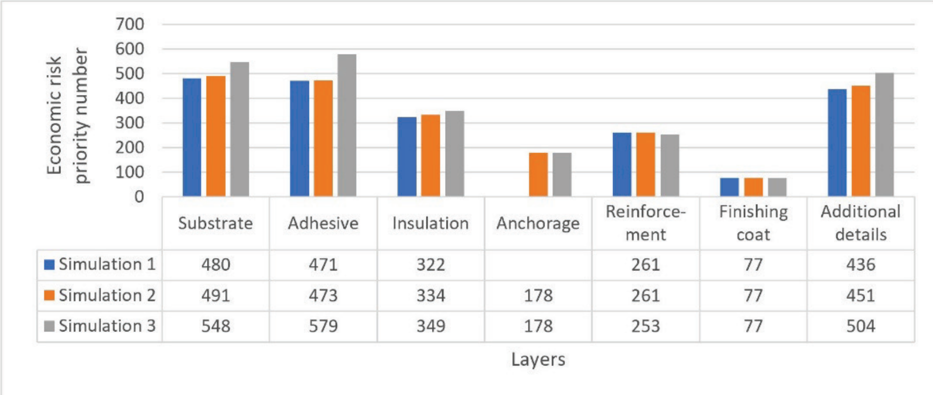


Figure 33. The concept of the economic risk assessment model.

The average ERPN values by layers and simulations are shown in Figure 34. The highest priorities have the degradation factors in the layers of substrate, adhesive, and additional details. The factors in the layer on insulation and reinforcement have modest values, while the mechanical anchors and the finishing coat are the least relevant. In the layers of adhesive, substrate, and additional details, the simulation 3 shows increased relevance in comparison with other simulations. According to the economic assessment values (Figure 29), the cause lies in the increased repair costs. A similar effect is seen in the layer or insulation on a smaller scale.



	Substrate	Adhesive	Insulation	Anchorage	Reinforce-ment	Finishing coat	Additional details
Simulation 1	480	471	322		261	77	436
Simulation 2	491	473	334	178	261	77	451
Simulation 3	548	579	349	178	253	77	504

Figure 34. The average economic risk priority numbers (ERPN) by layer.

Figure 35 presents the ERPN of the degradation factor in the sequence of the construction works and highlights the approximate range of layers (coloured areas). The horisontal lines represent the average ERPN for the three simulations. There are groups of shortcomings with noticeable deviations, which are signified by green lines. As the economic assessment value had a very low differentiation within a single layer, the major deviations within one layer occur due to the impact of occurrence and detectability variables.

The group of E1 in the layer of substrate describes the degradation factors in all three simulations and concerns the shortcomings that influence the adhesion properties as well as mechanical fixations. The adhesion properties are concerned with the remains of old paint (S4a, S4b), low humidity of the existing wall (S7a, S7b), and unsuitable adhesive type (S7a, S7b). The load-bearing capacity of the external wall (S5a, S5b) as well as detached areas on the surface (S6a, S6b) are also problematic. The very low risk is for the group E2, which represents the external surface covered with oil (S1a, S1b), having very low occurrence and detectability value.

The group E3 concerns the factors with high ERPN in the layer of adhesive, which are relevant for simulation 2 and 3. Problems in simulation 2 occur due to the application of insufficient amount of adhesive (D3a), which is relevant for prohibiting air movement internally and has increased importance of the stability of the system. Additionally, the effect of exceeded working time (D7a) has a high relevance. These degradation factors have relatively high detectability value, as the shortcoming is covered with insulation plates immediately and is observable only during the application process. Simulation 3 is affected by the lack of pressure on the installation plates during application (D8a) and of the failure to use notch towel (D5), leaving the possibility for air movement behind the system. Furthermore, the drying out of inorganic mixture due to high temperature (M11a) and dry curing conditions (M10a) are relevant.

The group E4 is a low relevance group that concerns the freezing of adhesive due to frozen external wall (S10a, S10b). As the degradation factors concern existing buildings, which are heated by the habitants, it is expected that after the application of insulation, the temperature will not fall into a critical freezing zone. The other factors concern the unsuitable adhesive storage conditions (M1a, M1b), clots in the mixture due to insufficient mixing (M2b), and low share of kneading water (M4a). Although these factors have high economic assessment value, the occurrence and detectability reduce the relevance of risk noticeably. The other low relevance group E5, representing 8 shortcomings out of 10 in the layer of mechanical anchors, has low values in all categories.

The high ERPN values concern the group E6, which represents four degradation factors of additional details in all simulations. Due to the high repair costs and occurrence value, the factors of insufficient shock resistance measures (X6), unfinished windowsills (X2), and fixed frame connections (X4), as well as problematic roof edge covers (X5) have relatively high economic priority.

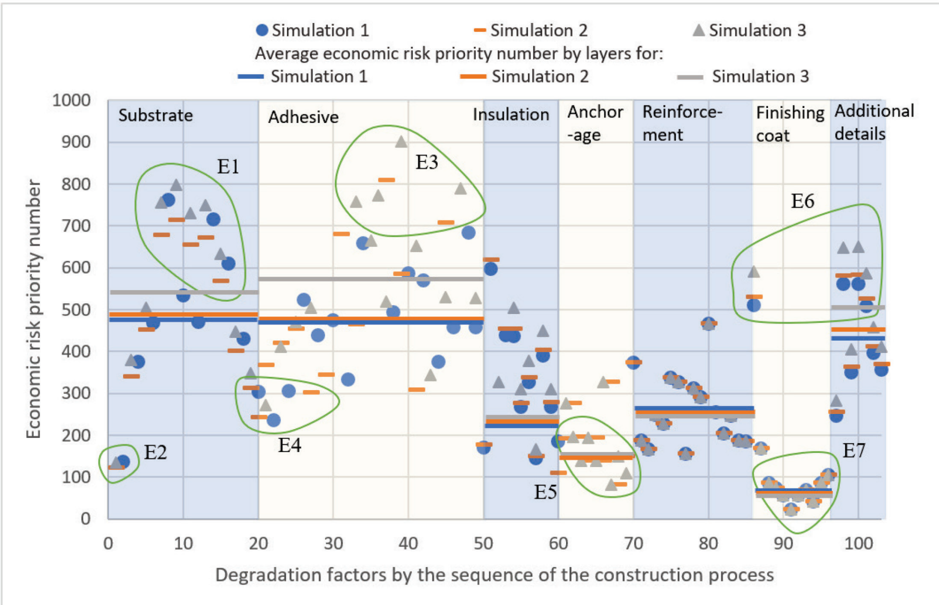


Figure 35. Economic risk priority number of the degradation factors by the sequence of the construction process.

5.2.1 Conclusions of the economic failure mode effects analysis

The financial relevance of construction activity is evaluated with the modified FMEA method, which considers the cost of repair as severity variable of the on-site degradation factors. The model is simulated on three construction projects.

The results of the analysis show that higher relevance of the on-site construction process activities in the layers of substrate and adhesive, as they are often occurring, are hard to detect and have a high financial impact if repair activity is required. High relevance can also be noticed for the often-occurring problems during the construction works with windowsills and roof edge covers. The results of the study reveal that the shortcomings in the finishing layer and by mechanical anchors have the lowest relevance.

The economic assessment model enables the enhancement of financial risk assessment of the on-site construction process of ETICS to highly relevant construction activities. The outcome supports the decision makers to increase the value of construction works by reducing future repair costs.

5.3 Technical-economic relevance model

The discussed ERPN and weighted technical severity is to be considered in one model. The traditional risk matrix concerns likelihood of occurrence and consequence on the x and y-axis. In this study, the consequence concerns the weighted technical severity impact of a degradation factor. However, more components are considered on the other axis. It concerns the occurrence, detectability, and economic impact that is combined into an economic risk priority number. The risk matrix (Figure 36) positions each degradation factor in a risk category. The positioning of the matrix is in the Cartesian coordinate system, and the numerical values correspond to risk levels – higher score, increased risk. This work bases on 5×5 cells matrix, having 25 risk cells as often used in researches (Ni, Chen, & Chen, 2010; Popov, Lyon, & Hollcroft, 2016). The 25 risk cells matrix is divided into three risk categories. The categories are described as: “low” – acceptable, no action required; “medium” – tolerable, additional action required; and “high” – not acceptable, immediate action required.

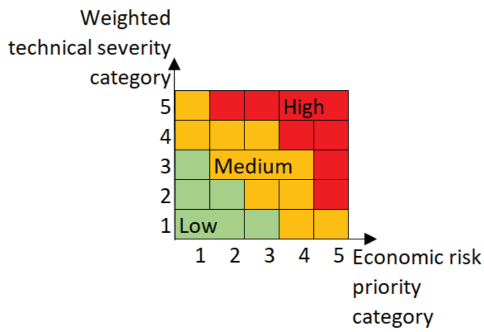


Figure 36. Relevance matrix.

As there are three risk categories, an additional ranking within a single risk category is required to prioritise the degradation factors for each other. Therefore, the degradation factor is also described with the technical-economic relevance number for further analysis with equation (8).

$$TER_{DF} = SV_{DF} \times ERPN_{DF} \text{ , where} \quad (8)$$

TER_{DF} – Technical-Economic Relevance Number;
SV_{DF} – weighted technical severity value;
$ERPN_{DF}$ – Economic Risk Priority Number.

The ERPN and weighted technical severity values are classified into five categories. Category 5 represents the highest economic or technical relevance and category 1 the lowest. The highest value is the maximum value received during the evaluations, and the other categories are distributed equally. For the conducted simulations, the maximum ERPN is 728,2 and the weighted technical severity value is 0,633. The evenly distributed category ranges are shown in Table 16. The input values for the technical-economic relevance simulation is the weighted technical severity value and the economic risk priority number, whose average impact by layers is shown in Figure 37. Higher value means higher relevance. The comparison shows which component influences the outcome to veer towards which direction.

Table 16. Categorisation of the ERPN and weighted technical severity value.

Category	Risk description	ERPN	Weighted technical severity value
5	very high	$728,2 < ERPN_{DF} < 910,2$	$0,506 < SV_{DF} < 0,633$
4	high	$546,1 < ERPN_{DF} < 728,1$	$0,380 < SV_{DF} < 0,505$
3	mediocre	$364,2 < ERPN_{DF} < 546,1$	$0,253 < SV_{DF} < 0,379$
2	low	$182,0 < ERPN_{DF} < 364,1$	$0,127 < SV_{DF} < 0,252$
1	very low	$ERPN_{DF} < 182,0$	$SV_{DF} < 0,126$

The average weighted severity value is very high in the layer of reinforcement for all simulations. Simulation 1 has high values in the same range in the layers of substrate and adhesive. The increased relevance of simulation 1 is caused by the fixing method (purely bonded), which emphasises the degradation factors that decrease adherence properties. The lowest average severity value has the layer of insulation. With regards to the severity values, it must be noted that the standard deviation is relatively high, which implies that the risk categorisation should provide relevant information for better decision making.

Economic relevance is the highest in the layers of substrate, adhesive, and additional details. The main cause is the high repair costs, as the replacement of the whole system is considered. The detectability has increased the relevance in the layers of adhesive and reinforcement. These defects are covered at the same time as they occur, and problem of identification can be determined mainly only during the short application period. Occurrence value was the highest by the additional details and followed by the layer of substrate.

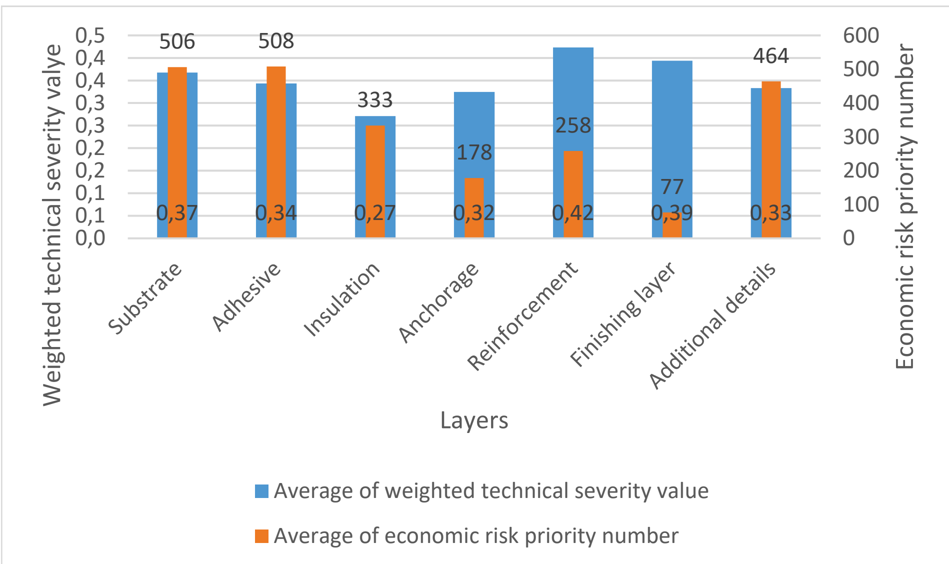
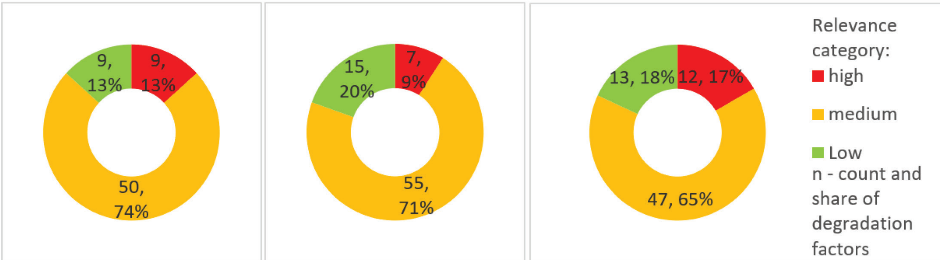


Figure 37. Average of weighted technical severity value and economic risk priority number by layers.

The categorisation distributes the degradation factors of the simulations into the three risk categories that are required to set focus on the more relevant shortcomings.

Figure 38 presents the share of degradation factors and their count in numbers. The visualisation shows that the high category concerns 9% to 17% (7 to 12 factors) of the degradation factors, medium category concerns 65% to 74% (47 to 55 factors), and low category concerns 13% to 18% (9 to 15 factors).



(a) (b) (c)

Figure 38. Count and share of degradation factors in risk categories for a) simulation 1, b) simulation 2, and c) simulation 3.

For the analysis of the degradation factors within a single risk category, the product of the two variables, the technical-economic relevance number, is used. Figure 39 compares the average TER values of the simulations by layers. The difference of values between the simulations in the layers of substrate, adhesive, and additional details exist mainly for two reasons. Simulation 1 describes the purely bonded ETICS with polystyrene as insulation material, which means that the adhesive layer has a higher significance for ensuring mechanical stability, thereby increasing the weighted technical severity value. Simulation 3 refers to the ETICS with mineral wool, fixed with mechanical anchors and additional adhesive. The higher repair costs of the inner layers, where the whole system is to be replaced, increases the average economic risk priority number. Simulation 2 has the lowest economic risk priory number due to the lower cost of polystyrene plates, which are fixed with mechanical anchors and supplementary adhesive.

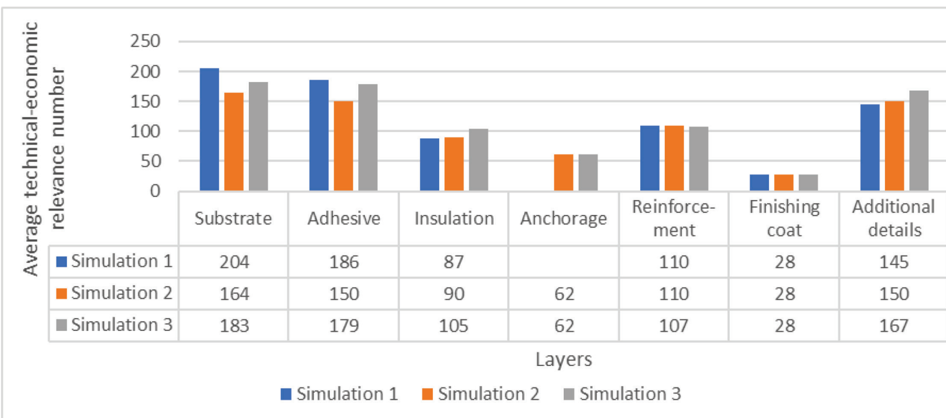


Figure 39. Average technical-economic relevance number of the simulations by layers.

The technical-economic relevance model is positioning the degradation factors on the risk matrix, as seen in Figure 40. For further analysis, the categories are discussed in the following groups:

- Technical severity value in category 5, ERPN in categories 2 to 5 (Risk1);
- ERPN value in category 5, technical severity values in categories 2 to 5 (Risk2);
- ERPN and technical severity value in category 4 (Risk3);
- Medium-risk category;
- Low-risk category.

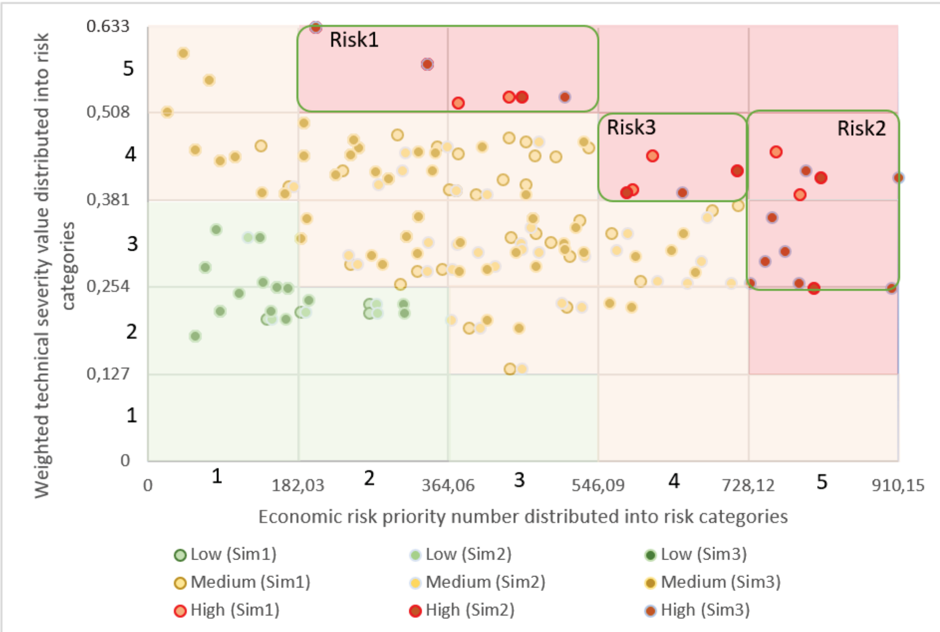


Figure 40. The positioning of the degradation factors of risk category on the risk matrix.

"Risk1" is the group with the highest technical severity and concerns three unique degradation factors that are relevant for all simulations and one degradation factor relevant for simulation 1. The freezing of adhesive during the curing process (M9b), relevant for simulation 1, has high influence on adhesion properties, as the system is purely bonded. Other shortcomings relevant for all simulations concern the layer of reinforcement and insulation – continuous gaps between substrate and adhesive, which enables the airflow in the system (I4), thin reinforcement mortar thickness (R6), and freezing of the reinforcement layer (M9c).

"Risk2" describes the degradation factors with the highest ERPN category and concerns eight shortcomings. All shortcomings in this group belong to the layers of substrate and adhesive. Only one degradation factor belongs to simulation 1 – substrate covered with old paint (S4b). All the others belong to simulation 3, which is the expected result due to higher repair cost of mineral wool. The highest values have the degradation factors that describe the low load-bearing capacity (S5a), coverage of the substrate with old or existing paint (S4a), and an insufficient amount of adhesive (D3a). The insufficient amount of adhesive has received high value in the technical severity category of safety against fire, which is reduced due to possible airflow in the system. The other relevant factors mainly influence the stability of the system influenced by fixation – unleveraged adhesive on the mineral wool (D5), dry curing conditions of the cement-based adhesive (M11a), usage of unsuitable adhesive (S7a), and not pre-processed detached areas (S6a) are the other relevant shortcomings in this group.

Group “Risk3” describes the shortcomings in category 4 for both components. Relevant degradation factor for all simulations is the improperly finished windowsills, enabling moisture penetration into the system (X2). Other risks concern simulation 1 and simulation 2. They describe the works that decrease adhesion properties – low humidity of the substrate (S8b), insufficient adhesive (D3b), problematic load-bearing capacity of the substrate (S5a), and reduced area of adhesive due to lack of pressure applied during the attachment of insulation plates (D8b).

The medium-risk category holds the largest amount of degradation factors. The highest TER values have received the degradation factors in the layers of substrate, adhesive, and additional details. The highly relevant shortcomings in the layer of the substrate concern the preparation works of the substrate surface – cleaning from biological growth (S3b), dust (S2b), and old paint (S4a), as well as problematic load-bearing capacity (S5b) and detached and unfilled areas of the surface (S6a). Additionally, the usage of unsuitable adhesive type (S72, S7b) is relevant. Higher TER values have received the mixture preparation and curing conditions. The weather factors of low humidity of the substrate (S8a), high temperature (M10b), and low relative humidity (M11a) are also relevant. For the application process, the exceeded working time of the mixture (D7a, D7b), high share of kneading water (M3b), and additionally added unsuitable ingredients (M8) are noted. The occasion when the adhesive is not applied on the border of the insulation plates (D1b) is relevant for simulation 1 and 2. The shortcomings during the application of additional details concern the moisture penetration into the system through problematic fixed frame connections(X4) and penetrations through the system due to attached objects on the façade (X7).

The low-risk category concerns mainly the shortcomings in the layers of the finishing coat, insulation, and mechanical anchors. In the finishing layer, the low relevance is set for the increased and decreased thickness of the applied mortar (F3, F4) and missing primer (F1). In the layer of mechanical anchors, the highly or deeply placed anchor plates (A7, A6), wrong placement of the anchors in comparison with the manufacturer’s recommendations (A5), as well as unclean anchor holes (A10) are noted to me irrelevant. The shortcomings during the application of insulation plates reveal that the increased width of the neighbouring polystyrene insulation plates (I7), crossed joints (I5), broken, and not filled polystyrene plates (I9), and missing fire reluctant areas, if required (I10), are the least problematic (I10). The reason for low values lying in the economic risk priority number, as the defects are easily detectable and do not occur that often.

For further analysis, the TER values of the simulations are positioned by their sequence of the construction process in Figure 41. The circles around the degradation factors show their belonging to the risk category. The horizontal lines show the average TER values by layers and the groups with green line are discussed more specifically. The figure visualises that the highest relevance has the construction works for simulation 1 in the layers of substrate and adhesive, while the impact is relatively similar to other simulations in other layers. The difference is caused mainly due to the fixation type, which increases the technical risk. The lowest risk can be noted for simulation 2, which is concerning the insulation plates made out of polystyrene and fixed with mechanical anchors and supplementary adhesive. Simulation 3 is in between, except with the works of additional details, which is marked as group TE9. Simulation 3 has a comparable average technical risk to simulation 2, but it has an increased economic impact due to the higher cost of mineral wool as insulation material.

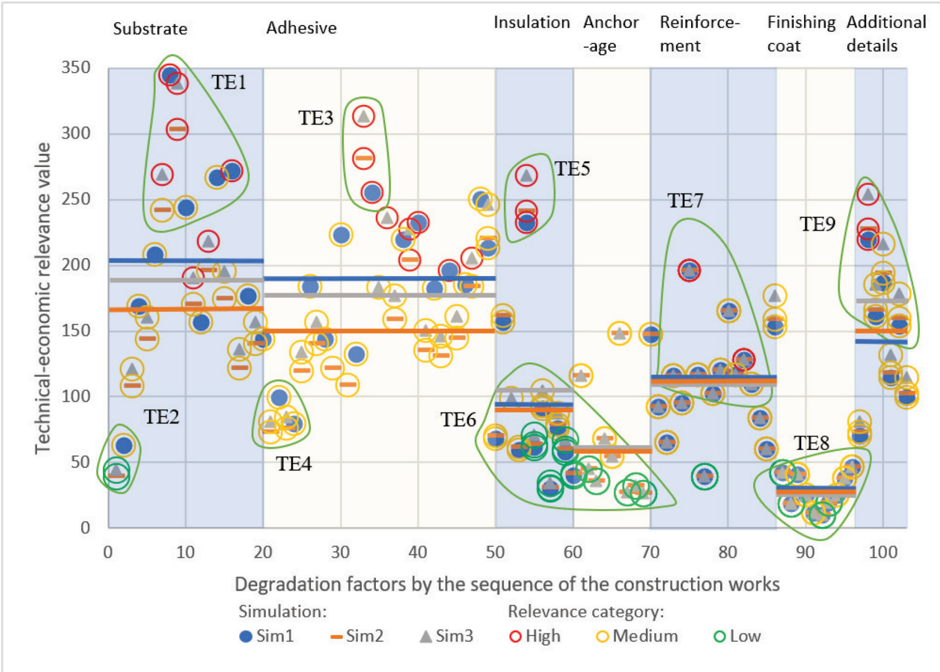


Figure 41. Technical-economic relevance value and risk category of the degradation factors by the sequence of construction works.

The increased deviation between simulations is noticed within the layer of substrate (group “TE1”). The group includes eight degradation factors in the layer of substrate, four of which concern simulation 1. The common factors are the occasions when the substrate is covered with old paint, and it reacts with adhesive (S4a, S4b) or is under load-bearing capacity (S5a, S5b). Other highly relevant shortcomings are very low humidity of the substrate (S8b), which is a risk in the curing process, mainly for inorganic mixtures and unsuitable adhesive type (S7b). In the low relevance group “TE2”, there are shortcomings that concern the substrate coverage with oil (S1a, S1b). Although the factors of substrate covered with old paint (S4a and S4b) and substrate covered with dust or dirt (S1a and S1b) have the same technical effect on the system, the economic risk priority number of the low relevance group is decreased substantially due to good detectability and low occurrence probability, which reduce the relevance value by more than five times.

The high relevance group “TE3” brings together the factors in the layer of adhesive, concerning the application of insufficient adhesive (D3a, D3b) as well as missing adhesive in the centre (D2a), as insulation plates made out of polystyrene are applied. The differentiation from the average is caused by high occurrence value. The low relevance group “TE4” describes wrong material storage conditions (M1a, M1b) and insufficient mixing procedure, which leaves clots in the mixture (M2a, M2b). Contrary to “TE3”, the high deviation is due to very low occurrence value. For the same reason, the group “TE5” differentiates from the average. The technical severity of the degradation factor from “TE5”, which describes continuous gaps in the system due to the installation application (I4), is highly influenced by the effect on fire protection, as the airflow within the system has a tremendous influence on the requirement.

The groups “TE6” and “TE8” include a number of factors that have a negative deviation from the trendline. The groups include the majority of degradation factors in the layer of insulation, mechanical anchors, and finishing layer. The degradation factors in the layer of reinforcement (group “TE7”) has a positive deviation, but the values still remain in the middle area as compared to all the factors. Relatively high values have received the degradation factors occurring during the installation of additional details (group “TE9”). The windowsills (X2) and fixed frame connections (X4) as well as unfinished penetrations through the system are problematic when objects are added on the surface of the system (X7). The value of the failures in this group is increased due to the high occurrence rate.

5.3.1 Distribution of the latency period by risk category

The stakeholders of the construction process should reduce the occurrence of the degradation factors for better overall outcome. However, the economic reasonability of resource allocation is influenced by the contractual defect liability period, which is two years by law in many cases.

The latency distribution of the degradation factors shows that the majority of shortcomings appear after the two years of the construction for the systems attached with mechanical anchors (simulation 1 and 2), while the majority of the shortcomings for the purely bonded system appear during the first two years (simulation 3). Figure 42 presents the distribution of the shortcomings according to the latency period. Simulation 1 and 2 hold more degradations factors with high and medium risk category, which appear after the latency period of two years.

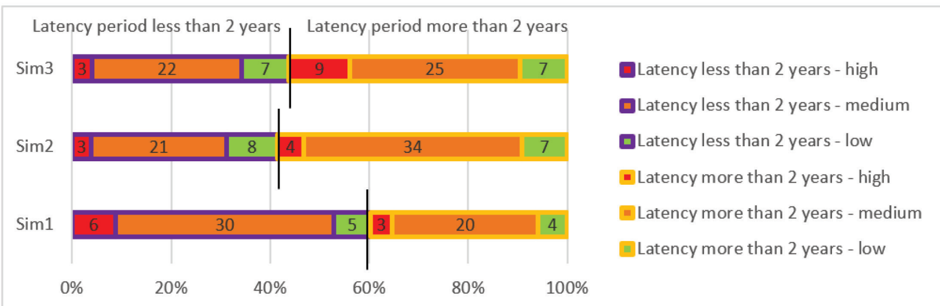
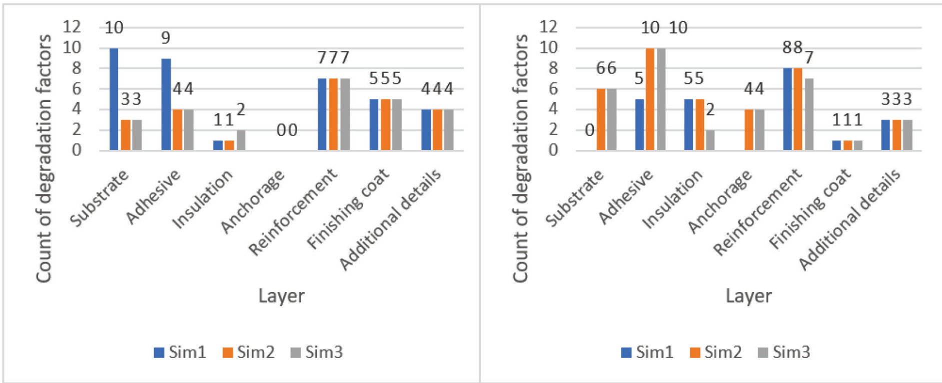


Figure 42. Count and share of degradation factors distributed by the two-year latency period and risk category.

In order to take a closer look, the high and medium risk category degradation factors are differentiated by layers and the two-year liability period in Figure 43. The latency period of the shortcomings in the layers of substrate and adhesive for the purely bonded system (simulation 1) are differentiated from the other simulations – 19 factors out of 24 appear during the first two years after construction. This means that the adhesion properties are more relevant to the contractor, and problems show visible deterioration signs during the short period after application. Additionally, five relevant shortcomings out of six in the finishing layer appear during the two-year period by all simulations.

These defects are technically less relevant, but they are visibly detectable and occur rather often. Especially in these layers, the legal liability is covered by the contractor.



(a) (b)

Figure 43. Distribution of the high and medium category degradation factors by the layer and by the latency period of a) less than two years and b) equal to or more than two years.

5.3.2 Conclusions of the technical-economic relevance assessment

The technical-economic relevance model expands the traditional FMEA approach by adding the impact of the future costs incurred by the shortcoming of the technical severity, detectability, and occurrence of the failure. The model evaluates and differentiates the significant on-site construction activities in terms of system type for more rational resource allocation and is also suitable for SMEs. The model is tested on three simulations that quantify the on-site degradation factors of ETICS.

In this study, 103 degradation factors have been evaluated through expert judgment. The data is validated with the Delphi technique and the non-parametric Friedman's test. Cost data for three simulations is received from one active company in the industry. The results emphasise the relevance of on-site activities during substrate preparation, i.e., application of adhesive and base coat with reinforcement mesh. Lower relevance is assigned to the activities during application of finishing coat and installation of insulation plates.

According to the results of the study, the following on-site aspects should be considered to increase the quality of the façade system:

1. The shortcomings of the preparation of the substrate and application of adhesive have a very high impact on technical severity as well as a fatal outcome for the system when the critical limit is exceeded. The possible high cost of replacement should be replaced by the quality increase and more careful inspection during the application process. The majority of the shortcomings of the purely bonded system appear during the two years following the construction.
2. The often-occurring and systematic problems are happening by the installation of additional details, such as windowsills, connections between fixed frames, and ETICS, and by other penetrations through the system. These defects cause significant technical degradations and also present high repair costs. Reduction of the moisture penetration into the systems is therefore recommended.

3. The weather-related degradation factors are relevant for most of the layers that concern mixtures. Freezing or drying out of the mixtures as well as the retention of a high amount of humidity in the system have a relatively high impact on the technical outcome. Good climate through coating and temperature control are highly suggested, especially during the winter period.
4. During the application of the adhesive and reinforcement layer, the shortcomings will be covered simultaneously, which makes it difficult to detect and repair the mistakes made during the process. The habits and working methods of individual artisans have a huge impact, as the activities are repeated. In order to prevent the shortcomings in these layers, the upscaling of skills and work methods are highly suggested.

The simulations have provided logical results and are relevant for the decision-making process. For more specific modelling, a sub-level of on-site activities could be applied in further studies. For example, the mixtures can be differentiated by their nature and ingredients, which are only partially observed in this research. The shortcomings of the construction process have different severity impact on various mixture types. Furthermore, the additional details in this study are only generally described. It would be significant to select specific solutions for additional details and develop their degradation factors in a more specific manner.

6 Discussion

External Thermal Insulation Composite System is a complex façade system whose quality is influenced by the work methods of artisans to a large extent. Numerous studies have researched the causes for degradation in isolation, making it difficult to establish the focus on the most relevant activities, as no comparative scale has been developed for the influencing factors. Enhanced quality, on the other hand, requires resources, and it should focus on the vital few activities. The aim of the research is to develop an on-site construction process evaluation model that quantifies decisive parameters and enables setting the focus on the most relevant activities during the construction process.

The model recommends the prioritisation of the technical and economic impact, which is supported by the probability of occurrence and difficult detectability of the shortcoming. The author selected the Failure Mode Effects Analysis as an appropriate evaluation tool for the quantification of the decisive parameters. The model has shown flexibility in including parameters required for the assessment process, depending on the needs of the user.

This research work initially selected 114 DFs and continued with 103 of them for further analysis after verification with the experts. Relatively large standard deviation within each layer emphasises the need to observe only relevant DFs. Additionally, the interpretation of the average values of the layers is affected by the amount and characteristic of the DFs observed in the simulation, and might change in some extent as additional factors are added according to the system. However, the visualisations show that the average relevance of the layers is still applicable for generalisation in some extent (see Figure 41).

The DFs are differentiated through three ETICS types and seven layers within the system. Each ETICS type concerned 68 to 77 DFs. Regarding the selection of DFs, it must be noted that the specific material properties alter the severity impact. Neumann (2009, p. 103) also described how the properties of the adhesive and base coat are influenced by the share of cement and synthetic resin in the mixture, which influences crack formation as the severity value in the context of this study as well. In the finishing layer, even more than the others, ingredients that alter the weather resistance properties are added. For more specific modelling consideration within mixtures, a sub-level classification could be applied in the further studies.

The technical considerations of the construction activities are evaluated as loss of systems' technical performance. The evaluation of the shortcomings show that the construction process has a relevant impact on mechanical resilience and stability (SC1), the ability to bypass tensions (SC8), long-term durability (SC6), and humidity and weather protection (SC5). The interrelation of these severity categories is described with correlation analysis (see Figure 9), which enables the interpretation that the failures impacting mechanical resilience and stability (SC1) and the ability to bypass tensions (SC8) are the main causes for reduced long-term durability and humidity and weather protection. The other severity categories, along with energy economy and heat retention (SC3), are less impacted by the construction activity failures. In their study, Institute of Building Research (2011) investigated 50 buildings in Germany to reveal the causes of failure to achieve energy-efficiency measures. Among other parameters, the external shell of the buildings, covered with ETICS, was noted. According to the study, 66% of the failures are caused in some extent also by the faults during the on-site construction activities. More specifically, the construction process of ETICS is responsible for 46% of the shortcomings. Within the 46% lie the most often occurring failures of hollow spaces, difference in the thickness of insulation, failure to install a sufficient number of mechanical anchors, usage of unsuitable materials, reduced use of adhesive, and the failure to place insulation plates tightly next to each other. According to the results of the current study, the effect of the mentioned shortcomings cannot be directly linked to the reduced energy efficiency to such an extent. It, however, remains as the primary causes for the further degradation of the façade and has an effect to the energy performance of the building when maintenance techniques are not applied.

The developed model enables the extension of the traditional FMEA approach that focuses on technical relevance, with economic influence. Resource allocation should focus on degradation factors that affect the internal layers, as they cause higher repair costs (see Figure 29). By adding the occurrence probability and detectability component, the focus can be set only on limited factors with a higher risk. The added components reduce the relevance of the degradation factors in the layers of insulation and mechanical anchors. When the components are observed in silos, then the probability of occurrence increased the risk in the layer of the substrate and in additionally added details, while the detectability of the failures increased the risk in the layer of adhesive and reinforcement.

For the owner as well as the contractor, the relevance of future cost depends primarily on the defect liability period as well as the latency period of the shortcoming. The results show that latency period of the shortcomings of ETICS vary in a relatively small range – half of them appear during the first two years. Neumann (2009) stated that 80% of the shortcoming occur during the first five years and 67% occur in two years. According to the results of this study, 90% occur during the first five years, while 50% occur during the two-year period. The variation can be caused by the selection of degradation factors in the sample as well as due to climatic changes.

Due to the fast appearance of the degradation signs, the interest rate has a relatively low impact on the results. However, the results of the latency period can be interesting to various parties, depending on their contractual terms. The construction company or the owner should consider the cost of deterioration in their risk assessment, depending on the warranty agreement between the parties. Additionally, the cost component is highly relevant in terms of the owner's and contractor's quality considerations. An equilibrium could be found in the future research between costs on quality increase and future risk mitigation.

The diverse results of the technical severity and ERPN lead to different relevance interpretation in some layers. The combination of occurrence ratio and detectability, as well as the cost of repair, have reduced the relevance on the values in the layer of finishing and mechanical anchorage in comparison with the technical severity rating. The technical severity of the finishing layer has received an unexpectedly high value. As the DFs in the finishing layer are mostly causing aesthetic problems, which is most probable cause of higher values given by the experts, the change in the interpretation of the final results is positive. The finishing coat is relevant for long-term durability (European Organisation for Technical Approvals, 2013); however, the defects in this layer have rather less impact on the system in general.

The debate about construction quality and its impact on life-cycle considerations of a building is an ongoing discussion in academia as well as in the industry. This thesis contributes to the academic literature in the field of construction technology of External Thermal Insulation Composite System and delivers an on-site construction activity prioritisation model. The Technical-Economic Relevance model is a complex assessment system that quantifies various technical and economic influencers required for better decision making. The results of the three simulations in this study can be considered as practical input in order to improve construction quality and reduce risk through focused resource allocation on the high-risk activities.

Conclusions

The increased number of energy efficiency requirements have increased the refurbishment rate of apartment buildings covered with ETICS. The majority of visible defects in the years following the completion are caused by shortcomings during the construction process. In order to avoid failures, quality control should focus on the factors that have increased technical relevance as well as financial impact. Durability of the façade, technical quality, and other requirements are essential and important to consider. Much research in the field of ETICS observes the quality aspects in isolation, making a rational comparison of the inadequacies impossible.

The main aim of the dissertation was to develop an on-site construction process relevance assessment method that enables quantification and prioritisation of the shortcomings. The research gap was approached by identifying the on-site shortcomings of ETICS, modelling the interaction of the decisive components, quantifying the impact of the shortcomings of the construction process, and providing a prioritisation method. The developed method expands the traditional FMEA approach by aggregating the technical severity, future repair costs, detectability, and occurrence of the failure. The objective of the study was achieved by enabling the prioritisation of the importance of various degradation factors of ETICS.

The technical severity components of the system are based on essential requirements delineated by the Construction Products Regulation, and their weights are introduced with Aurnhammer's method, where the loss of performance is quantified. The 103 degradation factors, which were identified in the literature review, have been evaluated on the Likert scale by the experts meeting the criterion relevant for the construction industry. These evaluations were validated with the non-parametric Friedman's test. The detectability, occurrence, and latency period of the shortcoming have been validated with the Delphi technique, while the historic cost data for the three simulations was received from an active construction company. The various components were mathematically aggregated, and the results were distributed into relevance categories that classify and prioritise the technical-economic impact of the failure.

The practical output of the technical severity evaluation shows that ETICS construction process significantly alters the resilience of the system with regards to mechanical stability and long-term durability. However, the craftsmen-related inadequacies have a very low impact on the energy efficiency and noise protection. The unified technical-economic relevance enables the differentiation of the most relevant factors. The highest average relevance has the activities in the layers of substrate and adhesive and during the application of additional details. The lowest average relevance has the inadequacies occurring during the application of the finishing coat and the installation of mechanical anchors and insulation plates. According to the results of this study, the following on-site aspects should be considered to increase the quality of the façade system:

- The shortcomings during the preparation of the substrate and the application of adhesive have a very high impact on the technical severity as well as a fatal outcome on the system as the critical limit is exceeded. The possible high cost of replacement should be replaced by an increase in the quality and more careful inspection during the application process. The majority of the shortcomings of the purely bonded system appear in the two years following construction.

- The frequently occurring and systematic problems occur due to the installation of additional details, such as windowsills, connections between fixed frames and ETICS, and other penetrations through the system. These defects cause significant technical degradation and present high repair costs.
- The weather-related degradation factors are relevant for most of the layers that concern mixtures. Freezing or drying out of the mixtures as well as high humidity remaining in the system have a relatively high impact on the technical outcome. Good climate through coating as well as temperature and humidity control are highly recommended.
- During the application of the adhesive and reinforcement layers, the shortcomings will be covered simultaneously, which makes it difficult to detect and repair the mistakes made during the process. The habits and working methods of individual artisans have a high impact, as the activities are repeated. In order to avoid the shortcomings in these layers, the upscaling of skills and work methods is highly suggested.

Limitations of the study

The research has limitations related to the scope of the system, generalisation of the results, and comparative studies that are relevant to point out.

First, ETICS is a technically complex system that can be built with a variety of construction materials. The material properties are subject to change, as new technology and building products emerge. The large amount of influencers of the materials are described by Neumann (2009) as well as Kussauer and Ruprecht (2011) and the specific variations in construction technology by Cziesielski and Vogdt (2007). Due to the high need for resources as well as the time limits on the doctoral study, the evaluations of the degradation factors are conducted in a generalized way and do not go into an in-depth examination of material properties and specific construction technologies which may be used in the construction industry.

Second, the method is evaluating only the systematic shortcomings, which address the ingrained work techniques of the craftsmen. The accidental defects cannot be evaluated with the developed ETICS assessment model, as the technical and economic effect is reduced to a large extent or does not have an effect at all.

Third, the author has not found similar holistic assessment models in the literature which evaluate similar relevance. The lack of comparative studies hinders the provision of an alternative point of view, although some components were comparable individually. Yet, the results have been logical and were discussed with the experts to ascertain the provision of practical usage.

Recommendations for further research

In this research, the decisive components of ETICS was investigated to enable better focus setting. As the façade system is technically complex, the degradation factors are highly influenced by the materials used in the system and also by the climate in the specific region. This not only provides opportunities to include additional components in the method, but also to have more specific evaluations that concern more specific materials. The following topics are suggested for further research:

- The degradation of the external shell is highly influenced by the climate conditions. Therefore, an additional climate parameter could be introduced into the mathematical aggregation to provide a comparison between climate conditions to transfer the results through various regions.

- A number of shortcomings are aggregators to the degradation factors in the subsequent layers and an interaction of degradation factors occurs. The increased relevance of these shortcomings could be included in the method.
- The degradation factors could be related to possible pathology routes. This would link the results of the ETICS assessment model with the studies, which focus on the visible degradation signs.
- Mixtures have received high relevance in this study. Further research could distribute the mixtures according to their characteristics.

List of Figures

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Acknowledgements

The dissertation was written as a part of the joint doctoral program of Tallinn University of Technology and Technical University of Berlin, and I am very thankful to both. I would like to express my gratitude to my two supervisors, Prof. Irene Lill from Tallinn University of Technology for her encouragement and support during these years, and Prof. Frank U. Vogdt from Technische Universität Berlin, who has provided me with me invaluable guidance, facilitated long discussions, and asked difficult questions to set the focus of my research.

I obtained valuable input during numerous discussions regarding the complexity of ETICS, design of the research, and data collection. I am indebted to the professionals who have contributed their valuable time for this study during the last years, including Antje Proft, Bodo Buecher, Marti Dengo, Jaan Vikat, Karli Kleemann, Erki Soekov, and Artur Kasak.

I would like to express my gratitude to my wife Sirja for her support and patience for the duration of my research work and also to our children Sirena and Sigmar, who will hopefully benefit from the change in my mindset as they grow up.

And finally, this study would not have been as successful without financial support, which was provided by the institutional research funding of the Estonian Ministry of Education and Research: IUT1−15 "Nearly-zero energy solutions and their implementation on deep renovation of buildings".

Abstract

Modelling Construction Process Impact Factors on Degradation of Thin Rendered Facades

The renovation rate of apartment buildings having the External Thermal Insulation Composite System (ETICS) has increased during the last decades as it enables to optimise the energy efficiency of building envelopes. However, identified deficiencies that appear after the completion of construction confirm the existence of systematic, but avoidable, construction process shortcomings. These systematic inadequacies of application process increase the financial risk for the stakeholders and reduce the long-term durability of the façade. The extent of on-site shortcomings can be reduced if the most significant causes are detected during construction supervision. This complex façade system is a combination of different, but matching, construction materials in several layers, all having specific requirements as well as application methods. As the relevance of construction materials is well-studied and the causes of degradations are often known, the question arises: why is the number of occurring defects in the industry so high?

The thesis contributes to researches which study the impact of the construction process shortcomings and the construction quality of ETICS. To compare the relevance of numerous degradation factors to each other, a unique relevance assessment method has been developed. The ETICS assessment model, which is built according to the developed method, prioritises the degradation factors for rational focus setting in the industry.

The method quantifies the technical significance of the degradation factors along with the future repair costs, probability of occurrence and detectability of the shortcoming. The technical significance is derived from the analysis of expert judgments and validated with the non-parametric Friedman's test. The method weighs the impact of the essential technical requirements and simulates an integrated weighted value. The relevant economic parameters are to be collected from national statistics and project-based historic cost data. The data collection of predictable components follows the Delphi technique. The method of failure mode and effects analysis, together with the usage of risk matrix, enables the mathematical aggregation of the components.

The ETICS assessment model is verified on three simulations that evaluate the impact of the 103 degradation factors collected through the literature review. The analysis of the results shows that the model enables priority setting for complex construction systems in the industry. The numerical results of the simulations emphasise that the on-site construction activities of ETICS strongly influence the long-term durability, the stability, as well as the ability to bypass tensions. The degradation factors that occur during the preparation of the substrate, application of adhesive, and installation of additional details that penetrate the system have the highest relevance. The on-site failures occurring during the application of mechanical anchors, insulation materials, and finishing layer have the lowest relevance. The results show that half of the shortcomings show visible degradation signs during the first two years after completion and 90% of the shortcomings appear within the first five years.

It is recommended to upskill the craftsmen as the occurrence of shortcomings reduces significantly and the detection rate increases already during the construction phase. This relates in particular to the measures for protection against external weather effects due to their high relevance.

Keywords: ETICS, quality control, durability, building defects

Kurzfassung

Methode zur Bewertung der Relevanz von beeinflussenden Faktoren im Bauprozess auf die Mängelfreiheit von Wärmedämmverbundsystemen

Der Einsatz von Wärmedämmverbundsystemen (WDVS) ermöglicht es, die Energie-effizienz äußerer Gebäudehüllen zu optimieren. Festgestellte Mängel nach Fertigstellung der Bauarbeiten belegen jedoch, dass häufig systematische, aber vermeidbare Fehler während des Bauprozesses auftreten. Durch diese systematischen Defizite beim WDVS steigt das finanzielle Risiko für die Beteiligten. Gleichzeitig sinkt die Dauerhaftigkeit der Fassade. Der Umfang der bauseitigen Fehler kann reduziert werden, wenn die hierfür wichtigsten Ursachen im Rahmen einer Bauüberwachung erkannt werden. Das komplexe WDVS besteht aus einer Kombination unterschiedlicher, aufeinander abgestimmter Baumaterialien in mehreren Schichten, die jeweils bestimmten Anforderungen gerecht werden müssen und spezifischer Verarbeitungs-methoden bedürfen. Da die Relevanz der Baumaterialen bereits eingehend untersucht wurde und die Abnutzungsursachen häufig bekannt sind, stellt sich die Frage: Warum treten die Mängel in der Branche so häufig auf?

In der vorliegenden wissenschaftlichen Arbeit wird eine neue Bewertungsmethode zur Qualitätssicherung von WDVS entwickelt. Durch diese Methode wird ein einheitliches Modell erstellt, das die Abnutzungsfaktoren priorisieren.

In der Methode werden die technische Signifikanz der Abnutzungsfaktoren und die zukünftigen Instandsetzungskosten quantifiziert, einschließlich der Eintritts-wahrscheinlichkeit und Schwierigkeit der Fehlerdetektion. Das Modell wägt die Auswirkungen der wesentlichen technischen Anforderungen ab und simuliert einen gewichteten technischen Schweregrad, der aus der Analyse der Expertenbewertungen hervorgeht, die anhand des nichtparametrischen Friedman-Tests validiert wurden. Die relevanten wirtschaftlichen Parameter werden aus den nationalen Statistiken und projektbasierten Kostendaten bezogen. Die vorhersehbaren Komponenten basieren auf der Delphi-Methode. Die Fehlermöglichkeits- und -einflussanalyse (FMEA) ermöglicht in Kombination mit einer Risikomatrix die mathematische Zusammenführung der Komponenten.

Das Modell wird in drei Simulationen verifiziert, die die Auswirkungen der im Rahmen einer Literaturrecherche gesammelten 103 Abnutzungsfaktoren auswerten. Die Ergebnisse zeigen, dass die Methode die Priorisierung bei komplexen Bausystemen ermöglicht und in der Praxis umsetzbar ist.

Das quantitative Simulationsergebnis zeigt, dass die Ausführungsarbeiten von WDVS insbesondere einen erheblichen Einfluss auf die Langzeitbeständigkeit, die Standsicherheit sowie die Rissgefährdung haben können. Die Abnutzungsfaktoren, die während der Vorbereitung des Untergrundes, dem auftragen des Klebstoffs und beim Aufbringen zusätzlicher Details, die sich durch das System ziehen, haben aufgrund der hohen Instandsetzungskosten, der großen Eintrittswahrscheinlichkeit sowie der schwierigeren Feststellbarkeit die höchste Relevanz. Bauseitige Fehler bei der Ausführung der mechanischen Verankerungen, Dämmmaterialien und Schluss-beschichtungen sind dagegen von geringerer Relevanz. Die Ergebnisse der Simulationen zeigen weiter, dass die Hälfte der Mängel innerhalb der ersten zwei Jahre nach Fertigstellung auftreten und 90% während fünf Jahren erkennbar sind.

Empfohlen wird, die Facharbeiter zur Ausführung von WDVS zu schulen, da dadurch zum Einen die Gefahr der Mängelentstehung und zum Anderen gleichzeitig der Aufwand zur Mängelerkennung deutlich reduziert wird. Dies betrifft insbesondere auch die aufgrund ihres relativ großen Einflusses empfohlenen Schutzmaßnahmen gegen äußere Witterungseinflüsse.

Schlagwörter: WDVS, Qualitätssicherung, Dauerhaftigkeit, Baumängel

Lühikokkuvõte
Ehitusprotsessi mõjufaktorite modelleerimine õhekrohv fassaadide lagunemisel

Energiatõhusa elamufondi väljaarendamisel on oluline osa Euroopa energiapoliitikas. Selle saavutamise üheks viisiks on olemasoleva elamufondi fassaadide uuendamine, kasutades soojusisolatsiooni liitsüsteeme (SILS). Liitsüsteemides on kombineeritud erinevad, kuid omavahel sobivad ehitusmaterjalid, millel on erisugused tehnilised eesmärgid, nõuded ning paigaldusviisid. Arvestades, et ehitusmaterjalide omadusi on suhteliselt palju uuritud ning fassaadide võimalikud ehitusvead on teada, jääb selgusetuks, mis põhjusel on hoonete defektide arv jätkuvalt sedavõrd suur. Liitsüsteemiga uuendatud fassaadidel esinevaid defekte on võimalik vältida ehitusprotsessi parema korraldamisega. Süstemaatilised ehitustegevuse puudujäägid suurendavad osapoolte finantsriske ning vähendavad fassaadi eesmärgipärast kasutusiga. Ehitustegevuse vigade esinemist ja nende ulatust on võimalik vähendada kui kõige olulisemad puudused ja nende põhjused on kaardistatud.

Käesolev doktoritöö annab arvestava panuse ehitustegevuse kõrvalekallete mõju ja olulisuse määramiseks ning fassaadide kvaliteedi suurendamiseks. Puudujääkide võrreldavuse tagamiseks loob autor unikaalse fassaadisüsteemi hindamismudeli, mis prioritiseerib ehitusvead, võimaldades parendusmeetmete fokusseerimist suurema mõjuga kõrvalekalletele. Välja töötatud mudel kvantifitseerib kõrvalekalde ehitustehnilise olulisuse, parandusmaksumuse, puuduste esinemise tõenäosuse ja tuvastatavuse komponendid ning loob nende põhjal ühtse vea olulisuse hindamisskaala.

Esiteks määratakse ehitusvea mõju kaheksale ehitise tehnilisele põhiomadusele, tuginedes eksperthinnangutele ning tulemus valideeritakse Friedmani testiga. Põhiomaduste mõju mudeldatakse ühiseks kaalutud väärtuseks. Teiseks hinnatakse majanduslikku mõju, mis määrab ehitusveast tingitud hilisema parandamise kulu, arvestades sarnaste projektide varasemaid maksumusi ning riiklikku statistika intressimäärasid. Puuduste esinemise tõenäosus, tuvastatavus ja nende esile kerkimise perioodi pikkus on prognoositavad andmed, mis kogutakse Delphi meetodit järgides. Komponendid koondatakse kasutades veariskianalüüsi meetodit koos riskimaatriksiga, mis loob vea olulisuse väärtuse. Hindamismudeli verifitseerimiseks hinnati 103 võimalikku ehitusviga kolmes liitsüsteemi tüübis.

Parema ehituskvaliteedi saavutamiseks on välja töötatud komplekssete süsteemide hindamismudeliga võimalik seada fookus olulisematele ehitustöödele. Simulatsioonide tulemused näitavad, et SILS paigaldustehnoloogia omab olulist mõju fassaadi pikaealisusele, stabiilsusele ja süsteemisiseste pingete ülekandmisele. Ehitustegevuse puudujäägid aluspinna ettevalmistamisel, liimikihi pealekandmisel ning süsteemi läbistavate detailide paigaldusel on suurima riskimääraga. Vead, mis on tehtud mehhaaniliste ankrute või soojustus- ja krohvikihi paigaldamisel omavad väiksemat mõju. Kolme simulatsiooni tulemused näitavad, et pooled fassaadisüsteemide ehitusvigadest ilmnevad järgneva kahe aasta ning 90% vigadest viie aasta jooksul peale ehitust.

On soovitatav tõsta töötajate oskusi korrektsete paigaldusviiside kasutamiseks, mis vähendab oluliselt vigade esinemise sagedust ning tõstab vea märkamise oskusi juba protsessi jooksul. See puudutab eelkõige meetmeid ilmastikumõjude eest, mis on läbivalt suure mõjuga.

Märksõnad: SILS, kvaliteedi tagamine, vastupidavus, ehitusvead

Appendix 1

Table A1. Data (1)

Seq.	ID	Layer	Factor	SR, SC1	SR, SC2	SR, SC3	SR, SC4	SR, SC5	SR, SC6	SR, SC7	SR, SC8	SV	SV-C	OV	DV	TRPN
1	S1a	S	Substrate is covered with grease or oil	2,73	0,36	0,00	0,18	0,36	2,73	0,36	1,55	0,327	3	1,00	1,20	0,39
2	S1b	S	Substrate is covered with grease or oil	4,33	0,33	0,00	0,17	0,33	3,33	0,33	1,75	0,460	4	1,00	1,40	0,64
3	S2a	S	Substrate is covered with dust or dirt	2,64	0,36	0,00	0,18	0,36	2,64	0,36	1,64	0,320	3	2,40	1,40	1,08
4	S2b	S	Substrate is covered with dust or dirt	4,17	0,33	0,00	0,17	0,33	3,25	0,33	1,92	0,449	4	2,40	1,60	1,72
5	S3a	S	Substrate is covered with biological growth	2,64	0,36	0,00	0,18	0,36	2,64	0,36	1,55	0,318	3	2,80	1,60	1,43
6	S3b	S	Substrate is covered with biological growth	3,91	0,36	0,00	0,18	0,36	3,55	0,36	2,09	0,445	4	3,00	1,60	2,14
7	S4a	S	Substrate is covered with paint or other material that can chemically react with adhesive	2,82	0,64	0,27	0,18	0,55	2,82	0,45	1,73	0,356	3	2,40	2,80	2,39
8	S4b	S	Substrate is covered with paint or other material that can chemically react with adhesive	4,00	0,30	0,30	0,00	0,40	3,60	0,10	2,20	0,452	4	2,60	3,00	3,53
9	S5a	S	Substrate is under required load-bearing capacity	3,73	0,36	0,00	0,18	0,36	3,36	0,64	1,82	0,425	4	2,20	3,20	2,99
10	S5b	S	Substrate is under required load-bearing capacity	4,00	0,36	0,00	0,18	0,36	3,64	0,64	2,09	0,457	4	1,60	3,40	2,49
11	S6a	S	Substrate has large unevenness or has detached areas	2,08	0,33	0,58	0,25	0,42	2,00	0,58	1,17	0,261	3	3,60	1,80	1,69
12	S6b	S	Substrate has large unevenness or has detached areas	2,92	0,33	0,58	0,25	0,42	2,42	0,58	1,25	0,333	3	3,00	1,60	1,60
13	S7a	S	Unsuitable surface (too smooth), which reduces adhesion properties	2,33	0,67	0,00	0,33	0,67	2,17	0,67	1,00	0,292	3	2,00	3,33	1,94
14	S7b	S	Unsuitable surface (too smooth), which reduces adhesion properties	3,71	0,00	0,43	0,00	0,00	2,43	0,71	1,43	0,373	3	2,00	3,67	2,73

Table A1. Data (2)

Seq.	ID	Layer	Factor	SR, SC1	SR, SC2	SR, SC3	SR, SC4	SR, SC5	SR, SC6	SR, SC7	SR, SC8	SV	SV-C	OV	DV	TRPN
15	S8a	S	Substrate has very low humidity (inorganic adhesive)	2,45	0,36	0,00	0,18	0,55	2,45	0,82	1,64	0,308	3	2,25	2,50	1,73
16	S8b	S	Substrate has very low humidity (inorganic adhesive)	4,00	0,36	0,00	0,18	0,73	3,18	0,82	1,91	0,445	4	2,50	2,50	2,78
17	S9a	S	Substrate is very wet (raining prior to application of adhesive)	2,40	0,50	0,30	0,20	0,70	2,40	0,70	1,30	0,305	3	2,20	1,80	1,21
18	S9b	S	Substrate is very wet (raining prior to application of adhesive)	3,60	0,50	0,30	0,20	0,70	3,00	0,70	1,50	0,411	4	2,20	2,00	1,81
19	S10a	S	Substrate is frozen during the application (inorganic adhesive)	4,00	0,20	0,40	0,00	0,00	3,80	0,00	2,20	0,450	4	1,40	2,20	1,39
20	S10b	S	Substrate is frozen during the application (inorganic adhesive)	4,20	0,20	0,40	0,00	0,00	4,20	0,00	2,20	0,476	4	1,40	2,20	1,47
21	M1a	D	Unsuitable mixture storage conditions	2,75	0,00	0,00	0,00	0,00	2,63	0,00	1,50	0,301	3	1,00	3,00	0,72
22	M1b	D	Unsuitable mixture storage conditions	4,00	0,00	0,00	0,00	0,00	3,63	0,00	1,75	0,424	4	1,00	3,00	1,02
23	M2a	D	Failure of mixing procedures to remove clots	2,14	0,00	0,00	0,00	0,00	1,57	0,00	0,43	0,206	2	1,40	2,60	0,75
24	M2b	D	Failure of mixing procedures to remove clots	2,63	0,00	0,00	0,00	0,00	2,00	0,00	0,75	0,259	3	1,20	2,60	0,81
25	M3a	D	High share of kneading water	2,44	0,33	0,00	0,22	0,67	2,22	0,44	1,00	0,284	3	1,40	3,00	1,19
26	M3b	D	High share of kneading water	3,22	0,33	0,00	0,22	0,78	2,44	0,44	1,22	0,351	3	1,80	3,00	1,90
27	M4a	D	Low share of kneading water	2,63	0,38	0,00	0,25	1,00	2,38	0,50	1,13	0,310	3	1,50	3,00	1,40
28	M4b	D	Low share of kneading water	3,14	0,00	0,00	0,00	0,71	2,29	0,00	1,57	0,327	3	1,50	3,00	1,47
29	D1a	D	Missing adhesive on the edges of insulation (polystyrene)	2,30	1,60	2,20	1,10	1,60	3,00	0,60	1,70	0,404	4	1,50	3,25	1,97
30	D1b	D	Missing adhesive on the edges of insulation (polystyrene)	3,27	1,45	2,00	1,00	1,73	3,36	0,55	1,55	0,472	4	1,50	3,25	2,30
31	D2a	D	Missing adhesive in the centre of insulation (polystyrene)	2,44	0,44	0,33	0,33	1,22	2,67	0,67	1,11	0,317	3	1,25	2,75	1,09

Table A1. Data (2)

Seq.	ID	Layer	Factor	SR, SC1	SR, SC2	SR, SC3	SR, SC4	SR, SC5	SR, SC6	SR, SC7	SR, SC8	SV	SV-C	OV	DV	TRPN
32	D2b	D	Missing adhesive in the centre of insulation (polystyrene)	3,30	0,40	0,30	0,30	1,50	3,20	0,60	1,30	0,396	4	1,25	2,75	1,36
33	D3a	D	Insufficient adhesive surface area	2,63	1,88	1,00	0,50	0,63	3,13	0,25	1,88	0,414	4	2,75	2,50	2,84
34	D3b	D	Insufficient adhesive surface area	3,22	0,89	0,67	0,44	0,33	2,89	0,22	1,22	0,389	4	2,75	2,50	2,67
35	D4	D	Adhesive is not rubbed into insulation plate (mineral wool)	2,40	0,00	0,00	0,00	0,60	2,60	0,00	1,20	0,276	3	2,00	3,00	1,66
36	D5	D	Adhesive is not treated with notch towel (mineral wool)	2,88	0,50	0,38	0,00	0,13	1,88	0,13	1,13	0,306	3	2,33	3,00	2,14
37	D7a	D	Working time of the adhesive is exceeded	2,80	0,50	0,30	0,20	0,30	2,70	0,30	1,70	0,342	3	1,80	2,60	1,60
38	D7b	D	Working time of the adhesive is exceeded	4,00	0,45	0,27	0,18	0,27	3,27	0,27	1,91	0,445	4	1,80	2,80	2,24
39	D8a	D	Low pressure during the application of insulation plates	1,88	0,63	0,25	0,25	0,38	2,13	0,38	1,00	0,253	2	2,67	3,00	2,02
40	D8b	D	Low pressure during the application of insulation plates	3,44	0,78	0,44	0,22	0,33	2,67	0,33	1,56	0,397	4	2,00	3,00	2,38
41	D9a	D	Large unevenness of the adhesive layer	1,88	0,38	0,38	0,25	0,13	1,75	0,00	1,25	0,231	2	1,67	3,50	1,35
42	D9b	D	Large unevenness of the adhesive layer	2,88	0,38	0,38	0,25	0,13	2,38	0,00	1,25	0,320	3	1,67	3,50	1,87
43	M9a	D	Low temperature (freezing) during the application and/or the curing process	3,55	0,36	0,00	0,09	1,09	3,18	0,36	2,55	0,425	4	1,40	2,20	1,31
44	M9b	D	Low temperature (freezing) during the application and/or the curing process	4,64	0,36	0,00	0,09	1,27	3,73	0,36	2,73	0,523	5	1,60	2,40	2,01
45	M10a	D	High temperature (hot) during the curing process	2,60	0,30	0,00	0,10	0,50	2,30	0,20	1,70	0,305	3	1,80	2,60	1,43
46	M10b	D	High temperature (hot) during the curing process	3,64	0,27	0,00	0,09	0,82	3,00	0,18	1,91	0,405	4	1,80	2,60	1,89
47	M11a	D	Low humidity (dry) during the curing process	2,57	0,00	0,00	0,00	0,43	1,86	0,00	1,00	0,260	3	2,33	3,00	1,82

Table A1. Data (3)

Seq.	ID	Layer	Factor	SR, SC1	SR, SC2	SR, SC3	SR, SC4	SR, SC5	SR, SC6	SR, SC7	SR, SC8	SV	SV-C	OV	DV	TRPN
48	M11b	D	Low humidity (dry) during the curing process	3,71	0,00	0,00	0,00	0,43	2,43	0,00	1,43	0,366	3	2,33	3,00	2,56
49	M8	D	Addition of ingredients that are not recommended to the mixture	3,43	0,86	0,00	0,00	1,86	3,86	0,00	2,86	0,466	4	1,80	2,60	2,18
50	I1	I	Polystyrene is exposed to UV-radiation for a extended period	3,33	0,44	0,22	0,11	0,89	3,33	0,67	1,56	0,401	4	1,25	1,40	0,70
51	I2	I	Insulation plates are installed shortly after manufacture (unfinished diffusion process)	1,38	0,38	0,75	0,50	1,00	2,75	0,38	2,13	0,263	3	1,75	3,50	1,61
52	I3a	I	Insulation plates with very high relative humidity (wet)	2,38	0,25	2,38	0,25	1,25	2,13	0,75	0,88	0,304	3	1,20	2,40	0,87
53	I3b	I	Insulation plates with very high relative humidity (wet)	0,80	0,60	1,40	0,20	1,00	0,60	0,80	0,20	0,136	2	1,50	3,00	0,61
54	I4	I	Continuous gaps between substrate and insulation material	2,22	3,33	4,33	2,22	2,11	3,67	2,00	1,33	0,532	5	1,40	3,20	2,38
55	I5	I	Corners of neighbouring insulation plates are crossed or too close	1,00	0,10	1,00	0,30	1,80	2,70	0,20	2,10	0,230	2	2,25	1,25	0,65
56	I6	I	Corners of the openings have crossed joints	1,36	0,09	1,27	0,09	2,18	3,09	0,45	2,27	0,277	3	2,80	1,20	0,93
57	I7	I	The joint width of neighbouring insulation plates is too wide	1,00	0,00	2,00	0,63	1,63	2,38	0,38	1,00	0,208	2	1,50	1,00	0,31
58	I8	I	Large height difference between neighbouring insulation plates	0,63	0,13	0,75	0,25	1,75	2,63	0,50	1,75	0,195	2	2,00	2,00	0,78
59	I9	I	Broken areas of the insulation plates are not filled with the same material	1,00	0,56	1,78	1,00	1,56	1,89	0,00	1,22	0,217	2	2,25	1,25	0,61
60	I10	I	Missing or narrow fire-reluctant areas	0,10	4,90	0,10	0,10	0,10	0,30	0,10	0,10	0,218	2	1,50	1,25	0,41
61	A1	A	Increased diameter of drilled anchor hole	4,00	0,67	0,33	0,22	0,56	2,44	0,33	1,44	0,423	4	1,50	3,00	1,91
62	A10	A	Hole of the anchor is not cleaned	2,33	0,33	0,00	0,00	0,00	1,50	0,00	0,67	0,235	2	1,33	2,33	0,73

Table A1. Data (4)

Seq.	ID	Layer	Factor	SR, SC1	SR, SC2	SR, SC3	SR, SC4	SR, SC5	SR, SC6	SR, SC7	SR, SC8	SV	SV-C	OV	DV	TRPN
63	A5	A	Location of anchors is not as foreseen	2,50	0,50	0,00	0,13	0,13	1,38	0,00	1,13	0,261	3	1,67	1,33	0,58
64	A3	A	Decreased number of anchors in the continuous areas	3,50	0,40	0,10	0,10	0,10	2,30	0,00	1,10	0,355	3	2,50	1,25	1,11
65	A8	A	Decreased number of anchors in the corner areas	3,56	0,56	0,22	0,11	0,56	2,56	0,44	1,56	0,392	4	1,67	1,33	0,87
66	A9	A	Usage of unsuitable anchor type	4,20	0,60	0,10	0,10	0,50	2,90	0,40	1,80	0,452	4	2,20	2,40	2,39
67	A2	A	Decreased diameter of anchor plate	3,40	0,30	0,10	0,10	0,30	2,10	0,20	0,90	0,338	3	1,33	1,00	0,45
68	A6	A	Anchor plate is installed too deeply into insulation material	1,11	0,11	1,00	0,33	1,56	2,56	0,22	1,44	0,219	2	2,40	1,00	0,53
69	A7	A	Anchor plate is placed too high on the surface of insulation material	1,67	0,11	0,44	0,22	1,00	2,44	0,33	1,56	0,246	2	1,75	1,00	0,43
70	R1	R	External layer of the insulation plate is too smooth; reduced adhesion	3,50	0,00	0,00	0,00	1,67	3,33	0,67	1,33	0,395	4	2,00	3,00	2,37
71	M1c	R	Unsuitable material storage conditions	4,00	0,00	0,00	0,00	2,57	4,29	0,00	3,00	0,494	4	1,00	3,00	1,48
72	M2c	R	The mixing procedures do not remove clots	3,14	0,00	0,00	0,00	2,14	3,29	0,00	2,57	0,391	4	1,20	2,20	1,03
73	M3c	R	High share of kneading water	3,75	0,00	0,25	0,00	2,88	3,75	0,25	3,00	0,469	4	1,80	2,20	1,86
74	M4c	R	Low share of kneading water	3,11	0,44	0,00	0,11	2,44	3,22	0,44	2,78	0,418	4	1,40	2,60	1,52
75	R6	R	Thin mortar layer	3,00	2,50	1,13	1,25	3,63	4,25	1,00	3,63	0,580	5	2,75	2,00	3,19
76	R2	R	Decreased overlap of the mesh	2,22	0,67	0,44	0,11	1,67	3,22	0,78	2,44	0,358	3	1,75	3,00	1,88
77	R3	R	Folded mesh	1,43	0,43	0,43	0,00	0,86	2,57	0,43	2,14	0,254	3	1,00	2,50	0,64
78	R4	R	Missing diagonal mesh	2,10	0,50	0,40	0,00	1,20	3,10	0,60	2,30	0,328	3	2,00	2,50	1,64
79	R5	R	Mesh not filled with mortar; placed on the edge of the layer	3,00	0,71	0,14	0,43	1,86	3,57	0,00	2,14	0,413	4	2,00	2,33	1,93

Table A1. Data (5)

Seq.	ID	Layer	Factor	SR, SC1	SR, SC2	SR, SC3	SR, SC4	SR, SC5	SR, SC6	SR, SC7	SR, SC8	SV	SV-C	OV	DV	TRPN
80	R7	R	Layer is not applied in wet to wet conditions	2,57	0,00	0,29	0,00	2,29	3,00	0,43	2,71	0,354	3	2,50	3,00	2,66
81	R8	R	Usage of incompatible mesh	3,20	0,90	0,40	0,00	1,40	3,90	0,50	2,90	0,458	4	1,40	3,00	1,92
82	M9c	R	Low temperature (freezing) during application and/or curing process	4,83	0,75	0,25	0,33	3,33	4,67	0,58	4,00	0,633	5	1,80	1,80	2,05
83	M10c	R	High temperature (hot) curing conditions	3,45	0,27	0,00	0,09	2,45	3,64	0,36	2,82	0,447	4	2,20	1,80	1,77
84	M11c	R	Low humidity (dry) curing conditions	3,50	0,00	0,00	0,00	3,00	3,63	0,00	3,13	0,446	4	2,00	1,50	1,34
85	M12c	R	Usage of winter mixtures during unsuitable weather conditions	2,40	0,00	0,00	0,00	2,60	3,20	0,00	1,80	0,326	3	1,00	3,00	0,98
86	X6	X	Shock resistance solution is not used (i.e. no double reinforcement mesh, corner details with metal, or additional protective plate installed)	1,89	0,33	0,11	0,44	1,44	3,67	0,22	1,11	0,300	3	2,60	2,00	1,56
87	F2	F	Reinforcement mixture or primary coat is not cured	1,67	0,00	0,22	0,00	1,78	2,78	0,56	1,33	0,252	2	2,00	3,00	1,51
88	F1	F	Missing primer if required	1,50	0,10	0,20	0,00	1,50	2,50	0,20	0,80	0,219	2	1,40	2,20	0,67
89	M1d	F	Unsuitable material storage conditions	4,33	0,44	0,00	0,11	3,44	4,44	0,89	2,89	0,557	5	1,00	2,60	1,45
90	M2d	F	Failure of mixing procedures to remove clots	3,60	0,00	0,00	0,00	3,40	3,80	1,00	2,20	0,454	4	1,00	2,00	0,91
91	M3d	F	High share of kneading water	3,17	0,67	0,33	0,17	4,33	4,50	1,17	3,33	0,510	5	1,00	1,67	0,43
92	F3	F	Thick render layer/differences in thickness	0,86	0,14	0,71	0,43	1,29	2,29	0,14	1,14	0,183	2	1,00	3,00	0,37
93	F4	F	Thin render layer	1,57	0,57	0,71	0,57	2,57	2,71	0,43	1,29	0,283	3	1,50	1,67	0,71
94	M9d	F	Low temperature (freezing) during the application and/or the curing process	4,55	0,55	0,27	0,36	3,36	4,73	0,64	3,36	0,595	5	1,50	1,00	0,89

Table A1. Data (6)

Seq.	ID	Layer	Factor	SR, SC1	SR, SC2	SR, SC3	SR, SC4	SR, SC5	SR, SC6	SR, SC7	SR, SC8	SV	SV-C	OV	DV	TRPN
95	M10d	F	High temperature (hot) curing conditions	3,45	0,27	0,00	0,09	2,55	3,55	0,27	2,55	0,439	4	2,20	1,40	1,35
96	M11d	F	Low humidity (dry) curing conditions	3,63	0,00	0,00	0,00	3,00	3,63	0,00	2,63	0,445	4	2,50	1,50	1,67
97	X1	X	Structural expansion joint is not installed/finished properly	1,50	0,25	0,50	0,25	2,00	2,75	0,25	3,00	0,288	3	1,40	1,80	0,72
98	X2	X	Windowsill is not appropriately finished (i.e., curved upwards, proper sealants)	2,11	0,56	1,11	0,33	4,00	4,11	1,11	1,67	0,392	4	3,60	1,60	2,26
99	X3	X	Unsolved rainwater drainage (i.e., drainpipe or drip profiles are not used)	2,57	0,29	2,00	0,14	4,29	4,29	2,29	2,57	0,459	4	3,00	1,20	1,65
100	X4	X	Fixed frame connection is not finished accurately (i.e., missing sealants)	1,60	0,50	1,70	0,50	3,50	3,50	0,90	1,50	0,333	3	3,20	1,80	1,92
101	X5	X	Roof edge covers are not installed correctly (i.e., vertical detail too short)	1,00	0,13	0,88	0,13	2,88	3,25	0,63	0,38	0,225	2	2,60	2,00	1,17
102	X7	X	Unfinished penetrations through the system (i.e., fixed without sealants)	1,75	1,25	1,38	0,75	3,88	3,88	1,25	1,38	0,389	4	3,40	1,20	1,59
103	X8	X	Unsuitable plinth detail solutions (i.e., incorrect fixing, overlapping of details)	1,67	0,33	0,78	0,11	2,67	3,00	0,44	1,00	0,280	3	2,60	1,40	1,02

Appendix 2

Table A2. Data (1)

Seq.	ID	Layer	Factor	LP	EAV Sim1	ERPN Sim1	ERPN-C Sim1	TER Sim1	TER-C Sim1	EAV Sim2	ERPN Sim2	ERPN-C Sim2	TER Sim2	TER-C Sim2	EAV Sim3	ERPN (Sim3)	ERPN-C Sim3	TER Sim3	TER-C Sim3
1	S1a	S	Substrate is covered with grease or oil	2,00						101	121	1	40	Low	113	135	1	44	Low
2	S1b	S	Substrate is covered with grease or oil	1,63	98	137	1	63	Med.										
3	S2a	S	Substrate is covered with dust or dirt	2,00						101	339	2	109	Med.	113	378	3	121	Med.
4	S2b	S	Substrate is covered with dust or dirt	1,63	98	375	3	169	Med.										
5	S3a	S	Substrate is covered with biological growth	2,33						101	451	3	144	Med.	112	504	3	160	Med.
6	S3b	S	Substrate is covered with biological growth	1,88	98	468	3	209	Med.										
7	S4a	S	Substrate is covered with paint or other material that can chemically react with adhesive	2,17						101	678	4	241	Med.	113	756	5	269	High
8	S4b	S	Substrate is covered with paint or other material that can chemically react with adhesive	1,75	98	762	5	344	High										
9	S5a	S	Substrate is under required load-bearing capacity	1,00						101	714	4	303	High	113	797	5	338	High
10	S5b	S	Substrate is under required load-bearing capacity	0,83	98	534	3	244	Med.										
11	S6a	S	Substrate has large unevenness or has detached areas	2,17						101	653	4	170	Med.	113	729	5	190	High
12	S6b	S	Substrate has large unevenness or has detached areas	1,33	98	470	3	157	Med.										
13	S7a	S	Unsuitable surface (too smooth), which reduces adhesion properties	2,67						101	670	4	196	Med.	112	748	5	218	High
14	S7b	S	Unsuitable surface (too smooth), which reduces adhesion properties	1,88	98	716	4	267	Med.										

Table A2. Data (2)

Seq.	ID	Layer	Factor	LP	EAV Sim1	ERPN Sim1	ERPN-C Sim1	TER Sim1	TER-C Sim1	EAV Sim2	ERPN Sim2	ERPN-C Sim2	TER Sim2	TER-C Sim2	EAV Sim3	ERPN (Sim3)	ERPN-C Sim3	TER Sim3	TER-C Sim3
15	S8a	S	Substrate has very low humidity (inorganic adhesive)	1,88						101	568	4	175	Med.	113	634	4	195	Med.
16	S8b	S	Substrate has very low humidity (inorganic adhesive)	1,63	98	611	4	272	High										
17	S9a	S	Substrate is very wet (raining prior to application of adhesive)	2,00						101	400	3	122	Med.	113	446	3	136	Med.
18	S9b	S	Substrate is very wet (raining prior to application of adhesive)	1,50	98	430	3	177	Med.										
19	S10a	S	Substrate is frozen during the application (inorganic adhesive)	1,17						101	312	2	140	Med.	113	348	2	157	Med.
20	S10b	S	Substrate is frozen during the application (inorganic adhesive)	0,75	98	302	2	144	Med.										
21	M1a	D	Unsuitable mixture storage conditions	1,75						101	243	2	73	Med.	113	271	2	82	Med.
22	M1b	D	Unsuitable mixture storage conditions	1,25	98	235	2	100	Med.										
23	M2a	D	Failure of mixing procedures to remove clots	1,75						101	368	3	76	Med.	113	411	3	84	Med.
24	M2b	D	Failure of mixing procedures to remove clots	1,25	98	305	2	79	Med.										
25	M3a	D	High share of kneading water	3,50						100	421	3	120	Med.	112	469	3	134	Med.
26	M3b	D	High share of kneading water	3,17	97	523	3	184	Med.										
27	M4a	D	Low share of kneading water	2,67						101	453	3	140	Med.	112	505	3	157	Med.
28	M4b	D	Low share of kneading water	1,83	98	439	3	144	Med.										
29	D1a	D	Missing adhesive on the edges of insulation (polystyrene)	3,13						62	302	2	122	Med.					
30	D1b	D	Missing adhesive on the edges of insulation (polystyrene)	2,75	97	474	3	223	Med.										

Table A2. Data (3)

Seq.	ID	Layer	Factor	LP	EAV Sim1	ERPN Sim1	ERPN-C Sim1	TER Sim1	TER-C Sim1	EAV Sim2	ERPN Sim2	ERPN-C Sim2	TER Sim2	TER-C Sim2	EAV Sim3	ERPN (Sim3)	ERPN-C Sim3	TER Sim3	TER-C Sim3
31	D2a	D	Missing adhesive in the centre of insulation (polystyrene)	4,00						100	343	2	109	Med.					
32	D2b	D	Missing adhesive in the centre of insulation (polystyrene)	2,75	97	334	2	132	Med.										
33	D3a	D	Insufficient adhesive surface area	6,00						99	680	4	281	High	110	758	5	314	High
34	D3b	D	Insufficient adhesive surface area	5,63	96	658	4	256	High										
35	D4	D	Adhesive is not rubbed into insulation plate (mineral wool)	5,50											111	664	4	183	Med.
36	D5	D	Adhesive is not treated with notch towel (mineral wool)	6,17											110	772	5	236	High
37	D7a	D	Working time of the adhesive is exceeded	5,38						99	464	3	159	Med.	111	518	3	177	Med.
38	D7b	D	Working time of the adhesive is exceeded	0,83	98	495	3	220	Med.										
39	D8a	D	Low pressure during the application of insulation plates	2,00						101	807	5	204	High	113	901	5	228	High
40	D8b	D	Low pressure during the application of insulation plates	1,50	98	587	4	233	High										
41	D9a	D	Large unevenness of the adhesive layer	3,25						100	585	4	135	Med.	112	653	4	151	Med.
42	D9b	D	Large unevenness of the adhesive layer	2,00	98	569	4	182	Med.										
43	M9a	D	Low temperature (freezing) during the application and/or the curing process	3,63						100	308	2	131	Med.	112	344	2	146	Med.
44	M9b	D	Low temperature (freezing) during the application and/or the curing process	1,38	98	376	3	196	High										
45	M10a	D	High temperature (hot) during the curing process	1,50						101	474	3	144	Med.	113	528	3	161	Med.
46	M10b	D	High temperature (hot) during the curing process	1,25	98	458	3	185	Med.										
47	M11a	D	Low humidity (dry) during the curing process	2,00						101	706	4	184	Med.	113	788	5	205	High

Table A2. Data (4)

Seq.	ID	Layer	Factor	LP	EAV Sim1	ERPN Sim1	ERPN-C Sim1	TER Sim1	TER-C Sim1	EAV Sim2	ERPN Sim2	ERPN-C Sim2	TER Sim2	TER-C Sim2	EAV Sim3	ERPN (Sim3)	ERPN-C Sim3	TER Sim3	TER-C Sim3
48	M11b	D	Low humidity (dry) during the curing process	1,67	98	684	4	250	Med.										
49	M8	D	Addition of ingredients that are not recommended to the mixture	1,63	98	457	3	213	Med.	101	473	3	220	Med.	113	528	3	246	Med.
50	I1	I	Polystyrene is exposed to UV-radiation for a extended period	2,75	97	170	1	68	Med.	101	176	1	71	Med.					
51	I2	I	Insulation plates are installed shortly after manufacture (unfinished diffusion process)	2,13	97	597	4	157	Med.	101	618	4	162	Med.					
52	I3a	I	Insulation plates with very high relative humidity (wet)	1,00											113	326	2	99	Med.
53	I3b	I	Insulation plates with very high relative humidity (wet)	2,25	97	438	3	60	Med.	101	454	3	62	Med.					
54	I4	I	Continuous gaps between substrate and insulation material	1,83	98	437	3	233	High	101	453	3	241	High	113	505	3	269	High
55	I5	I	Corners of neighbouring insulation plates are crossed or too close	6,75	95	268	2	62	Low	98	277	2	64	Low	110	309	2	71	Low
56	I6	I	Corners of the openings have crossed joints	2,63	97	327	2	91	Med.	101	338	2	94	Med.	112	377	3	105	Med.
57	I7	I	The joint width of neighbouring insulation plates is too wide	4,63	96	144	1	30	Low	100	149	1	31	Low	111	167	1	35	Low
58	I8	I	Large height difference between neighbouring insulation plates	2,50	97	389	3	76	Med.	101	403	3	79	Med.	112	449	3	88	Med.
59	I9	I	Broken areas of the insulation plates are not filled with the same material	6,13	95	268	2	58	Low	99	278	2	60	Low	110	310	2	67	Low
60	I10	I	Missing or narrow fire-reluctant areas	0,50	98	184	2	40	Low	102	191	2	42	Low					
61	A1	A	Increased diameter of drilled anchor hole	5,50						61	275	2	117	Med.	61	275	2	117	Med.

Table A2. Data (5)

Seq.	ID	Layer	Factor	LP	EAV Sim1	ERPN Sim1	ERPN-C Sim1	TER Sim1	TER-C Sim1	EAV Sim2	ERPN Sim2	ERPN-C Sim2	TER Sim2	TER-C Sim2	EAV Sim3	ERPN (Sim3)	ERPN-C Sim3	TER Sim3	TER-C Sim3
62	A10	A	Hole of the anchor is not cleaned	1,17						63	195	2	46	Low	63	195	2	46	Low
63	A5	A	Location of anchors is not as foreseen	1,67						62	139	1	36	Low	62	139	1	36	Low
64	A3	A	Decreased number of anchors in the continuous areas	4,17						62	193	2	68	Med.	62	193	2	68	Med.
65	A8	A	Decreased number of anchors in the corner areas	2,50						62	138	1	54	Med.	62	138	1	54	Med.
66	A9	A	Usage of unsuitable anchor type	3,00						62	327	2	148	Med.	62	327	2	148	Med.
67	A2	A	Decreased diameter of anchor plate	5,25						61	82	1	28	Low	61	82	1	28	Low
68	A6	A	Anchor plate is installed too deeply into insulation material	3,75						62	148	1	32	Low	62	148	1	32	Low
69	A7	A	Anchor plate is placed too high on the surface of insulation material	0,83						63	110	1	27	Low	63	110	1	27	Low
70	R1	R	External layer of the insulation plate is too smooth; reduced adhesion	2,13	62	374	3	148	Med.	62	374	3	148	Med.					
71	M1c	R	Unsuitable material storage conditions	0,67	63	188	2	93	Med.	63	188	2	93	Med.	63	188	2	93	Med.
72	M2c	R	The mixing procedures do not remove clots	0,67	63	166	1	65	Med.	63	166	1	65	Med.	63	166	1	65	Med.
73	M3c	R	High share of kneading water	0,75	63	248	2	116	Med.	63	248	2	116	Med.	63	248	2	116	Med.
74	M4c	R	Low share of kneading water	1,25	63	228	2	95	Med.	63	228	2	95	Med.	63	228	2	95	Med.
75	R6	R	Thin mortar layer	4,63	61	338	2	196	High	61	338	2	196	High	61	338	2	196	High
76	R2	R	Decreased overlap of the mesh	2,13	62	327	2	117	Med.	62	327	2	117	Med.	62	327	2	117	Med.
77	R3	R	Folded mesh	1,75	62	156	1	40	Low	62	156	1	40	Low	62	156	1	40	Low
78	R4	R	Missing diagonal mesh	1,38	63	313	2	103	Med.	63	313	2	103	Med.	63	313	2	103	Med.

Table A2. Data (6)

Seq.	ID	Layer	Factor	LP	EAV Sim1	ERPN Sim1	ERPN-C Sim1	TER Sim1	TER-C Sim1	EAV Sim2	ERPN Sim2	ERPN-C Sim2	TER Sim2	TER-C Sim2	EAV Sim3	ERPN (Sim3)	ERPN-C Sim3	TER Sim3	TER-C Sim3
79	R5	R	Mesh not filled with mortar; placed on the edge of the layer	2,00	62	291	2	120	Med.	62	291	2	120	Med.	62	291	2	120	Med.
80	R7	R	Layer is not applied in wet to wet conditions	2,38	62	466	3	165	Med.	62	466	3	165	Med.	62	466	3	165	Med.
81	R8	R	Usage of incompatible mesh	6,88	61	255	2	117	Med.	61	255	2	117	Med.	61	255	2	117	Med.
82	M9c	R	Low temperature (freezing) during application and/or curing process	0,75	63	203	2	129	High	63	203	2	129	High	63	203	2	129	High
83	M10c	R	High temperature (hot) curing conditions	3,00	62	245	2	110	Med.	62	245	2	110	Med.	62	245	2	110	Med.
84	M11c	R	Low humidity (dry) curing conditions	0,75	63	188	2	84	Med.	63	188	2	84	Med.	63	188	2	84	Med.
85	M12c	R	Usage of winter mixtures during unsuitable weather conditions	4,50	61	184	2	60	Med.	61	184	2	60	Med.	61	184	2	60	Med.
86	X6	X	Shock resistance solution is not used (i.e. no double reinforcement mesh, corner details with metal, or additional protective plate installed)	0,50	98	511	3	153	Med.	102	529	3	159	Med.	114	590	4	177	Med.
87	F2	F	Reinforcement mixture or primary coat is not cured	0,75	28	169	1	43	Low	28	169	1	43	Low	28	169	1	43	Low
88	F1	F	Missing primer if required	1,00	28	86	1	19	Low	28	86	1	19	Low	28	86	1	19	Low
89	M1d	F	Unsuitable material storage conditions	0,50	28	73	1	41	Med.	28	73	1	41	Med.	28	73	1	41	Med.
90	M2d	F	Failure of mixing procedures to remove clots	0,33	28	56	1	26	Med.	28	56	1	26	Med.	28	56	1	26	Med.
91	M3d	F	High share of kneading water	3,17	28	23	1	12	Med.	28	23	1	12	Med.	28	23	1	12	Med.
92	F3	F	Thick render layer/differences in thickness	0,83	28	56	1	10	Low	28	56	1	10	Low	28	56	1	10	Low
93	F4	F	Thin render layer	3,33	28	69	1	20	Low	28	69	1	20	Low	28	69	1	20	Low

Table A2. Data (7)

Seq.	ID	Layer	Factor	LP	EAV Sim1	ERPN Sim1	ERPN-C Sim1	TER Sim1	TER-C Sim1	EAV Sim2	ERPN Sim2	ERPN-C Sim2	TER Sim2	TER-C Sim2	EAV Sim3	ERPN (Sim3)	ERPN-C Sim3	TER Sim3	TER-C Sim3
94	M9d	F	Low temperature (freezing) during the application and/or the curing process	0,50	28	42	1	25	Med.	28	42	1	25	Med.	28	42	1	25	Med.
95	M10d	F	High temperature (hot) curing conditions	0,83	28	87	1	38	Med.	28	87	1	38	Med.	28	87	1	38	Med.
96	M11d	F	Low humidity (dry) curing conditions	0,83	28	105	1	47	Med.	28	105	1	47	Med.	28	105	1	47	Med.
97	X1	X	Structural expansion joint is not installed/finished properly	2,38	97	245	2	71	Med.	101	254	2	73	Med.	112	283	2	81	Med.
98	X2	X	Windowsill is not appropriately finished (i.e., curved upwards, proper sealants)	2,38	97	561	4	220	High	101	580	4	228	High	112	648	4	254	High
99	X3	X	Unsolved rainwater drainage (i.e., drainpipe or drip profiles are not used)	2,17	97	351	2	161	Med.	101	363	2	166	Med.	113	405	3	186	Med.
100	X4	X	Fixed frame connection is not finished accurately (i.e., missing sealants)	1,88	98	562	4	187	Med.	101	582	4	194	Med.	113	649	4	216	Med.
101	X5	X	Roof edge covers are not installed correctly (i.e., vertical detail too short)	1,88	98	507	3	114	Med.	101	525	3	118	Med.	113	586	4	132	Med.
102	X7	X	Unfinished penetrations through the system (i.e., fixed without sealants)	2,50	97	397	3	154	Med.	101	411	3	160	Med.	112	458	3	178	Med.
103	X8	X	Unsuitable plinth detail solutions (i.e., incorrect fixing, overlapping of details)	1,50	98	356	2	100	Med.	101	368	3	103	Med.	113	411	3	115	Med.

Appendix 3

PUBLICATION I

Publication I
Sulakatko, V.; Vogdt, F. U. (2018). Construction Process Technical Impact Factors on Degradation of the External Thermal Insulation Composite System. Sustainability, 10 (11).10.3390/su10113900.

sustainability

MDPI

Article

Construction Process Technical Impact Factors on Degradation of the External Thermal Insulation Composite System

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Received: 16 September 2018; Accepted: 20 October 2018; Published: 26 October 2018

Abstract: The European climate strategy has encouraged the usage of the External Thermal Insulation Composite System (ETICS) to increase the energy efficiency of external building envelopes. This externally and relatively easily applicable façade solution must meet various technical requirements. This paper develops a technical severity evaluation model of on-site construction activities of ETICS to prioritize the risks of the construction process. The model can be used independently by any stakeholder of the construction process. The relevance of the activities is assessed with the Failure Mode Effects Analysis method. The model weights the impact of the essential technical requirements and simulates an integrated weighted technical severity value, which is derived from the analysis of experts' judgments validated with the non-parametric Friedman's test. The data collection for probability of occurrence and difficulty of detectability follows the Delphi technique to quantify the opinions of a group. The simulation, conducted on 103 degradation factors, shows that the on-site construction activities of ETICS strongly influence the decrease in the technical resilience of long-term durability, mechanical resistance, and stability, as well as the ability to bypass tensions. The highest risk is detected by the shortcomings in the layers of substrate, reinforcement, adhesive, and additional details.

Keywords: External Thermal Insulation Composite System; ETICS; quality control; durability; building defects

1. Introduction

European countries need to refurbish existing dwellings and increase their quality as well as energy efficiency, as 70% of the housing stock in the European Union was built before 1980 [1]. It is expected that the life-span for multi-story dwellings is between 50 and 70 years, which emphasizes the need for imminent updates. The energy efficiency requirements have increased the usage of the External Thermal Insulation Composite System (ETICS) as a refurbishment possibility to extend the service life of the external shell [2,3]. Due to the increased interest in this construction technology, the durability of the ETICS, as well as the pathology of the degradation signs, has become a popular research subject.

The ETICS has many advantages, which have made it a favourable façade solution and increased its usage in European countries. This complex system is a combination of different construction materials in several layers, all having specific requirements as well as application methods. Each layer of the system is designed to provide particular value and has a significant role. Possible deterioration causes include poor design, unsuitable usage of building materials, or on-site construction technology inadequacies [4]. Institut für Bauforschung [5] revealed in their study that construction activities cause 66% of the defects in the ETICS, which have failed to achieve energy performance requirements.

Neumann [6], in turn, stated that three-quarters of the on-site activities are avoidable. These statements raise the question as to why the number of occurring defects is so high, as the relevance, as well as the main causes of degradation, are known to the industry.

Construction influences the resilience as well as the future deterioration of the ETICS in each layer. As each layer has a different purpose, the relevance to the system is diverse. The research conducted in the field of the quality of the ETICS rationalizes the specific reasons for degradation in silos. These silos have caused a situation where a large number of reasons for degradation have been identified, but it is impossible to prioritize their impact on the ETICS system as a whole. Amaro et al. [7] and Silva [8] approached the problem from the maintenance point of view, developing a predictive maintenance assessment model. Their top-down approach detects deterioration and connects multiple possible causes. To investigate the cause for visible deterioration with in situ analysis, a destructive test is most often required. A number of conducted destructive tests have been discussed [6,9,10], as well as reconstructed in laboratory conditions [11–13]. Additionally, the behavior of deviations of specific components has been studied in isolation, which determined the pathology routes to consider. These routes include the change in mechanical properties through added kneading water to the mixture [14], freezing or drying of the mixture caused by weather effects while the façade is insufficiently covered [12,14,15], increased vapor resistance due to increased thickness of the mortar [16], or increased thermal conductivity through the gaps between insulation materials [17]. These and many other degradation factors are included in our study in a single framework to enable the setting of priorities during the construction process.

The research problem is approached using the developed technical relevance model, which follows the method of Failure Mode Effects Analysis (FMEA) and is suitable for use in small and medium enterprises (SME), who are the main performers in this industry. The method quantifies the technical severity and considers the difficulty of detectability as shortcomings occur and the probability of occurrence [18,19]. Although this approach is most often used for production, the method has also been relevant in the construction industry [20,21]. The method is not flawless and has been criticised due to the mathematical model by Puente [22] and Bowles [23]. They argued that as the occurrence and detectability factors are linear, their effect might be overrated in comparison to the technical severity. Pillay and Wang [24] improved the model with a weighting factor to balance the subjective evaluations. Researchers even included various other factors in the model to provide more specific results according to their research goals [25,26].

The main aim of this research was to develop an assessment model of the shortcomings that quantify the on-site degradation factors of the ETICS using the FMEA method [27] for SMEs. To achieve this, we develop a severity weighting system according to the essential requirements set for the façade system and integrate it into a technical relevance assessment model. The results are presented by the sequence of the construction process as individual components, as well as the final output—technical risk priority number (TRPN). The developed tool enables clients, supervisors, and contractors to focus their attention on the most relevant on-site activities to increase the quality of the ETICS and their benefits. The assessment of the impact factors differentiates the high-risk activities during construction.

2. Materials and Methods

The developed technical relevance model evaluates the on-site degradation factors of the ETICS and is suitable for SMEs who have a limited number of experts. The research design is divided into six phases (Figure 1). The model can be followed by individual companies to calculate firm-specific risks as construction products are improving rapidly and new construction technology is constantly emerging. To start, the scope of the model and limitations were set (Step 1), followed by the selection of experts (Step 2) and development of the questionnaire (Step 3). The data collection and analysis were divided into two sets of experts' judgements due to the differences in the nature of the data. The evaluation of technical aspects requires in-depth knowledge and understanding of the façade system (Step 4). The occurrence ratio and detectability of the shortcomings is more region-, company-, and craftsmen-specific and concerns the forecasting as well as practical experience (Step 5). The technical risk is calculated as the converged values are established (Step 6).

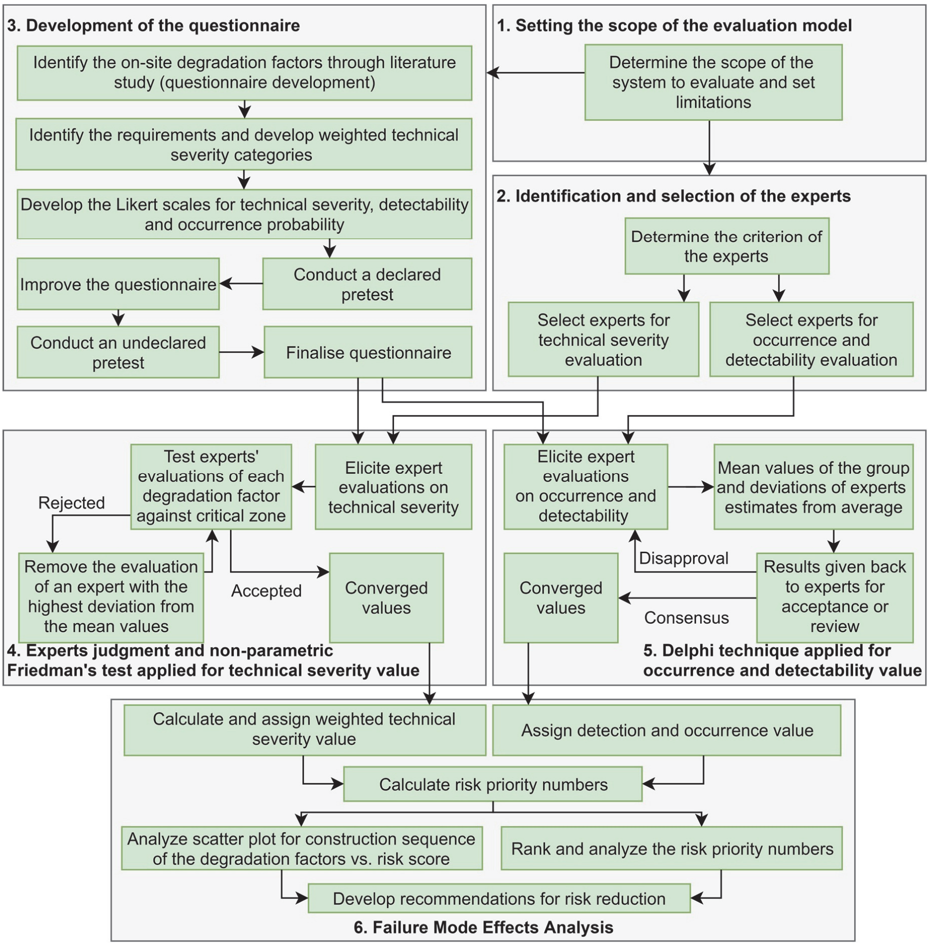


Figure 1. Research design for the technical relevance model.

2.1. Study Scope and Limitations

The data collected to test the simulation model concerned the ETICS with the following characteristics, which are correspondingly the limitations of data collection: the subject is an existing multi-apartment building; external walls are made out of masonry or prefabricated concrete panels; the fixing method for the ETICS is either purely bonded with adhesive or mechanically fixed with anchors and supplementary adhesive; reinforcement consists of a mixture and glass–fiber mesh; the thermal insulation product is composed of mineral wool or expanded polystyrene with a thickness of 150 mm to 250 mm; and the study concerns the region-specific aspects of Estonia, which lies in the Dfb (snow climate, fully humid, warm summer) zone according to the Köppen-Geiger Map.

2.2. Identification and Selection of Experts

There is no quantified data available on the research subject. Hence, expert judgement was suitable for use in this study. The selection of experts considerably affects the quality of the data [28].

The terms for the selection of experts was their in-depth knowledge and understanding of the technical considerations of the ETICS as well as practical on-site experience. According to Olson [29], variations in reviewer backgrounds are allowed. Hallowell et al. [30] suggested that in the construction industry, expert identification could be conducted through the membership of nationally recognized committees or by participation in similar studies. The expert should meet at least four of the following requirements: (1) at least five years of professional experience in the construction industry; (2) tertiary education degree in the field of civil engineering or other related fields; (3) professional registration in the field of construction; (4) member or chair of a nationally recognized committee for the ETICS; (5) writer or editor of a book or book chapter on the topic; (6) faculty member at an accredited institution of higher learning; (7) invited to present at a conference on the topic; and (8) primary or secondary writer of at least three peer-reviewed journal articles.

As the model was developed for usage in SMEs, the number of required experts was small. The most suitable number of panelists has not been exactly determined in the literature to quantify the experts' evaluations. The size of the group depends on the availability of the experts, available resources, and research topic [31]. In other studies of the construction industry, a small number of experts was often used. Chan et al. [28] involved eight panelists to study the selection process of a procurement system in the construction industry. Chau [32] included seven experts to evaluate the estimated probability of unit costs. Six experts were identified and selected for a risk assessment of road projects [33] and five experts evaluated construction business risks [34]. Studies have included 3–144 experts in the studies of various industries [35] and 3–93 panelists in the construction industry [31]. Hallowell et al. [30] proposed a panel size between 8 and 12, whereas Rowe et al. [36] suggested including five or more experts in the panel and pointed out that there are "no clear distinctions in panel accuracy" when the panel size varies from 5 to 11 experts. Hence, for the user of the model, at least five experts should be inclued.

To test the developed technical severity evaluation model, 14 experts with the required characteristics were identified through nationally recognized ETICS committees in Estonia and Germany who agreed to participate in various phases of the study. The panel included seven experts each from Germany and Estonia. Seven of them were consultants/supervisors, two were managers/project managers in façade construction companies, and five were technical specialists from ETICS manufacturers. Two of the experts pre-tested the questionnaire and 12 out of the 14 were involved in the judgment of technical severity in 2016. The demographics of the experts participating in the technical severity evaluation are shown in Figure 2.

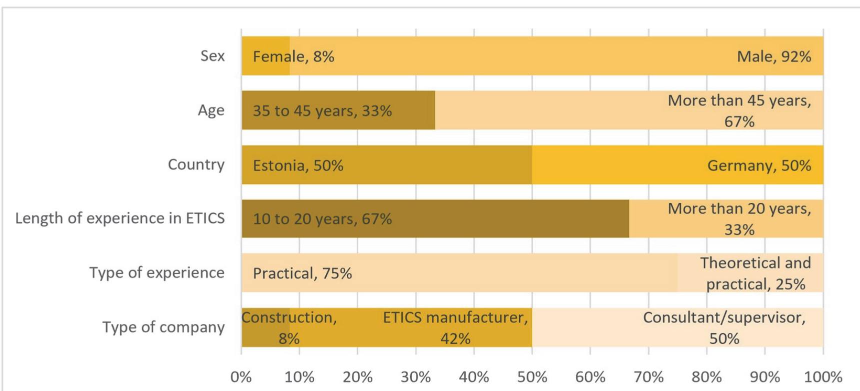


Figure 2. Demographics of the experts participating in the technical severity evaluation. ETICS = External Thermal Insulation Composite System.

As the study aimed to identify the situation in Estonia, the Estonian experts were asked to participate in the region-specific data collection. Five of the seven Estonian experts agreed to participate in the survey conducted in 2018. All of them had 10 to 20 years of practical experience in the field. Figure 3 visualizes the demographics. All the data were collected during face-to-face meetings due to the requirement of a high response rate. Due to the small panel size of the region-specific data collection, it can be argued that the full capacity of the Delphi technique was not fully used. As the quality of the expert panel is more significant than the size [37], and since the aim of the study was to test the developed model, the small panel size in the Delphi study was satisfactory.

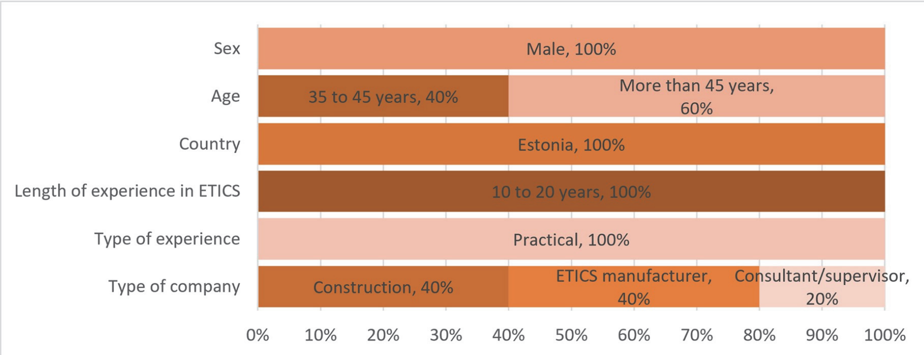


Figure 3. Demographics of the experts participating in the occurrence and detectability evaluation.

2.3. Selection of Degradation Factors

The list of degradation factors was collected through a literature review. The list of shortcomings is based on descriptive instructions, recommendations, harmonized standards, set requirements [38–43], studies regarding simulations or material studies made in laboratory conditions [11–14,44–67], field research [2,3,5,7,51,68–80], and books on the topic [6,9,10]. Based on these references published between 1996 and 2015, a list of identified on-site degradation factors was created. The degradation factors were distributed according to the seven layers of the system. The construction works in the substrate layer mainly concern the preparation of the existing external wall. Adhesive, reinforcement, and finishing layers include work practices with mixtures and mesh application. Insulation and mechanical anchors specify the requirements for the insulation panels and mechanically fixed anchors. The additional details generalize the defects of the installations of auxiliary products, like windowsills and plinth areas. Table 1 shows the literature used for the selection of degradation factors and the layer to which the factor is related, whereas entire list of revealed on-site shortcomings for further evaluation is presented in Appendix A.

Table 1. Most relevant degradation factors based on the literature review.

Layer	Literature Source
Substrate (S)	[6,9,10,56,64,68,73]
Adhesive (D)	[6,7,9–12,14,15,46,56,69,73,76]
Insulation (I)	[6,9,10,13,49,50,58,72,73]
Mechanical anchors (A)	[6,9,10,40,41]
Reinforcement (R)	[2,6,9,10,55]
Finishing layer (F)	[6,9–11,14,69]
Additional details (X)	[6,9,10,53,62]

To reveal questionnaire errors, one declared and one undeclared pre-test were conducted. Similarly, individual pre-testing has been used by other researchers [81] and shown good results in identifying misinterpretations [82]. The reviews were conducted individually and independently, and the results of the other evaluations were not revealed. One expert was located in Germany, had a doctoral degree, and had more than 20 years of experience with the ETICS as a consultant and supervisor. The second was located in Estonia, had a master's degree in civil engineering, and more than 15 years of experience as project manager in ETICS construction. Both experts were participating in the National ETICS Standards Committee. During the reviews, 11 irrelevant factors were removed from further analysis, and the wording of 16 degradation factors was rephrased to improve the legibility and suitability for systems checked.

2.4. Technical Risk Priority Number of Degradation Factors

The evaluation system focused on the essential technical performance requirements set for the ETICS. We assumed that if the performance of the system does not meet the desired characteristics, a failure occurs. To classify and rate the significance of each failure, the risk assessment methodology Failure Mode Effects Analysis (FMEA) was used as it enables the quantification and prioritization of risk [20,21,83]. The technical risk priority number of a degradation factor was calculated with:

$$TRPN_{DF} = \overline{SV_{DF}} \times \overline{OV_{DF}} \times \overline{DV_{DF}}\,, \tag{1}$$

where $TRPN_{DF}$ is the technical risk priority number of a degradation factor, SV_{DF} is technical severity value of a degradation factor, OV_{DF} is occurrence value of a degradation factor, and DV_{DF} is the detectability value of a degradation factor.

The simulation data were divided into technical and region-specific components. The framework of the model is visualized in Figure 4, where the occurrence and detectability are individual components, and the weighted technical severity value is a combination of eight severity categories.

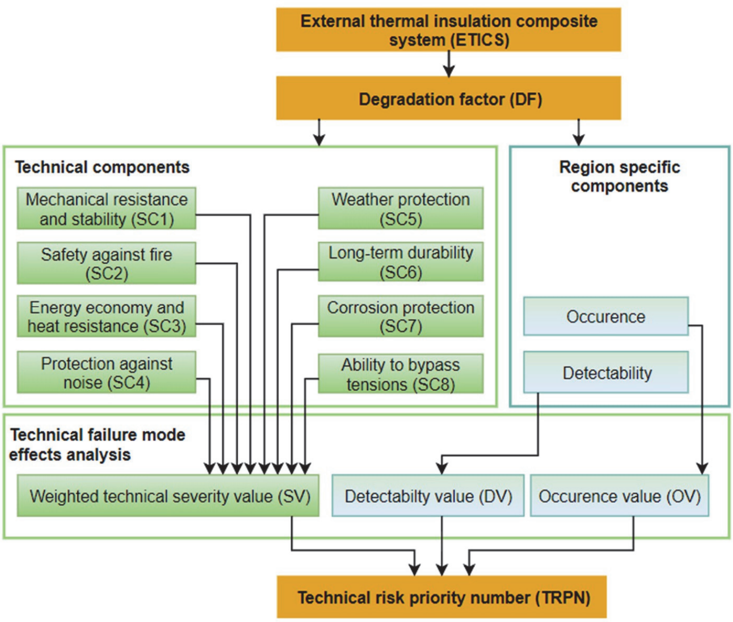


Figure 4. The framework of the technical relevance model. SC = severity category.

The experts evaluated the severity of the system's performance, the likelihood of occurrence, and detectability on a Likert scale. Likert scales from two up to 11 points have been used in other research [84]. According to Preston [84], scales below or equal to four points should be avoided. For the severity evaluation, a six-point Likert scale was used to include the value of zero, which simplifies the interpretation of the cases where no influence is foreseen. The detectability and occurrence were evaluated in a five-point Likert scale. The developed Likert scales are shown the following section.

2.4.1. Technical Severity

For the building products used in the European Union, the general international technical requirements are set by Regulation (EU) Number 305/2011 [85] (also Construction Products Regulation or CPR), which is the basis for the "Guideline for European technical approval of External Thermal Composite System (ETICS) with rendering" (also ETAG 004) [41]. The Construction Products Regulation presumes that buildings and construction products meet the performance requirements during their economically reasonable working life and describes seven essential requirements for construction products. "Mechanical resistance and stability" (SC1), "safety in case of fire" (SC2), "energy economy and heat retention" (SC3), and "protection against noise" (SC4) are considered in this study as described in the CPR. "Sustainable use of natural resources" is explained in ETAG 004 as measures on the "aspects of durability and serviceability", which concern durability from several aspects that are differentiated in this study. The system must protect against short-term weather effects like "humidity and weather protection" (SC5), deliver its functions during the whole service life ("long-term durability", SC6), and be resistant to corrosion ("corrosion protection", SC7). "Safety in use" considers the resistance to combined stresses caused by normal loads. For clarity in this research, the label "ability to bypass tensions" (SC8) is used. "Hygiene, health, and environment" considers the effect on the indoor and outdoor environment as well as pollution due to the release of dangerous substances, which is not seen as a separate severity category in this façade construction technology-related study.

Each degradation factor affects the performance of each severity category, which influences the total performance of the façade. Aurnhammer [86] estimated technical defects concerning the diminishing value to the users. In the case of a shortcoming in any segment, the final resulting value decreases. The degradation severity was evaluated with a weighted impact method, in which all categories totaled 100%, describing the total failure in each category. Based on the weighting method developed by Aurnhammer [86], the adjusted distribution (Figure 5) provides an evaluation model to calculate the weighted technical severity value.

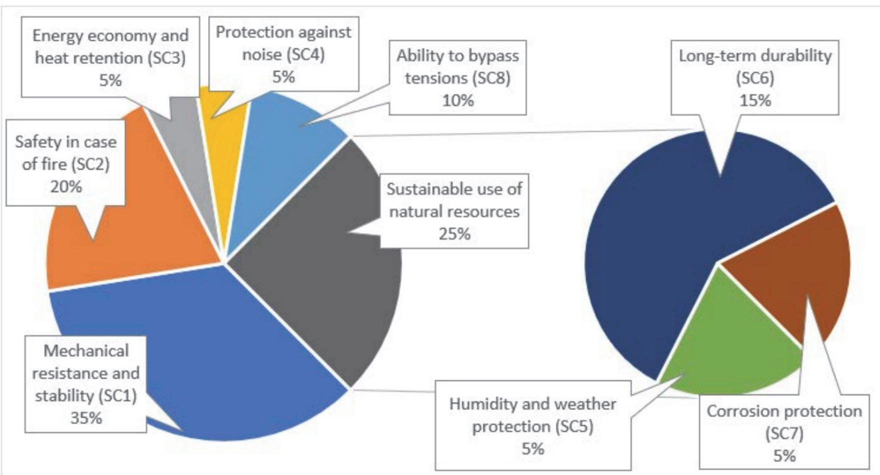


Figure 5. The weight distribution of the severity categories.

The weighted technical severity value for each expert is calculated with Equation (2). The mean severity value of all experts is the input value for the technical risk priority number calculation in Equation (1).

$$SV_{DF,e} = \sum \left(\frac{SR_{DF,SC,e}}{SR_{SC,max}} \times T_{SC} \right), \quad (2)$$

where $SV_{DF,e}$ is the weighted severity value of an expert, $SR_{DF,SC,e}$ is the individual rating of an expert for a severity category, $SR_{SC,max}$ is the maximum rating value for the severity category, and T_{SC} is the weight of the severity category according to Figure 5.

The developed Likert scale for the technical severity rating is shown in Table 2. The highest rating was assigned if the failure has a very high effect on the requirement and a score of zero was given when the failure has no impact on the requirement. These expert ratings were the input data for the calculation of weighted technical severity value.

Table 2. Likert scale for the evaluation of technical severity.

Risk Level	Characteristic	Severity Rating
Very high	Total failure of the requirement	5
High	Requirement is highly influenced	4
Moderate	Requirement is moderately influenced	3
Low	Requirement is slightly influenced	2
Very low	Requirement is minimally influenced	1
No effect	No effect on the requirement	0

The validity of the severity values based on expert judgement was tested with the non-parametric Friedman's test, which increases the credibility of quantification of subjective evaluations [87,88]. The non-parametric Friedman's test assesses the difference between a number of related samples. The test is used as an alternative for analysis of variances for repeated measures when the same parameters have been measured on the same subjects, but under different conditions [88]. Friedman's test was used for each degradation factor separately to detect expert values that are in the critical zone. The 103 degradation factors included 991 individual evaluations; 53 degradation factors received positive Friedman's test results with the first analysis, 82 individual evaluations were in the critical zone and a maximum of four rounds were applied. After the Friedman's test, the data sets included four to 12 experimental units. As there were enough different components in the calculation, the inaccuracy of the evaluations did not have a major impact on the final results.

2.4.2. Occurrence and Detectability Value

The probability of occurrence rates the incident frequency during the construction process. It is a subjective evaluation by the expert and is dependent on personal experience. The pre-test questionnaire revealed that it is impossible to quantify the occurrences in a specific range and quantification of subjective evaluation was required. The rating scale is shown in Table 3. The highest value was given to often-occurring failures and the lowest value to unlikely failures.

Table 3. Likert scale for the evaluation of occurrence probability.

Risk Level	Characteristic	Occurrence Value
Very high	Failure is almost certain	5
High	Often repeated failures	4
Moderate	Occasional failures	3
Low	Relatively few failures	2
Very low	Failure is unlikely	1

The detectability and occurrence evaluations were classified into five categories. The detectability value rates the difficulty level of on-site detection of the shortcoming. The characteristics are shown in Table 4.

Table 4. Likert scale for the evaluation of detectability.

Risk Level	Characteristic	Detectability Value
Very high	A potential cause of failure cannot be detected visually. Additional tests need to be used. High experience required.	5
High	In between very high and moderate conditions.	4
Moderate	A potential failure can be detected visually before completion of the layer, during the application process or through markings on the material packages. Mediocre experience required.	3
Low	In between very low and moderate conditions.	2
Very low	Cause of failure can be detected after completion of the layer with the less experienced observer.	1

The data collection to determine the detectability and occurrence values was developed using the Delphi technique, where independent and anonymous expert judgements are combined through mathematical aggregation [35]. The expected outcome was a consensus between the experts. The Delphi technique should be used if there is no quantifiable data available [89]. The technique requires the circulation of a questionnaire amongst the selected experts. There is no specific guideline to determine when a consensus has been achieved. In this study, the consensus was achieved when the experts agreed upon the mean values of the group.

The experts were asked individually and anonymously to provide their evaluations. According to the questionnaire, each expert needed to provide evaluations for occurrence and detectability. To obtain a high response rate, a meeting time with each expert was individually organized. During the face-to-face meeting, the questionnaire was completed by the expert. The responses from all experts were summarized and mean values were calculated. The collective mean results were sent to each expert and they were asked to revise their evaluation or agree/disagree with the collective result. During the next two weeks, three participants agreed with the collective results. Two experts reviewed the group results after a reminding phone call and stated their agreement with consensus. Hallowell et al. [30] described the "bandwagon effect", where decision makers may feel pressure to confirm the opinion of a group. Due to the fast agreement with the consensus and to investigate whether this described effect was present, the team of experts was brought physically together. The highest and lowest evaluations were discussed with the group to check if there were hidden assumptions. Positively, the consensus did not change after the meeting. The primary reason was that the individual evaluations depend highly on the skills and experience of the expert and the results may vary. The data collection process was conducted in 2018.

3. Results

The objective of this study was to prioritize on-site construction process activities to enable better resource allocation to quality control during construction. The developed technical severity model combines the effect of weighted technical severity, the probability of occurrence, and the detectability of the on-site construction work. The output values were divided into layers of the applied system and ETICS types for analysis. ETICS 1 concerns the purely bonded system with polystyrene. Polystyrene with mechanically fixed anchors and supplementary adhesive describe ETICS 2. ETICS 3 represents the mineral wool system with the same fixation type as ETICS 2. The benefit of the differentiation by ETICS type is to provide the ability to assign only relevant degradation factors to the simulation under evaluation. The differentiation by layers of the system allows the comparison between the sequences of the construction process.

3.1. Weighted Technical Severity Value

The primary variable for TRPN calculation is the average weighted technical severity value, which considers the technical significance of the degradation factors in the eight severity categories. The distribution of the average severity values by layers is shown in Figure 6, where higher values denote higher significance. The degradation factors in the substrate and adhesive layers have significantly different severity values when ETICS types are compared. ETICS 1 is highly dependent on the characteristics of adhesion and has a higher severity value, whereas ETICS 2 and 3 share the fixation risk with mechanical anchors and have lower values. In other layers, the ETICS types have comparable values.

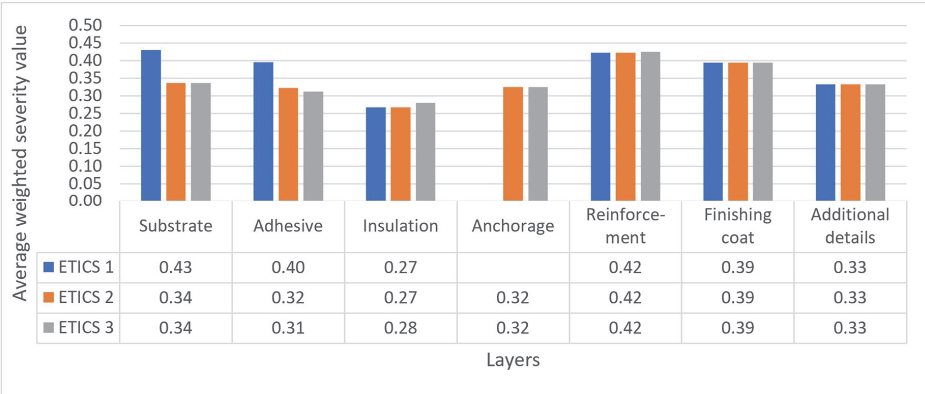


Figure 6. The average severity value by the layer of the system.

The severity values (SVs) of the degradation factors were placed in the order of the construction, shown in Figure 7. The colored horizontal lines visualize the average values of the weighted technical relevance for each ETICS type by layer. The standard deviations were the smallest in the substrate (0.04 to 0.06) and adhesive (0.07 to 0.08) layers. The colored areas represent the range of a specific layer. The groups of degradation factors discussed more specifically are identified with green lines.

The SV1 group includes the degradation factors of the purely bonded system in the substrate layer, which involves preparation of the surface. Substrate coverage with oil (S1b), dust (S2b), biological growth (S3b), old paint (S4b), as well as decreased load bearing capacity (S5b), have high technical severity.

The second highly relevant group was SV2, which describes missing adhesive on the edges of insulation (D1b), freezing of the mixture (M9b), exceeded working time of the adhesive (D7b), and adding unsuitable ingredients (M8). The high technical severity of the substrate and adhesive layers is caused by the construction activities that are responsible for the fixation of the system to the existing external shell of the building. The degradation factors in the substrate layer include the pre-treatment of the surface and the properties of the substrate that affect the characteristics of adhesion. The existing exterior wall of the building must resist the additional load caused by the ETICS and is responsible, to a large extent, for the stability and adhesion characteristics of the attached system, whether the fixation relies on mechanical anchors or adhesive. The factors in the substrate and adhesive layers have a relatively high impact on the mechanical stability of the system and mediocre influence on long-term durability.

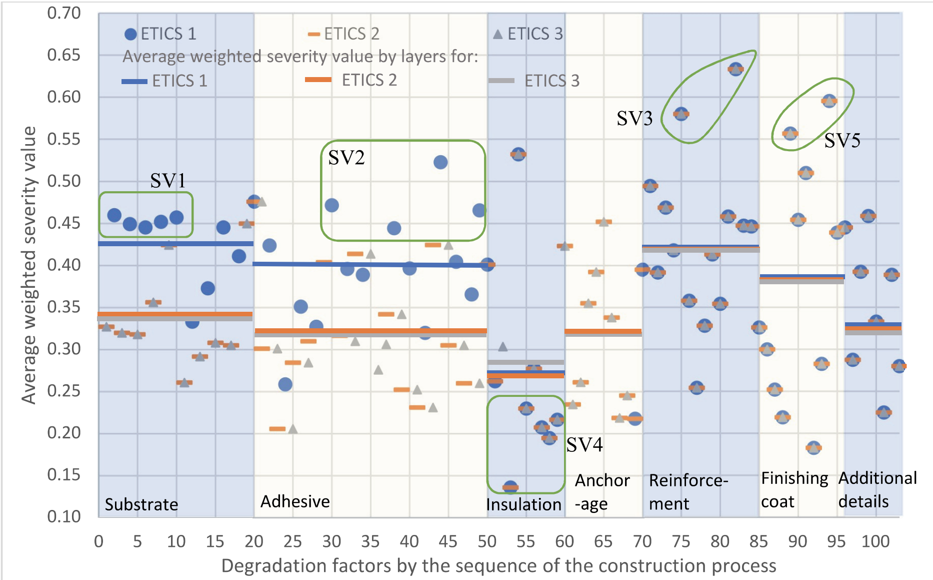


Figure 7. Severity value of the degradation factors based on the steps of the construction process.

The highest technical impact was caused by the shortcomings in the reinforcement layer, which is responsible for the essential task of stress transmission within the system. In a correctly applied layer, the stresses are transmitted to the mesh applied. These factors considerably impact mechanical stability, but also the ability to bypass tensions, long-term durability, and weather protection. The relatively high impact of these severity categories can be explained by the requirement to bear stresses caused by the external environment, like hygrothermal changes during different seasons and freeze-thaw cycles. The two degradation factors with high severity were in the SV3 group: a thin layer of reinforcement mixture (R6) and the freezing of the reinforcement mixture (M9c).

Similar to the adhesive layer, mechanical anchors fix the system to the existing external shell and bear wind suction loads. Their technical effect mainly concerns the mechanical stability of the system, whereas all other severity categories remained rather irrelevant.

The degradation factors in the additional details layer were technically as relevant. In this study, the layer includes more generally described shortcomings that reflect the installation of additional products in contact with the system (i.e., application of windowsills, fixations that require penetration through the system, and installation of roof edge details). The additional details have high ratings on the severity categories of energy efficiency, and, to some extent, protection against noise, weather protection, long-term durability, and corrosion protection. In comparison to the internal layers of the system, the shortcomings in this layer mostly affect the moisture-induced problems as sealants fail and enable the external moisture to penetrate the system.

An unexpectedly high severity value was assigned to the finishing coat and the degradation factors in group SV5. The external layer, in addition to its aesthetic function, is responsible for weather protection to some extent, although the ETICS is designed to function without the finishing layer. The natural conditions include a combination of effects from which the external layer provides protection: wind, rain, pollutants, relative humidity, temperature, and solar radiation. The results show a higher influence on the severity categories that consider the external effects: weather protection, long-term durability, and ability to bypass tensions. The shortcomings in the finishing layer had the highest standard deviation of 0.15. The degradation factors with high severity value include the risks of the mixture: freezing of the mixture (M9d), unsuitable storage conditions (M1d), and increased amount of kneading water (M3d). The lesser risks concern the adhesion with the previous layer, including missing primer (F1) and a not cured reinforcement layer (F2).

The insulation layer received the lowest average technical severity value. Although the primary function of the insulation is to reduce thermal conductivity, defects also affect noise protection, and all other shortcomings have extremely low influence (group SV4). The broken insulation plates (I9) and airflow on the surface of the substrate (I4) have an increased effect on noise protection, as well as on safety in case of fire. To some extent, the shortcomings influence the ability of corrosion protection due to moisture-induced problems in the system. Otherwise, the shortcomings regarding the application of the insulation layer have minimal influence.

3.2. Technical Severity Ratings

The comparison of unweighted severity ratings of singular severity categories to each other (Figure 8) showed that the severity categories of mechanical resistance and stability, and long-term durability were affected the most. The standard deviations were 1.02 and 0.81, respectively. The upper quartile of the mechanical resistance and stability category included nine degradation factors, which emphasizes the relevance of freezing of mixtures (M9c, M9b, and M9d) and the substrate (S10a and S10b), unsuitable mixture storage conditions (M1b, M1c, and M1d), unprepared substrate surface (S1b, S2b, and S4b), and usage of unsuitable anchor type (A9). The long-term durability category induced three factors: freezing of reinforcement (M9c) and finishing mixtures (M9d) and a high share of kneading water of the finishing layer (M3d).

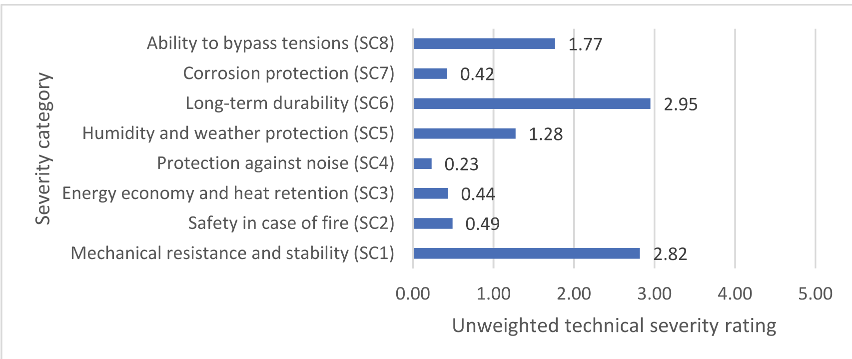
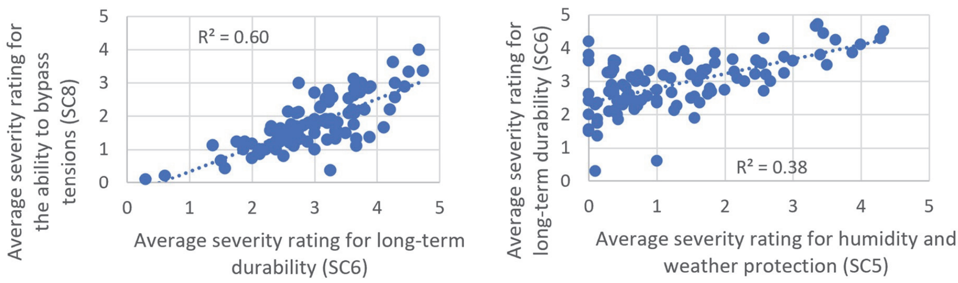


Figure 8. Average unweighted technical severity ratings by severity category.

The correlation analysis of the severity categories revealed high correlations within the groups of high-ranking severity categories (SC1, SC5, SC6, and SC8) and within low-ranking categories (SC2, SC3, SC4, and SC7). The regression analysis of the low-ranking categories included many variables that received a low score, as they have no impact, which enabled the interpretation of the correlation analysis results as irrelevant. The regression analysis in the high-ranking group had a highly positive R^2 value (0.60) for the pair of long-term durability and ability to bypass tensions (Figure 9a). The results showed 60% of the degradation factors that affect the ability to bypass tensions also increase the value for humidity and weather protection. A similar result was obtained from the linear regression analysis for the pair of weather protection and long term-durability (Figure 9b), which had an R^2 value of 0.38. The failure in the category of weather protection also reduced the long-term durability of the system. The other three pairs (SC1 and SC8, SC1 and SC6, and SC5 and SC8) had R^2 values between 0.28 and 0.29, providing a modest explanation of the model. We interpreted this as meaning that the defects that cause a decrease in mechanical stability also decrease the long-term durability and the ability to bypass tensions. Weather protection decreases through the defects in the ability to bypass tensions.



(a) **(b)**

Figure 9. (**a**) Linear regression for long-term durability (SC6) and ability to bypass tensions (SC8), and (**b**) humidity and weather protection (SC5) and long-term durability (SC6).

3.3. Probability Value

The second relevant component to the prioritization of the shortcomings is the probability of occurrence, as it rates the frequency of an incident during the construction process. The higher value emphasizes the shortcomings that occur more often. The average values of the likelihood of the occurrence in the seven layers ranged from 1.43 to 2.80 out of 5.0, as shown in Figure 10.

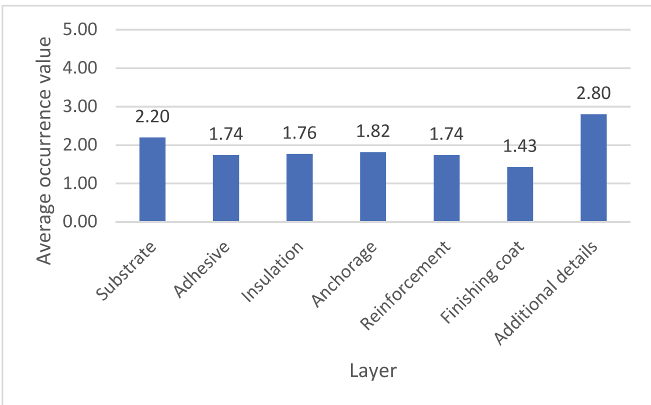


Figure 10. Average occurrence value by layers.

The average occurrence values of the degradation factors were placed in the order of the construction process in Figure 11. The average values by layer are shown with colored lines. The comparison between the three ETICS showed no significant effect, and the difference is not shown separately.

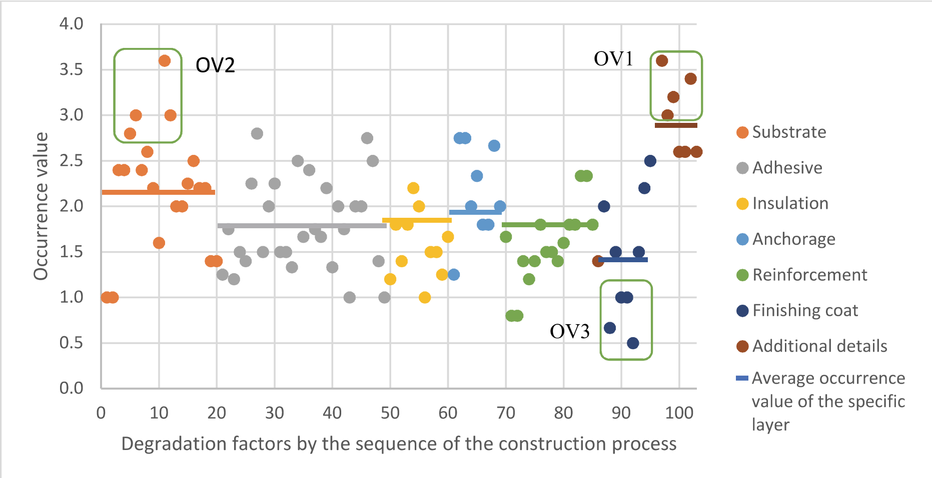


Figure 11. Occurrence value (OV) of the degradation factors placed in order of the construction process.

The degradation factors including the additional details received the highest average rating (2.80), followed by the substrate layer (2.12). The shortcomings in the additional details layer are described in a more general manner and therefore include an increased variety of risks, which probably increase the occurrence rate in comparison to other layers to some extent, which are more specifically described. In the OV1 group, the highest occurrence values included problematic structural expansion joints (X1) and penetrations through the system due to fixation (X7).

The substrate layer included activities that are often intentionally not conducted, and they do not cause a visible problem unless other failures occur (OV2 group). Such degradation factors included cleaning of the surface from biological growth (S3a, S3b) and levelling the surface (S6a, S7b). An increased amount of adhesive is sufficient to decrease the risk. A slightly lower occurrence value was detected for the finishing layer (1.43), pointed out in the OV3 group.

3.4. Detectability Value

The third component of the TRPN calculation is the detectability of degradation factors during construction. The average detectability value ranged from 1.20 to 2.82, as shown in Figure 12, where higher values indicate increased risk and lower detectability.

The degradation factors with the highest detectability values were in the adhesive layer, as this layer is covered immediately with the insulation plate, making it impossible to detect shortcomings after application without a destructive test. The second highest rating was for the reinforcement layer, where the mesh is covered during the application. The detectability remained slightly better, as the surface stays open and visible defects can be detected. The layers that are accessible for quality control for a longer period had lower detectability values. These layers included mechanical anchors, insulation, additional details, and the finishing layer.

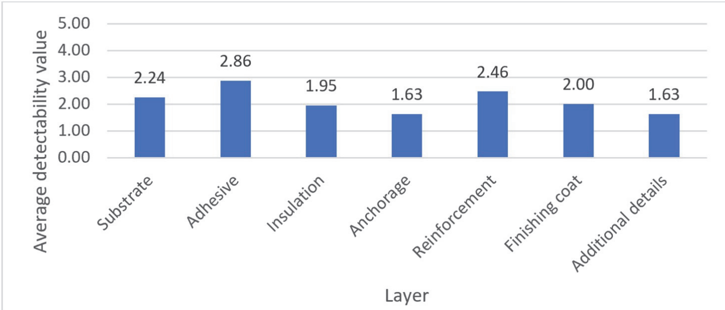


Figure 12. Average detectability value by layer.

The detectability values of the degradation factors are visualized in the order of the construction process in Figure 13, where the average values are shown with colored lines. The shortcomings in the substrate layer are visible for quality control for a longer period. However, the defects are often hard to detect and require additional measures to be taken in some cases (DV1 group), which is the reason for the high standard deviation (0.76). These degradation factors included the low load-bearing capacity (S5b, S5a), unsuitable type of adhesive (S7a, S7b), and chemical reaction between the remaining paint and applied adhesive (S4a, S4b). Additional measures should be taken to check the adhesion properties of the external surface and to test the pull-through strength of the structure. The variance between the different ETICS was very low.

The insulation layer had a high standard deviation (0.92) due to the DV2 group that had a low detectability value, and the DV3 group that had a high value. High detectability values in the DV3 group included two shortcomings: continuous gaps between the insulation layer and substrate (I4) and unfinished diffusion process of the polystyrene insulation plates (I2). On average, the mechanical anchors had good detectability (group DV5), except for the three factors in group DV4: cleaning of the anchor hole (A10), application of unsuitable anchor type (A9), and increased diameter of drilled anchor hole (A1).

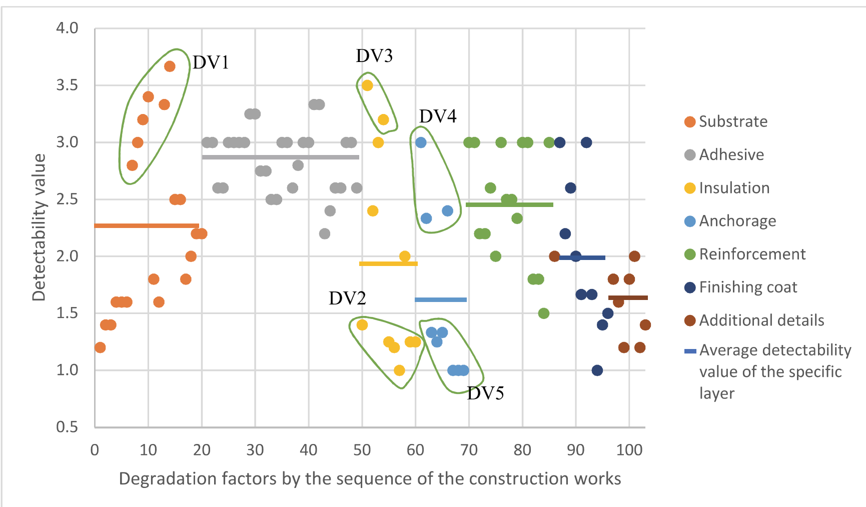
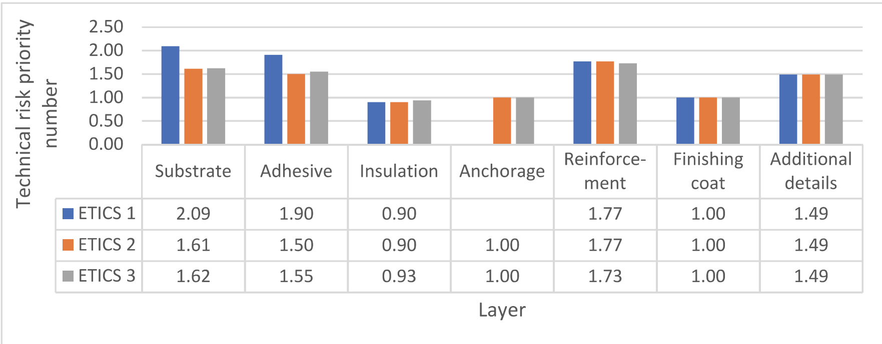


Figure 13. Detectability value (DV) of the degradation factors by the sequence of the construction process.

3.5. Technical Relevance According to the Risk Priority Number

The technical risk priority number (TRPN) is a combination of the weighted technical severity value, the detectability value, and the occurrence value. The results by layer and ETICS type are shown in Figure 14, whereas Figure 15 positions the degradation factors according to the TRPN in the order of the construction process.



	Substrate	Adhesive	Insulation	Anchorage	Reinforce-ment	Finishing coat	Additional details
ETICS 1	2.09	1.90	0.90		1.77	1.00	1.49
ETICS 2	1.61	1.50	0.90	1.00	1.77	1.00	1.49
ETICS 3	1.62	1.55	0.93	1.00	1.73	1.00	1.49

Figure 14. Average value of technical risk priority number by layer and ETICS type.

The correlation and regression analysis between the pairs of severity value and occurrence value, and severity value and detectability value, showed no relevant correlation. Between the variables of occurrence value and detectability value, there is a weak negative correlation ($r = -0.24$), though the R^2 in the linear regression was 0.059, which does not explain the relationship between the variables. In comparison to the average weighted severity values shown in Figure 7, the reinforcement, substrate, and adhesive layers retained their high average relevance rating. The deviation in all layers was relatively high. In the substrate and adhesive layers, ETICS 1 increased TRPN values due to the differences in severity values between the systems. Occurrence and detectability values had no significant difference in comparison to the ETICS types observed.

The highly relevant degradation factors in the substrate layer are shown in the technical risk (TR)1 group (Figure 15). The incidence when the substrate is covered with chemically reacting remaining paint (S4b), usage of unsuitable adhesive type (S7b), and low humidity of the substrate as inorganic adhesion is applied (S8b) are highly relevant for ETICS 1. The systems with mechanical anchors and supplementary adhesive (ETICS 2 and ETICS 3) were highly influenced by the low load-bearing capacity of the substrate (S5a). In the low relevance group TR2 (substrate covered with oil; S1a, S1b), the relevance decreased due to very low values of occurrence and detectability.

The adhesive layer had the most relevant shortcomings in the TR3 group. Insufficient adhesive (S3a, S3b) received very high occurrence and detectability values, increasing its relevance. Three degradation factors with relatively high detectability values also belong to this group: dry curing conditions (M11b), lack of pressure during application of insulation plates (D8b), and adhesive not rubbed into mineral wool insulation plate (D4a). The low relevance group TR4 included the mixture-related factors that reduced their relevance due to their low occurrence value. The factors include only the mixture preparation process: wrong material storage conditions (M1a, M2b), clots remain in the mixture during mixing process (M2a, M2b), and high share of kneading water (M3a).

The insulation layer and mechanical anchors included the majority of the degradation factors in the low relevance group TR6. Although the occurrence value of the shortcomings for mechanical anchors was relatively high (Figure 11), the good detectability and below average technical severity reduced the TRPN relevance. However, there were three degradation factors with a high TRPN in the TR5 group. Although continuous gaps that enable an internal airflow (S4) had high relevance in all three components, increased diameter of drilled anchor hole (A1) and unsuitable anchor type (A9) had increased relevance due to difficult detectability. The detection is more problematic in this layer as the quality check must occur during the application process.

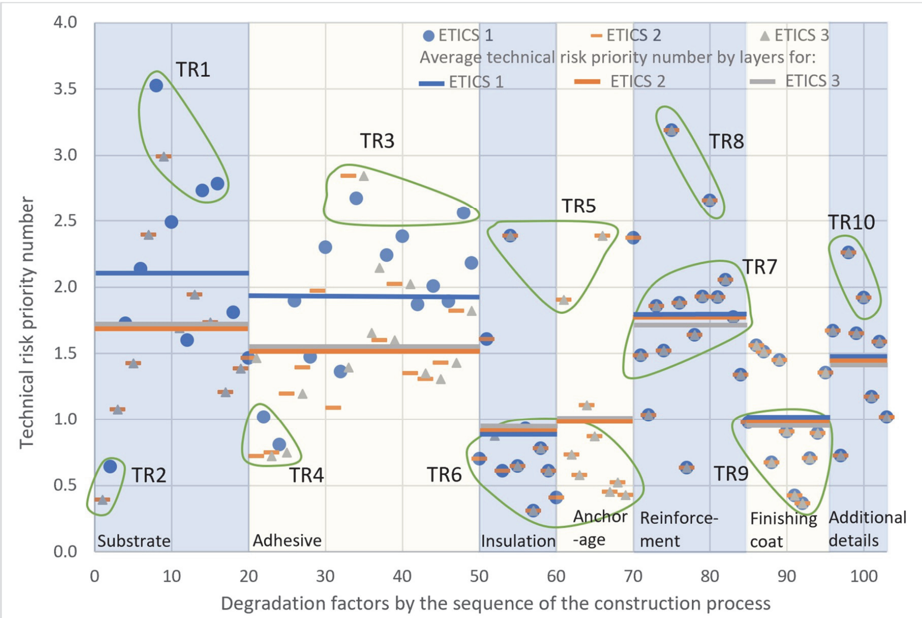


Figure 15. Technical risk (TR) priority number of the degradation factors in order of the construction process.

The reinforcement layer had the highest average TRPN and the majority of the degradation factors were positioned near the average value (the TR7 group). The degradation factors of the thin reinforcement layer (R6) and layers not applied in wet to wet condition (R7) in the TR8 group reduced the ability to bypass tensions into the mesh and were the most relevant. Thin reinforcement layer (R6) had, in comparison, a higher severity value due to the impact on the long-term durability but is easier to detect as the pattern of the mesh is visible after completion of the layer. Layers not applied in wet to wet condition (R7) can be detected only during the application process.

The risks in the finishing layer, mostly assembled in the TR9 group, decreased its relevance due to the low occurrence value. The layer has no degradation factors that are considered highly relevant to the system's performance.

The shortcomings in the additional details layer decreased the relevance due to their low detectability value but remained relatively high as the failures occur rather often. Most problematic was moisture penetration into the system due to problematic solution windowsills (X2) and other fixed frame connections (X4) in the TR10 group.

4. Discussion

This section reviews the research method from two aspects and discusses future applications.

The FMEA method was initially developed in the 1950s as a military procedure in the USA, and since then, critics have pointed out the flaws. The FMEA method has been used in the construction industry in several studies [20,21,83]. Layzell [83] applied the method to a similar cladding system and stated that the application and the results of the method depend on the availability of the data. The data in this research involved quantifying the subjective evaluations of the experts. If more quantifiable observations are made for any of the components (severity, occurrence, or detectability), the data could be more specific. However, comparative relevance is not expected to differ significantly. At this moment, there are no more specific quantified data available. Nevertheless, the outcomes of the single parameters as well as the TRPN results were logical. Additional degradation factors should be integrated into the model and evaluated as technical aspects of ETICS or its application process alter.

Secondly, the results of the model are a product of three variables: severity, occurrence, and detectability. Puente [22], Bowles [23], and Wang [24] argued that simple multiplication of ordinal scales might be misleading, as different combinations might produce the same output value. There are also concerns about the interpretation of the results of this research. The outcomes of detectability and occurrence are the result of subjective expert judgement. The change in one variable has a relatively large impact on the risk, upon which the final recommendations were based. In the earlier work of Bowles [90], a disadvantage was detected in the occasion when multiple severity effects are occurring. To reduce the impact of this disadvantage, a weight factor of the technical severity categories was implemented, and the analysis aimed to observe the impact on the system's total performance.

The external envelope of a building is also exposed to weather effects after the completion of the application process. The materials are affected by radiation [79], pollution [3], freeze-thaw cycles [44], humidity, the direction of the façade, and changes in porosity [45,67], which all impact the durability of the façade. Finnish research on the hygrothermal behavior of ETICS [60] highlighted that the high relative humidity during freeze-thaw cycles is problematic, and there is a need for increased protection against frost attack in cold climates. Therefore, we expect that in milder climate conditions, on-site shortcomings will appear in the long term. In this study, the climate condition considerations may have affected the probability of occurrence of the degradation factor. To mitigate this influence, the experts evaluated the occurrence frequency of the shortcomings observed during the construction process and this was not confused with the occurrence of visible degradation during the exploitation period.

Additionally, the latency of the shortcoming has an economic effect, as repair costs increase the size of investment and affect the decisions on quality control. The cost component is highly relevant in terms of the owner's and contractor's quality considerations. Equilibrium could be found in future research between quality increase and risk mitigation. To find the cost component of ETICS, several aspects should be considered. The economic component is project-specific and depends on the chosen system, logistics, general economic situation in the region, latency period of the shortcoming, and other aspects.

In this study, the model included three components in the mathematical aggregation. To consider the impact of climate and the cost of repair, a multiplier could be developed to calibrate the relevance. Future research could implement these considerations into a unified model.

5. Conclusions and Recommendations

The usage of External Thermal Insulation Composite Systems (ETICSs) is increasing in Europe as the existing dwellings are refurbished according to newly introduced energy efficiency measures. The façade system has advantages for the building and owners but requires additional quality control to reduce the degradation caused by often-occurring minor shortcomings during the construction process.

We developed a technical severity evaluation model to quantify the relevance of on-site shortcomings of ETICS. The model followed the Failure Mode Effects Analysis method and considered the technical severity, and the probability of occurrence and detectability of deviations. The data were collected from experts' judgement and validated with the non-parametric Friedman's test and the Delphi technique. The impact of the selected 103 degradation factors were quantified and presented in the order of the construction process. The technical relevance assessment model considered the technical severity, occurrence probability, and detectability of the degradation factors.

The technical severity evaluation revealed that the ETICS construction process significantly alters the resilience of the system in regard to mechanical stability, long-term durability, ability to bypass tension, and weather protection. The preparation of substrate and application of adhesive are important factors, as are the activities that involve the reinforcement and finishing layer. The occurrence probability component reduced the relevance of the finishing layer, but added value to additionally added details (i.e., windowsills, plinth details). The detectability component was more relevant for the application of mixtures in the adhesive and reinforcement layers. The final output of the study, technical risk priority number (TRPN), emphasized that the most relevant aspect is the reinforcement layer for all ETICS types, and the significance of adhesion for the purely bonded system.

Based on the results of the study; the following general aspects should be considered during resource allocation for quality control:

1. The adhesion to the exterior façade of the building is highly relevant for the purely bonded ETICS. During the application process, the degradation factors which influence the adhesion characteristics have a very high impact on the technical severity of the system. These shortcomings are hard to detect as they are covered for further inspection shortly.
2. The preparation process of the reinforcement mixture and the application of the mesh have a high technical risk as shortcomings occur often. The layer is responsible for distributing internal and external stress. If a failure occurs, the anomalies evolve and enable moisture to penetrate the system.
3. The failures during the application of additional details (windowsills, fixed frames, plinth areas, and other fixings) often occur and have severe technical consequences but are detectable.
4. The failures that occur during construction in the insulation, anchorage, and finishing layers have reduced risk, as they occur rather rarely and are visually detectable. Nevertheless, the technical severity remains high for mechanical anchors.

The outcomes of the technical relevance model enable the allocation of resources on more relevant degradation factors, which occur often and are hard to detect, to avoid the loss of technical performance. In case of relevant changes to the requirements, construction technology, or construction materials, the developed model can be reapplied after the components are quantified according to the developed method.

Author Contributions: V.S. designed the study, collected and analyzed the data and wrote the paper. F.V. supervised and reviewed the paper.

Funding: This work was supported by institutional research funding of the Estonian Ministry of Education and Research IUT1−15 "Nearly-zero energy solutions and their implementation on deep renovation of buildings".

Acknowledgments: We would like to express our gratitude to the experts in Germany and Estonia who shared their experience and knowledge during this research.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

Appendix A

Table A1. Data for Equation (1).

Sequence	ID	Layer	Description	ETICS 1	ETICS 2	ETICS 3	SC1	SC2	SC3	SC4	SC5	SC6	SC7	SC8	SV	OV	DV	TRPN
1	S1a	S	Substrate is covered with grease or oil		x	x	2.7	0.4	0.0	0.2	0.4	2.7	0.4	1.5	0.33	1.0	1.2	0.39
2	S1b	S	Substrate is covered with grease or oil	x			4.3	0.3	0.0	0.2	0.3	3.3	0.3	1.8	0.46	1.0	1.4	0.64
3	S2a	S	Substrate is covered with dust or dirt		x	x	2.6	0.4	0.0	0.2	0.4	2.6	0.4	1.6	0.32	2.4	1.4	1.08
4	S2b	S	Substrate is covered with dust or dirt	x			4.2	0.3	0.0	0.2	0.3	3.3	0.3	1.9	0.45	2.4	1.6	1.72
5	S3a	S	Substrate is covered with biological growth		x	x	2.6	0.4	0.0	0.2	0.4	2.6	0.4	1.5	0.32	2.8	1.6	1.43
6	S3b	S	Substrate is covered with biological growth	x			3.9	0.4	0.0	0.2	0.4	3.5	0.4	2.1	0.45	3.0	1.6	2.14
7	S4a	S	Substrate is covered with paint or other material which can chemically react with adhesive		x	x	2.8	0.6	0.3	0.2	0.5	2.8	0.5	1.7	0.36	2.4	2.8	2.39
8	S4b	S	Substrate is covered with paint or other material which can chemically react with adhesive	x			4.0	0.3	0.3	0.0	0.4	3.6	0.1	2.2	0.45	2.6	3.0	3.53
9	S5a	S	Substrate is under required load-bearing capacity		x	x	3.7	0.4	0.0	0.2	0.4	3.4	0.6	1.8	0.42	2.2	3.2	2.99
10	S5b	S	Substrate is under required load-bearing capacity	x			4.0	0.4	0.0	0.2	0.4	3.6	0.6	2.1	0.46	1.6	3.4	2.49
11	S6a	S	Substrate has large unevenness or has detached areas		x	x	2.1	0.3	0.6	0.3	0.4	2.0	0.6	1.2	0.26	3.6	1.8	1.69
12	S6b	S	Substrate has large unevenness or has detached areas	x			2.9	0.3	0.6	0.3	0.4	2.4	0.6	1.3	0.33	3.0	1.6	1.60
13	S7a	S	Unsuitable surface (too smooth) which reduces adhesion properties		x	x	2.3	0.7	0.0	0.3	0.7	2.2	0.7	1.0	0.29	2.0	3.3	1.94
14	S7b	S	Unsuitable surface (too smooth) which reduces adhesion properties	x			3.7	0.0	0.4	0.0	0.0	2.4	0.7	1.4	0.37	2.0	3.7	2.73
15	S8a	S	Substrate has very low humidity (inorganic adhesive)		x	x	2.5	0.4	0.0	0.2	0.5	2.5	0.8	1.6	0.31	2.3	2.5	1.73
16	S8b	S	Substrate has very low humidity (inorganic adhesive)	x			4.0	0.4	0.0	0.2	0.7	3.2	0.8	1.9	0.45	2.5	2.5	2.78
17	S9a	S	Substrate is very wet (raining in prior to application of adhesive)		x	x	2.4	0.5	0.3	0.2	0.7	2.4	0.7	1.3	0.31	2.2	1.8	1.21
18	S9b	S	Substrate is very wet (raining in prior to application of adhesive)	x			3.6	0.5	0.3	0.2	0.7	3.0	0.7	1.5	0.41	2.2	2.0	1.81

Table A2. Data for Equation (2).

Sequence	ID	Layer	Description	ETICS 1	ETICS 2	ETICS 3	SC1	SC2	SC3	SC4	SC5	SC6	SC7	SC8	SV	OV	DV	TRPN
19	S10a	S	Substrate is frozen during the application (inorganic adhesive)		x	x	4.0	0.2	0.4	0.0	0.0	3.8	0.0	2.2	0.45	1.4	2.2	1.39
20	S10b	S	Substrate is frozen during the application (inorganic adhesive)	x			4.2	0.2	0.4	0.0	0.0	4.2	0.0	2.2	0.48	1.4	2.2	1.47
21	M1a	D	Unsuitable mixture storage conditions		x	x	2.8	0.0	0.0	0.0	0.0	2.6	0.0	1.5	0.30	0.8	3.0	0.72
22	M1b	D	Unsuitable mixture storage conditions	x			4.0	0.0	0.0	0.0	0.0	3.6	0.0	1.8	0.42	0.8	3.0	1.02
23	M2a	D	The mixing procedures do not remove clots		x	x	2.1	0.0	0.0	0.0	0.0	1.6	0.0	0.4	0.21	1.4	2.6	0.75
24	M2b	D	The mixing procedures do not remove clots	x			2.6	0.0	0.0	0.0	0.0	2.0	0.0	0.8	0.26	1.2	2.6	0.81
25	M3a	D	High share of kneading water		x	x	2.4	0.3	0.0	0.2	0.7	2.2	0.4	1.0	0.28	1.4	3.0	1.19
26	M3b	D	High share of kneading water	x			3.2	0.3	0.0	0.2	0.8	2.4	0.4	1.2	0.35	1.8	3.0	1.90
27	M4a	D	Low share of kneading water		x	x	2.6	0.4	0.0	0.3	1.0	2.4	0.5	1.1	0.31	1.5	3.0	1.40
28	M4b	D	Low share of kneading water	x			3.1	0.0	0.0	0.0	0.7	2.3	0.0	1.6	0.33	1.5	3.0	1.47
29	D1a	D	Missing adhesive on the edges of insulation (polystyrene)		x		2.3	1.6	2.2	1.1	1.6	3.0	0.6	1.7	0.40	1.5	3.3	1.97
30	D1b	D	Missing adhesive on the edges of insulation (polystyrene)	x			3.3	1.5	2.0	1.0	1.7	3.4	0.5	1.5	0.47	1.5	3.3	2.30
31	D2a	D	Missing adhesive in the center of insulation (polystyrene)		x		2.4	0.4	0.3	0.3	1.2	2.7	0.7	1.1	0.32	1.3	2.8	1.09
32	D2b	D	Missing adhesive in the center of insulation (polystyrene)	x			3.3	0.4	0.3	0.3	1.5	3.2	0.6	1.3	0.40	1.3	2.8	1.36
33	D3a	D	Insufficient adhesive surface area		x	x	2.6	1.9	1.0	0.5	0.6	3.1	0.3	1.9	0.41	2.8	2.5	2.84
34	D3b	D	Insufficient adhesive surface area	x			3.2	0.9	0.7	0.4	0.3	2.9	0.2	1.2	0.39	2.8	2.5	2.67
35	D4	D	Adhesive is not rubbed into insulation plate (mineral wool)			x	2.4	0.0	0.0	0.0	0.6	2.6	0.0	1.2	0.28	2.0	3.0	1.66
36	D5	D	Adhesive is not treated with notch towel (mineral wool)			x	2.9	0.5	0.4	0.0	0.1	1.9	0.1	1.1	0.31	2.3	3.0	2.14

Table A3. Data for Equation (3).

Sequence	ID	Layer	Description	ETICS 1	ETICS 2	ETICS 3	SC1	SC2	SC3	SC4	SC5	SC6	SC7	SC8	SV	OV	DV	TRPN
37	D7a	D	Working time of the adhesive is exceeded		x	x	2.8	0.5	0.3	0.2	0.3	2.7	0.3	1.7	0.34	1.8	2.6	1.60
38	D7b	D	Working time of the adhesive is exceeded	x			4.0	0.5	0.3	0.2	0.3	3.3	0.3	1.9	0.44	1.8	2.8	2.24
39	D8a	D	Low pressure during application of insulation plates		x	x	1.9	0.6	0.3	0.3	0.4	2.1	0.4	1.0	0.25	2.7	3.0	2.02
40	D8b	D	Low pressure during application of insulation plates	x			3.4	0.8	0.4	0.2	0.3	2.7	0.3	1.6	0.40	2.0	3.0	2.38
41	D9a	D	Large unevenness of the adhesive layer		x	x	1.9	0.4	0.4	0.3	0.1	1.8	0.0	1.3	0.23	1.7	3.5	1.35
42	D9b	D	Large unevenness of the adhesive layer	x			2.9	0.4	0.4	0.3	0.1	2.4	0.0	1.3	0.32	1.7	3.5	1.87
43	M9a	D	Low temperature (freezing) during application and/or curing process		x	x	3.5	0.4	0.0	0.1	1.1	3.2	0.4	2.5	0.42	1.4	2.2	1.31
44	M9b	D	Low temperature (freezing) during application and/or curing process	x			4.6	0.4	0.0	0.1	1.3	3.7	0.4	2.7	0.52	1.6	2.4	2.01
45	M10a	D	High temperature (hot) during curing process		x	x	2.6	0.3	0.0	0.1	0.5	2.3	0.2	1.7	0.31	1.8	2.6	1.43
46	M10b	D	High temperature (hot) during curing process	x			3.6	0.3	0.0	0.1	0.8	3.0	0.2	1.9	0.40	1.8	2.6	1.89
47	M11a	D	Low humidity (dry) during curing process		x	x	2.6	0.0	0.0	0.0	0.4	1.9	0.0	1.0	0.26	2.3	3.0	1.82
48	M11b	D	Low humidity (dry) during curing process	x			3.7	0.0	0.0	0.0	0.4	2.4	0.0	1.4	0.37	2.3	3.0	2.56
49	M8	D	Not recommended ingredients added to the mixture	x	x	x	3.4	0.9	0.0	0.0	1.9	3.9	0.0	2.9	0.47	1.8	2.6	2.18
50	I1	I	Polystyrene is exposed to ultraviolet (UV)-radiation for an extended period	x	x		3.3	0.4	0.2	0.1	0.9	3.3	0.7	1.6	0.40	1.3	1.4	0.70
51	I2	I	Insulation plates are installed shortly after manufacturing (unfinished diffusion process	x	x		1.4	0.4	0.8	0.5	1.0	2.8	0.4	2.1	0.26	1.8	3.5	1.61
52	I3a	I	Mineral wool insulation plates have very high relative humidity (are wet			x	2.4	0.3	2.4	0.3	1.3	2.1	0.8	0.9	0.30	1.2	2.4	0.87
53	I3b	I	Insulation plates which have very high relative humidity (wet)	x	x		0.8	0.6	1.4	0.2	1.0	0.6	0.8	0.2	0.14	1.5	3.0	0.61
54	I4	I	Continuous gaps between substrate and insulation material	x	x	x	2.2	3.3	4.3	2.2	2.1	3.7	2.0	1.3	0.53	1.4	3.2	2.38

Table A4. Data for Equation (4).

Sequence	ID	Layer	Description	ETICS 1	ETICS 2	ETICS 3	SC1	SC2	SC3	SC4	SC5	SC6	SC7	SC8	SV	OV	DV	TRPN
55	I5	I	Corners of neighboring insulation plates are crossed or too close	x	x	x	1.0	0.1	1.0	0.3	1.8	2.7	0.2	2.1	0.23	2.3	1.3	0.65
56	I6	I	Corners of the openings have crossed joints	x	x	x	1.4	0.1	1.3	0.1	2.2	3.1	0.5	2.3	0.28	2.8	1.2	0.93
57	I7	I	Insulation plates joint width of neighboring insulation plates is too wide	x	x	x	1.0	0.0	2.0	0.6	1.6	2.4	0.4	1.0	0.21	1.5	1.0	0.31
58	I8	I	Large height difference between neighboring insulation plates	x	x	x	0.6	0.1	0.8	0.3	1.8	2.6	0.5	1.8	0.20	2.0	2.0	0.78
59	I9	I	Broken areas of the insulation plates are not filled with same material	x	x	x	1.0	0.6	1.8	1.0	1.6	1.9	0.0	1.2	0.22	2.3	1.3	0.61
60	I10	I	Missing or narrow fire reluctant areas	x	x		0.1	4.9	0.1	0.1	0.1	0.3	0.1	0.1	0.22	1.5	1.3	0.41
61	A1	A	Increased diameter of drilled anchor hole		x	x	4.0	0.7	0.3	0.2	0.6	2.4	0.3	1.4	0.42	1.5	3.0	1.91
62	A10	A	Hole of the anchor is not cleaned		x	x	2.3	0.3	0.0	0.0	0.0	1.5	0.0	0.7	0.24	1.3	2.3	0.73
63	A5	A	Location of anchors is not as foreseen		x	x	2.5	0.5	0.0	0.1	0.1	1.4	0.0	1.1	0.26	1.7	1.3	0.58
64	A3	A	Decreased number of anchors in the continuous areas		x	x	3.5	0.4	0.1	0.1	0.1	2.3	0.0	1.1	0.36	2.5	1.3	1.11
65	A8	A	Decreased number of anchors in the corner areas		x	x	3.6	0.6	0.2	0.1	0.6	2.6	0.4	1.6	0.39	1.7	1.3	0.87
66	A9	A	Usage of unsuitable anchor type		x	x	4.2	0.6	0.1	0.1	0.5	2.9	0.4	1.8	0.45	2.2	2.4	2.39
67	A2	A	Decreased diameter of anchor plate		x	x	3.4	0.3	0.1	0.1	0.3	2.1	0.2	0.9	0.34	1.3	1.0	0.45
68	A6	A	Anchor plate is installed too deeply into insulation material		x	x	1.1	0.1	1.0	0.3	1.6	2.6	0.2	1.4	0.22	2.4	1.0	0.53
69	A7	A	Anchor plate is placed too high on the surface of insulation material		x	x	1.7	0.1	0.4	0.2	1.0	2.4	0.3	1.6	0.25	1.8	1.0	0.43
70	R1	R	External layer of the insulation plate is too smooth, reduced adhesion	x	x		3.5	0.0	0.0	0.0	1.7	3.3	0.7	1.3	0.40	2.0	3.0	2.37
71	M1c	R	Unsuitable material storage conditions	x	x	x	4.0	0.0	0.0	0.0	2.6	4.3	0.0	3.0	0.49	1.0	3.0	1.48
72	M2c	R	The mixing procedures do not remove clots	x	x	x	3.1	0.0	0.0	0.0	2.1	3.3	0.0	2.6	0.39	1.2	2.2	1.03

Table A5. Data for Equation (5).

Sequence	ID	Layer	Description	ETICS 1	ETICS 2	ETICS 3	SC1	SC2	SC3	SC4	SC5	SC6	SC7	SC8	SV	OV	DV	TRPN
72	M2c	R	The mixing procedures do not remove clots	x	x	x	3.1	0.0	0.0	0.0	2.1	3.3	0.0	2.6	0.39	1.2	2.2	1.03
73	M3c	R	High share of kneading water	x	x	x	3.8	0.0	0.3	0.0	2.9	3.8	0.3	3.0	0.47	1.8	2.2	1.86
74	M4c	R	Low share of kneading water	x	x	x	3.1	0.4	0.0	0.1	2.4	3.2	0.4	2.8	0.42	1.4	2.6	1.52
75	R6	R	Thin mortar layer	x	x	x	3.0	2.5	1.1	1.3	3.6	4.3	1.0	3.6	0.58	2.8	2.0	3.19
76	R2	R	Decreased overlap of the mesh	x	x	x	2.2	0.7	0.4	0.1	1.7	3.2	0.8	2.4	0.36	1.8	3.0	1.88
77	R3	R	Folded mesh	x	x	x	1.4	0.4	0.4	0.0	0.9	2.6	0.4	2.1	0.25	1.0	2.5	0.64
78	R4	R	Missing diagonal mesh	x	x	x	2.1	0.5	0.4	0.0	1.2	3.1	0.6	2.3	0.33	2.0	2.5	1.64
79	R5	R	Mesh not filled with mortar, placed on the edge of the layer	x	x	x	3.0	0.7	0.1	0.4	1.9	3.6	0.0	2.1	0.41	2.0	2.3	1.93
80	R7	R	Layer is not applied in wet to wet conditions	x	x	x	2.6	0.0	0.3	0.0	2.3	3.0	0.4	2.7	0.35	2.5	3.0	2.66
81	R8	R	Usage of not compatible mesh	x	x	x	3.2	0.9	0.4	0.0	1.4	3.9	0.5	2.9	0.46	1.4	3.0	1.92
82	M9c	R	Low temperature (freezing) during application and/or curing process	x	x	x	4.8	0.8	0.3	0.3	3.3	4.7	0.6	4.0	0.63	1.8	1.8	2.05
83	M10c	R	High temperature (hot) curing conditions	x	x	x	3.5	0.3	0.0	0.1	2.5	3.6	0.4	2.8	0.45	2.2	1.8	1.77
84	M11c	R	Low humidity (dry) curing conditions	x	x	x	3.5	0.0	0.0	0.0	3.0	3.6	0.0	3.1	0.45	2.0	1.5	1.34
85	M12c	R	Usage of winter mixtures during unsuitable weather conditions	x	x	x	2.4	0.0	0.0	0.0	2.6	3.2	0.0	1.8	0.33	1.0	3.0	0.98
86	X6	X	Shock resistance solution is not used (i.e., no double reinforcement mesh, corner details with metal or additional protective plate installed)	x	x	x	1.9	0.3	0.1	0.4	1.4	3.7	0.2	1.1	0.30	2.6	2.0	1.56
87	F2	F	Reinforcement mixture or primary coat is not cured	x	x	x	1.7	0.0	0.2	0.0	1.8	2.8	0.6	1.3	0.25	2.0	3.0	1.51
88	F1	F	Missing primer if required	x	x	x	1.5	0.1	0.2	0.0	1.5	2.5	0.2	0.8	0.22	1.4	2.2	0.67
89	M1d	F	Unsuitable material storage conditions	x	x	x	4.3	0.4	0.0	0.1	3.4	4.4	0.9	2.9	0.56	1.0	2.6	1.45
90	M2d	F	The mixing procedures do not remove clots	x	x	x	3.6	0.0	0.0	0.0	3.4	3.8	1.0	2.2	0.45	1.0	2.0	0.91
91	M3d	F	High share of kneading water	x	x	x	3.2	0.7	0.3	0.2	4.3	4.5	1.2	3.3	0.51	0.5	1.7	0.43

Table A6. Data for Equation (6).

Sequence	ID	Layer	Description	ETICS 1	ETICS 2	ETICS 3	SC1	SC2	SC3	SC4	SC5	SC6	SC7	SC8	SV	OV	DV	TRPN
91	M3d	F	High share of kneading water	x	x	x	3.2	0.7	0.3	0.2	4.3	4.5	1.2	3.3	0.51	0.5	1.7	0.43
92	F3	F	Thick render layer/differences in thickness	x	x	x	0.9	0.1	0.7	0.4	1.3	2.3	0.1	1.1	0.18	0.7	3.0	0.37
93	F4	F	Thin render layer	x	x	x	1.6	0.6	0.7	0.6	2.6	2.7	0.4	1.3	0.28	1.5	1.7	0.71
94	M9d	F	Low temperature (freezing) during application and/or curing process	x	x	x	4.5	0.5	0.3	0.4	3.4	4.7	0.6	3.4	0.60	1.5	1.0	0.89
95	M10d	F	High temperature (hot) curing conditions	x	x	x	3.5	0.3	0.0	0.1	2.5	3.5	0.3	2.5	0.44	2.2	1.4	1.35
96	M11d	F	Low humidity (dry) curing conditions	x	x	x	3.6	0.0	0.0	0.0	3.0	3.6	0.0	2.6	0.45	2.5	1.5	1.67
97	X1	X	Structural expansion joint is not installed/finished properly	x	x	x	1.5	0.3	0.5	0.3	2.0	2.8	0.3	3.0	0.29	1.4	1.8	0.72
98	X2	X	Windowsill not appropriately finished (i.e., curved upwards, proper sealants)	x	x	x	2.1	0.6	1.1	0.3	4.0	4.1	1.1	1.7	0.39	3.6	1.6	2.26
99	X3	X	Unsolved rainwater drainage (i.e., drainpipe or drip profiles not used)	x	x	x	2.6	0.3	2.0	0.1	4.3	4.3	2.3	2.6	0.46	3.0	1.2	1.65
100	X4	X	Fixed frame connection is not finished accurately (i.e., missing sealants)	x	x	x	1.6	0.5	1.7	0.5	3.5	3.5	0.9	1.5	0.33	3.2	1.8	1.92
101	X5	X	Roof edge covers are not installed correctly (i.e., vertical detail too short)	x	x	x	1.0	0.1	0.9	0.1	2.9	3.3	0.6	0.4	0.23	2.6	2.0	1.17
102	X7	X	Unfinished penetrations through the system (i.e., fixed without sealants)	x	x	x	1.8	1.3	1.4	0.8	3.9	3.9	1.3	1.4	0.39	3.4	1.2	1.59
103	X8	X	Unsuitable plinth detail solutions (i.e., incorrect fixing, overlapping of details)	x	x	x	1.7	0.3	0.8	0.1	2.7	3.0	0.4	1.0	0.28	2.6	1.4	1.02

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Appendix 4

PUBLICATION II

Publication II
Sulakatko, V.; Lill, I. (2019). The Economic Relevance of On-Site Construction Activities with the External Thermal Insulation Composite System (ETICS). International Journal of Strategic Property Management, 23 (4), 213−226.

International Journal of Strategic Property Management
ISSN: 1648-715X / eISSN: 1648-9179 2019
Volume 23 Issue 4: 213–226
https://doi.org/10.3846/ijspm.2019.7071

THE ECONOMIC RELEVANCE OF ON-SITE CONSTRUCTION ACTIVITIES WITH THE EXTERNAL THERMAL INSULATION COMPOSITE SYSTEM (ETICS)

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Received 23 September 2018; accepted 07 December 2018

Abstract. The systematic inadequacies of the External Thermal Insulation Composite System (ETICS), which occur during the construction phase, increase the financial risk for stakeholders, while reducing the long-term durability of the facade. The economic effect of on-site shortcomings can be reduced if the most significant on-site activities are recognised. The current paper develops an economic relevance assessment model for on-site construction activities of ETICS to increase economic rationality of resource allocation and emphasise the high-risk systematic shortcomings. The economic assessment model quantifies the financial risk of the on-site degradation factors with the method of modified Failure Mode Effects Analysis (FMEA). The data collection is followed by experts' judgments and is validated with the Delphi technique. The study reveals that degradation factors in the early phases of construction have the highest relevance due to high costs of repair as well as high occurrence possibility and higher detection difficulty due to rapid coverage. Ninety percent of the shortcomings appear during the first five years of completion of the construction. The on-site failures occurring during the application of mechanical anchors and finishing layer cause the lowest financial risk. The model enables the economic effect of the on-site activities to be prioritised for better resource allocation.

Keywords: ETICS, risk management, economic model, project management, quality, building technology.

Introduction

The European Commission has indicated that by 2020 all new builds must be Nearly Zero-Energy Buildings (NZEBs) to meet the European climate strategy targets. The energy use reduction will have to be achieved largely through the renovation of existing buildings. Using a thin-layer rendering system on the building's exterior facade is one refurbishment possibility. In European countries, the usage of the External Thermal Insulation Composite System (ETICS) and the interest in the aspects of construction quality are increasing. Until now the features of on-site construction process management and building technology on the quality of ETICS have been studied in isolation and comparison of different research findings have received too little attention. It is important to understand that shortcomings in the construction process and different construction technology aspects have an essential impact on future costs.

The technical aspects of ETICS degradation have interested researchers over many decades. H. Künzel, H. M. Künzel, and Sedlbauer (2006) and Gaspar and De Brito (2008) have observed the long-term performance of the system. Neumann (2009), Kussauer and Ruprecht (2011) and Cziesielski and Vogdt (2007) have published specialized books on the causes of such degradations. Flores-Colen and De Brito (2010) have approached the aspect of economic rationality of ETICS with the focus on maintenance and are observing the visible signs of the defects. These and many other studies point out a large number of possible deviations, which can occur during the construction process and have a severe impact on the quality of the system.

This study focuses on the shortcomings during the on-site construction process of ETICS with an emphasis on their impact on future costs. Woodward (1997), Skitmore and Marston (1999) have stated that construction technology and quality are in correlation to cost. The elimination of shortcomings after completion takes more effort and resources in comparison to their avoidance during the primary installation process. Due to this snowballing economic effect, it is relevant to realise which activities

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have high impact and how to conduct the tradeoff between the future repair costs and quality assurance in the early construction phase.

Failure Mode Effects Analysis (FMEA) is a risk prioritisation method, which considers the severity, occurrence and detectability of shortcomings. Although it is widely used in production, some studies (Abdelgawad & Fayek, 2010; Layzell & Ledbetter, 1998; Mecca & Masera, 1999) have implemented the method in the construction industry. Traditionally, the severity consideration focuses on the impact of technical severity. Bowles (2003) has argued that the financial aspect is undervalued to give recommendations on risk reduction. Similar research which uses financial aspects as severity input for FMEA has been conducted by Shafiee and Dinmohammadi (2014) for the production and erection of wind turbines. They point out that there is a relevant difference in future cash flows if offshore or onshore placement is observed. Their research is focused on the cost of the failure consequences, which supports managers in their investment decision-making process. The economic risk assessment concluded that the financial relevance is beneficial as more detailed considerations are required from the operational phase to evaluate the ultimate effects of the shortcomings.

There are two major points criticizing the usefulness and interpretation of FMEA models, which have been modified by including the financial aspects. The general criticism is focused on the calculation of the Risk Priority Number, which multiplies the variables without any weighting factor (Bowles, 2003; Carmignani, 2009; Pillay & Wang, 2003). The researchers argue that the occurrence and detectability values should not be linear. The second aspect is focused on the difficulty of predicting the corrective action cost (Bowles, 2003; Carmignani, 2009). This model observes the specific façade system of ETICS, which reduces the number of repair methods and data requirements from a specific company. The data is gathered from actual construction projects, which represents the current economic situation and is reliable. It can be agreed that many variables change – the location of the project, the economic situation, and the cost of artisans and materials, and therefore, the cost data should be project-specific. The repair methods are also subject to change as alternatives emerge or are more relevant.

This paper develops an ETICS economic assessment model, which considers the future cost of shortcomings as the variable of severity with the modified FMEA method. The on-site shortcomings are evaluated according to their repair methods, detectability during the construction works and their occurrence probability. The results enable resources to be identified and allocated during the construction process on the activities, which have a higher financial impact.

1. Materials and methods

The economic evaluation focuses on the costs caused by degradation factors, which occur during the construction process of ETICS. The aim is to develop an economic comparison system to differentiate the construction process shortcomings by their financial relevance. The FMEA modified risk assessment methodology is applied to classify and rate the significance of each failure separately.

The FMEA approach has been proven to be a flexible model which can be adapted according to the specific needs of the user. Traditionally, the severity evaluation focuses on the technical impacts of a failure. In this model, the risk differentiation focuses on the economic impact and is therefore substituted for economic value. Shafiee and Dinmohammadi (2014) have shown the value of such differentiation for decision making on the shortcomings of on-shore and off-shore wind turbine assembly, where the repair costs vary to a large extent. Rhee and Ishii (2003) have pointed out the need to include costs into the risk calculation approach and developed a "Life Cost-Based FMEA" which includes traditional FMEA, Life Cycle Costs and Service Mode Analysis. Carmignani (2009) included in the developed FMECA model the cost of preventive action, which enables the estimated profitability be calculated if measures are taken. These FMEA modifications point out the relevance of cost in risk management as it is the expected benefit for reducing the systematic failure during the process.

The outcome of the economic relevance calculation for each degradation factor is the economic risk priority number ($ERPN_{DF}$), calculated as follows:

$$ERPN_{DF} = EAV_{DF} \times OV_{DF} \times DV_{DF}, \quad (1)$$

where: $ERPN_{DF}$ – economic risk priority number; EAV_{DF} – economic assessment value of a degradation factor; DV_{DF} – detectability of the degradation factor; OV_{DF} – likelihood of occurrence.

ERPN is the value of a single degradation factor which enables the prioritization and comparison to other evaluated factors. Although the repair costs include the actual costs in monetary units provided by the user of the model, the ERPN expresses the criticality without a specific unit. The development procedure of the model defines the components required for the calculation of the economic impact as shown in Figure 1. The economic model is influ-

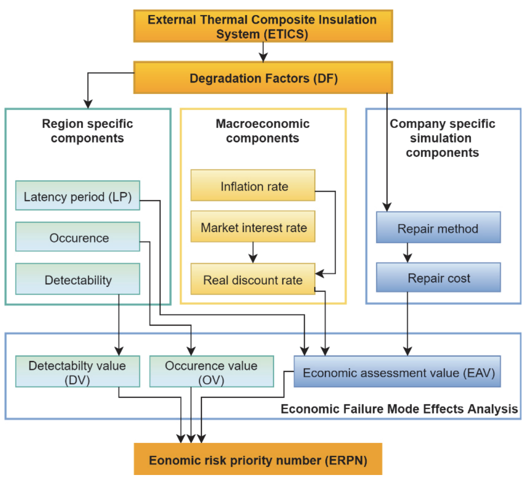


Figure 1. The concept of the economic risk assessment model

enced by regional, macroeconomic and company-specific components, which are the input values to the calculation of ERPN. The following chapters describe the method for selection of degradation factors, data collection and calculation steps as well as the characteristics of the sample simulations.

1.1. Degradation factors

The list of degradation factors in the model involves different on-site contruction activities. The user of the model can introduce new activities if required. The model is simulated for the shortcomings, which are collected and described in (Sulakatko, Liisma, & Soekov, 2017). The authors have verified the degradation factors through two experts, as suggested by Converse and Presser (1986), who had experience with ETICS for more than 12 years. The experts were identified through the membership of a nationally recognized committee for ETICS. One expert who verified the list was located in Germany, had a doctoral degree, while the second expert was in Estonia, and had master's degree in the field of construction. The reviews were conducted individually and independently. Eventually 11 irrelevant factors were removed from further analysis, and the wording of 16 factors was rephrased in order to improve intelligibility. The list of factors is presented in the Appendix.

1.2. Components of the model: latency period, detectability and occurrence probability

For each degradation factor, the developed model requires data regarding detectability and occurrence probability as well as the latency period for the discounting of repair costs. The latency period is a time range between the occurrence of the on-site shortcoming and the time when the degradation has evolved and requires repair activities. The occurrence probability measures show the frequency of shortcomings, and detectability measures show how difficult these shortcomings are to notice during the construction works. As this study aims to identify the situation in Estonia, the Estonian experts were asked to participate in the region-specific data collection. The data was collectied with the single Delphi technique, where the judgements of independent and anonymous experts are combined through mathematical aggregation (Skulmoski & Hartman, 2007).

There is no quantified data available on the research subject. Hence, expert judgement was suitable for use in this study. Indeed, the selection of experts considerably affects the quality of the data (Chan, Yung, Lam, Tam, & Cheung, 2001). Therefore, the criteria of experts' selection were their in-depth knowledge in technical aspects of ETICS as well as practical on-site experience. According to Olson (2010), variations in reviewers' backgrounds are allowed. Hallowell and Gambatese (2010) suggested that in the construction industry, selection of experts could be conducted through nationally recognized associations or by participation in similar studies. The expert should meet at least four of the following requirements: (1) have at least five years of professional experience in the construction industry; (2) have a tertiary education degree in the field of civil engineering or other related fields; (3) be professional registered in the field of construction; (4) be a member or chair of a nationally recognized committee for ETICS; (5) be a writer or editor of a book or book chapter on the topic; (6) be a faculty member at an accredited institution of higher learning; (7) have been invited to present at a conference on the topic; and (8) be a primary or secondary writer of at least three peer-reviewed journal articles. Five Estonian experts out of seven identified agreed to participate in the survey conducted in 2018. Their practical experience in the field of ETICS was between 10 and 20 years and they hold tertiary education. All five have practical experience, three work in an ETICS manufacturing and retail company, and one works at a construction firm and one as supervisor.

For the evaluation of detectability and occurrence probability, 5-point Likert scales were developed. Preston and Coleman (2000) pointed out that a detectability value below four points should be avoided. The detectability value rates how difficult it is to detect the shortcoming on the construction site. The characteristics of the detectability classification are shown in Table 1.

Likelihood of occurrence rates incident frequency during the construction process. It is an expert's subjective evaluation and it is dependent on his/her personal experience. The pre-test questionnaire revealed that it is impossible to quantify the occurrences in a specific range and quantification of subjective evaluation is required. The rating scale is shown in Table 2, where ranks with the highest

Table 1. Likert scale for the evaluation of detectability

Risk level	Characteristic	Detectability value
Very high	A potential cause of failure cannot be detected visually. Additional tests need to be used. High experience required	5
High	In-between very high and moderate conditions	4
Moderate	A potential failure can be detected visually before completion of the layer, during the application process or through markings on the material packages. Mediocre experience required	3
Low	In-between very low and moderate conditions	2
Very low	Cause of failure can be detected after completion of the layer by less experienced observer	1

Table 2. Likert scale for the evaluation of occurrence probability

Risk level	Characteristic	Occurrence value
Very high	Failure is almost certain	5
High	Often repeated failures	4
Moderate	Occasional failures	3
Low	Relatively few failures	2
Very low	Failure is unlikely	1

value are set for the frequently occurring failures, and the lowest value for unlikely failures.

The latency period was detected with the accuracy of one year. The degradation factors which occur only due to unpredictable situations (i.e. outbroke of fire, vandalism) are marked as a happening in the year 0. Additionally, it was considered that the latency period could not exceed the service life of ETICS. According to studies by Flores-Colen and De Brito (2010) and Künzel et al. (2006), the service life can be more than 35 but can decrease to 16 years if no maintenance is conducted. The average service life expectancy is 30 years (Pelzeter, 2007; Wetzel & Vogdt, 2007), which is also used as the latency period limitation in this study. For the latency period, the experts predicted the year when the shortcoming shows visible signs. After the data collection, the mean values of the experts were calculated.

The most preferred number of panelists has not been determined in the literature as it depends on the availability of experts, the research topic and resources (Ameyaw, Hu, Shan, Chan, & Le, 2016). Wilson (2017) emphasises the duration of the experience on the topic, which was the primary criterion for the selection of experts to the panel. A small number of experts has often been used in other studies of the construction industry. Six experts were identified and selected for a risk assessment of road projects (Thomas, Kalidindi, & Ganesh, 2006) and five experts evaluated construction business risks (Dikmen, Birgonul, Ozorhon, & Sapci, 2010). Studies have included from 3 to144 experts in the studies of various industries (Skulmoski & Hartman, 2007) and from 3 to 93 panelists in the construction industry (Ameyaw et al., 2016). Hallowell and Gambatese (2010) proposed a panel size between 8–12, whereas Rowe and Wright (2001) suggested including five or more experts in the panel and pointed out that there are "no clear distinctions in panel accuracy" when the panel size varies from 5 to 11 experts. As this model is aimed at SMEs, it is expected that the size will be small. Therefore, at least five experts should be included to collect the data.

The experts were asked individually and anonymously to provide their evaluations. According to the questionnaire, each expert needed to provide evaluations for occurrence, detectability and latency period. To obtain a high response rate, a meeting time with each expert was individually organized. During the face-to-face meeting, the questionnaire was completed by the expert. The responses from all experts were summarized and mean values were calculated. The collective mean results were sent to each expert and they were asked to revise their evaluation or agree/disagree with the collective result. During the next two weeks, three participants agreed with the collective results. Two experts reviewed the group results after a reminding phone call and stated their agreement with consensus. The similar one-round method is exercised in environmental planning (Kuo & Yu, 1999) and other civil engineering researches (Hartman & Baldwin, 1995).

1.3. Cost component of the model: economic assessment value

The life cycle costing method reflects the expenses in each phase of the building (Li, J. Zhu, & Z. Zhu, 2012). To simplify the economic considerations the current model focuses on the costs of initial construction and the repair costs at the time when the degradation factors show visible degradation signs. The data needs to differentiate the financial relevance of shortcomings and consider the future monetary value at the time when the investement will be needed. The discounting technique enables the long-term economic effect to be introduced and compares the future investments required during upcoming years. As the model is developed for the internal use of a company, it is beneficial as the results of different simulations conducted during various years are comparable. The retrospective short-term economic changes are introduced to the model with the construction cost index. The relevance of the constrction cost index is relevant only if the cost data is collected during dissimilar years; otherwise there is no effect to the simulation. The ratio which differentiates the financial relevance of the shortcomings is expressed with the following equation:

$$EAV_{DF} = \frac{NPV_{DF}}{CCI}, \quad (2)$$

where: EAV_{DF} – Economic assessment value [monetary unit/m^2]; NPV_{DF} – discounted repair costs of a degradation factor [monetary unit/m^2]; CCI – construction cost index.

The discounted repair costs of a degradation factor are leveraged with the construction cost index for new residential buildings provided by Eurostat to maintain the comparability during economic fluctuations. The simulations in this research are based on the Estonian situation, where the value of quarter 4 in 2017, compared to 2010 as a reference year, is 116.6% (Eurostat, 2018).

A repair method is the set of construction activities required to remove the defect and restore the functionality of ETICS. Professionals in the field (Amaro, Saraiva, de Brito, & Flores-Colen, 2014; Cziesielski & Vogdt, 2007; Fraunhofer IRB Verlag, 2016; Krus & Künzel, 2003; Kussauer & Ruprecht, 2011; Neumann, 2009) thoroughly describe the reliable repair methods for ETICS. Maintenance techniques like cleaning, disinfecting and coating the external layer, or crack filling, required due to externally applied forces or ageing, are not observed. The defects caused by shortcomings in the sealants of additionally fixed details and roof edges are handled as a requirement to remove the insulation as moisture-induced problems have been caused. The possibility to cover degradated ETICS with second ETICS was not observed; instead the reapplication of the whole system was considered. As the current simulation model is explicitly developed for systematic on-site shortcomings of ETICS, the scope of works can be specified by the affected layers (Sulakatko, Lill, & Liisma, 2015) – replacement of the finishing layer, reinforcement layer, or the whole system.

For the cost comparison, all the cost components of the model are adjusted to the unit €/m^2 without VAT. In this study the economic relevance model is simulated on three different project-based cost scenarios. The characteristics of the simulations are shown in Table 3.

The usage of industry data has provided valuable and more exact results in other studies (Serpell, 2004). Therefore the cost data for the simulations is provided by an experienced professional from one active construction company and is based on the costs of projects simultaneously under construction from September 2017 until January 2018 in Estonia. The cost difference to construction costs of simulations is shown in Table 4. The table shows the cost difference ratio to the initial construction cost of simulation 1.

The repair techniques dismantle the existing system up to the defected layer and replace these by re-applying the layers. The utilisation of insulation materials is responsible on average for 50% of the dismantling costs, artisans for 21% and lifting mechanisms, covers and other minor accessories for 29%. The repair costs are time-relevant components in the life cycle consideration and are calculated as follows:

$$NPV_{DF} = \frac{C_R}{\left(1+R_r\right)^{LP_{DF}}}, \quad (3)$$

where: NPV_{DF} – net present value of the repair costs for a degradation factor [monetary unit/m^2]; R_r – real discount rate per annum [%]; LP_{DF} – latency period of a degradation factorm [years]; C_R – repair cost of selected repair method [monetary unit/m^2].

1.4. Real interest rate

The discounting technique compares costs that take place in different time periods and the discount rate represents the time value of money. Although it is recommended to use the real discount rate of 2% for the LCC calculation by other researchers (Langdon, 2007), the inflation rate and the market interest rate provide a more specific outcome. The real interest rate is calculated as follows:

$$R_r = R_m - R_i, \quad (4)$$

where: R_r – real discount rate; R_i – inflation rate; R_m – market interest rate.

The economic relevance model focuses on the features of the Estonian market, and for the inflation rate the value of the harmonised consumer price index (HCPI) is used. The average of the 12 months harmonised inflation rate of a calendar year is shown in Figure 2a (Eurostat, 2017). In the case of Estonia, the inflation rate of 3.73% is applied. In comparison, the average HCIP in the European Union is 1,96%, The selected long-term market interest rate is based on the national average interest reported by the national statistics of the central bank of Estonia. The average 5- to 10-year loan interest rate for entrepreneurs is 4.25% as shown in Figure 2b (Bank of Estonia, 2017). The real interest rate in the NPV calculation is 0.52%.

1.5. Limitations

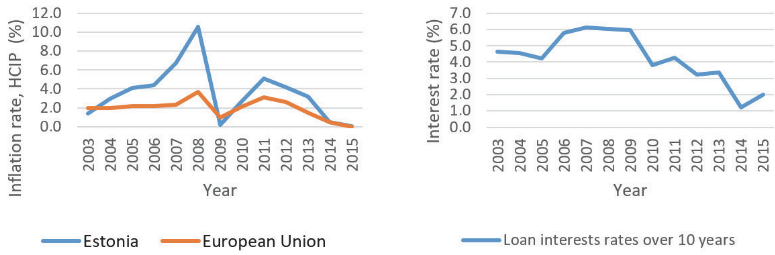
The construction products are improving rapidly, and new construction technology emerges. The degradation factors as well as the data collected concern ETICS with the following characteristics:
- the subject is an existing multi-apartment building;
- external walls are made out of masonry or prefabricated concrete panels;

Table 3. Characteristics of simulations

Simulation No.	ETICS type	Insulation type	Insulation thickness	Fixing method
Simulation 1	ETICS 1	Polystyrene	200 mm	Purely bonded kit
Simulation 2	ETICS 2	Polystyrene	200 mm	Mechanically fixed kit with supplementary adhesive
Simulation 3	ETICS 3	Mineral wool	200 mm	Mechanically fixed kit with supplementary adhesive

Table 4. The comparative ratio of the construction and repair costs to the initial construction cost of simulation 1

Description of construction work	Simulation 1	Simulation 2	Simulation 3
The initial construction ETICS	1.00	1.08	1.30
Replacement of insulation	1.74	1.80	2.01
Replacement of reinforcement layer	1.11	1.11	1.11
Replacement of finishing layer	0.50	0.50	0.50



a) b)

Figure 2. a) Annual HCIP in Estonia and EU (Eurostat, 2017);
b) Interest rates in Estonia (Bank of Estonia, 2017)

- the fixing method is either purely bonded with adhesive or mechanically fixed with anchors and supplementary adhesive;
- reinforcement consists of the mixture and fiberglass mesh;
- the thermal insulation product is made out of mineral wool or expanded polystyrene with a thickness from 150 mm to 250 mm;
- the simulations concern the economic situation of Estonia.

2. Results

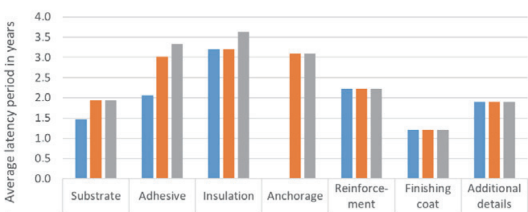
2.1. Latency period of the degradation factors

The average latency period of the 103 degradation factors is 2.32 years with a standard deviation of 1.5 years; distribution by layers is shown in Figure 3. The correlation and linear regression analysis between the latency period, occurrence and detectability did not reveal relevant results.

The degradation factors in the layers of reinforcement, finishing coat and additional details do not depend on the system (simulation) and have an equal latency period. The layers of substrate, adhesive and insulation have a noticeable difference in comparison to the ETICS types under observation. The degradation factors that concern ETICS 3 have the longest latency period. In the layer on insulation, the difference is caused by two shortcomings – insulation material open to UV radiation for a longer period (I1) and continuing diffusion process of the insulation material (I2). Both are relevant for the polystyrene-based insulation and decrease the average value of the systems. The difference in the layer of adhesive is due to the fixing mechanism. ETICS 1 depends highly on the properties of adherence. ETICS 2 and ETICS 3 are primarily mechanically fixed, and the relevance of adhesive is significantly lower, as is the latency period. The layer of substrate is the most homogenous layer and shows the lowest standard deviation of 0.50 years.

Figure 4 reveals the latency periods of the degradation factors by the sequence of the construction process and draws the average values for different ETICS types by layer. The degradation factors in the layer of substrate appear rather fast. The latency period rises in the layers of adhesive and insulation and begins to fall after the installation of mechanical anchors. The shortcomings in the layer of reinforcement and finishing layer appear within the shortest period. The trend is similar for all the three ETICS types.

The groups LP1 and LP2 shown in Figure 4 have the longest latency period, above five years, and are relevant for their long-term durability. The layer of adhesive has a group of five degradation factors (LP1), which according to the discussion in the expert panel depend on the ap-



	Substrate	Adhesive	Insulation	Anchorage	Reinforce-ment	Finishing coat	Additional details
ETICS 1	1.48	2.06	3.21		2.22	1.21	1.90
ETICS 2	1.94	3.01	3.21	3.09	2.22	1.21	1.90
ETICS 3	1.94	3.34	3.64	3.09	2.23	1.21	1.90

Layer

Figure 3. The average latency period by layer

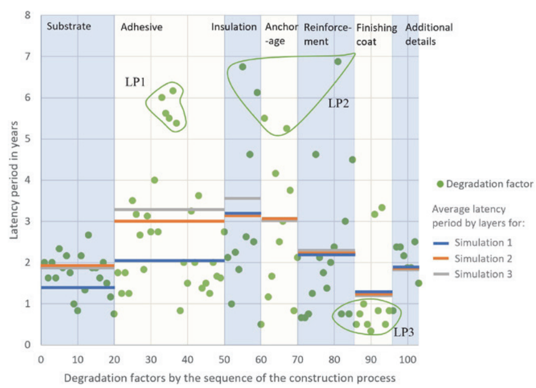


Figure 4. Latency period of the degradation factors by the sequence of the construction process

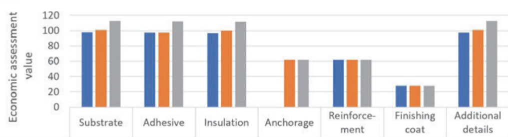
pearance of natural disasters as well as ageing. The shortcomings in the group LP1 are insufficient adhesive (D3a, D3b), adhesive not rubbed into mineral wool (D4a) or treated with a notch towel (D5) and exceeded working time of the mixture (D7a). The group LP2 concerns five factors from several layers – decreased diameter of anchor plate (A2), increased diameter of anchor hole (A1), crossed joints of insulation plates (I5), broken and not properly filled insulation plates (I9) and usage of not compatible mesh (R8), The glass fibre mesh in the base coat is required to be resistant to the alkaline environment. In the case of non-resistant mesh application, the required residual strength properties will be reduced until a critical level is achieved and failure of the system occurs.

The group LP3 diverges with a very low latency period. The majority in this group belongs to the finishing layer, and eight degradation factors out of ten in the finishing layer reveal problems during the first year after application. The two factors with high values are the thin render layer (F4) and high kneading water share (M3d) with a latency period of 3.2 and 3.3 years accordingly. However, both degradation factors have low occurrence and detectability values as shown in the next sub-chapter. Low values state that the shortcomings happen rarely and have good visibility.

The net present value calculations take into account the latency period, which is relatively low, as is its impact on the results. The maximum change of economic assessment value through NPV calculation was 3.5%. To compare the difference of the results between the simulations, each shortcoming is appointed to a suitable simulation. The average values of economic assessment values for applicable shortcomings are shown in Figure 5. In the comparison between layers, lower repair costs have the degradation factors in the layers of anchorage and reinforcement, while the finishing layer has the lowest values in general.

2.2. Probability of occurrence and detectability during construction works

The discussed economic value is the first component in the ERPN calculation, while the occurrence and detectability values are the second and third components. To give an overview of the influence of the components, Figure 6 presents the average impact of the two factors by layer and Figure 7 visualizes the impact of the degradation factors according to their sequence in the construction process. Higher values show higher risks to consider. As



Layer	Substrate	Adhesive	Insulation	Anchorage	Reinforce-ment	Finishing coat	Additional details
Simulation 1	98	97	97		62	28	98
Simulation 2	101	98	100	62	62	28	101
Simulation 3	113	112	112	62	62	28	113

Figure 5. The average economic assessment value by layers

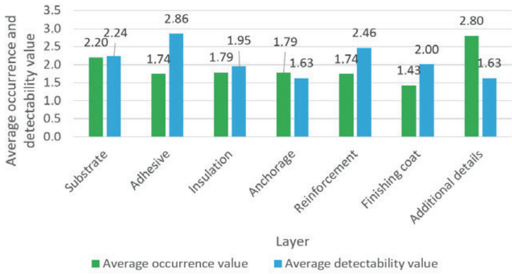


Figure 6. The average occurrence and detectability value by layers

no significant difference between ETICS types was found, the difference of average values is occurring only as some degradation factors are applicable for a specific system.

The figures show that higher occurrence values appear in the layers of substrate and additional details, while fewer shortcomings occur during the application of the finishing coat. The detectability value is the highest in the layers of adhesive and reinforcement as they can be observed only during the mixture application process. The standard deviation of the average values of the layers is between 0.31 and 0.76. The lowest standard deviation for detectability of the shortcomings is in the layers of adhesive (0.31), and additional details (0.33) visualised as groups DV1 and DV2 in Figure 7. These results are as expected as the detectability is more difficult by layer of adhesive due to fast coverage with insulation material, and the defects with additional details have relatively good visual detectability. For the occurrence value, lower standard deviation is found for the group OV1, shortcomings with anchorage (0.46). In other layers the standard deviation is above 0.5 and the distribution is higher.

2.3. Economic risk priority number

The average ERPN values by layer and simulation are shown in Figure 8. The highest priorities have the degradation factors in the layers of substrate, adhesive and additional details. The factors in the layer of insulation and reinforcement have modest values, while the mechanical anchors and the finishing coat are the least relevant.

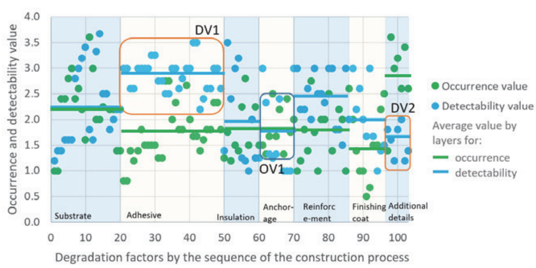
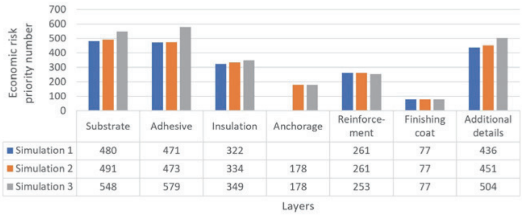


Figure 7. The average occurrence and detectability value of the degradation factors by the sequence of the construction process



	Substrate	Adhesive	Insulation	Anchorage	Reinforce-ment	Finishing coat	Additional details
Simulation 1	480	471	322		261	77	436
Simulation 2	491	473	334	178	261	77	451
Simulation 3	548	579	349	178	253	77	504

Figure 8. The average ERPN values by layer

In the layers of adhesive, substrate and additional details, simulation 3 shows increased relevance in comparison to the other simulations. According to the economic assessment values (Figure 5), the cause lies in the increased repair costs. A similar effect is in the layer of insulation on a smaller scale.

Figure 9 illustrates the ERPN values of the degradation factors in the sequence of the construction works and points out the approximate range of layers (colored areas). The horizontal lines show average ERPN for the three simulations by layer. There are groups of shortcomings with noticeable deviations, which are grouped by green lines. As the economic assessment value had a very low differentiation within a single layer, the major deviations occur due to the impact of the occurrence and detectability variables.

Group E1 in the layer of substrate describes the degradation factors in all three simulations and concerns the shortcomings which influence the adhesion properties as well as mechanical fixations. The adhesion properties are concerned by the remains of old paint (S4a, S4b), the low humidity of the existing wall (S7a, S7b) and unsuitable adhesive type (S7a, S7b). Also problematic is the load-bearing capacity of the external wall (S5a, S5b) as well as detached areas on the surface (S6a, S6b). Group E2 demonstrates very low risk and represents the external surface covered with oil (S1a, S1b), having very low occurrence and detectability values.

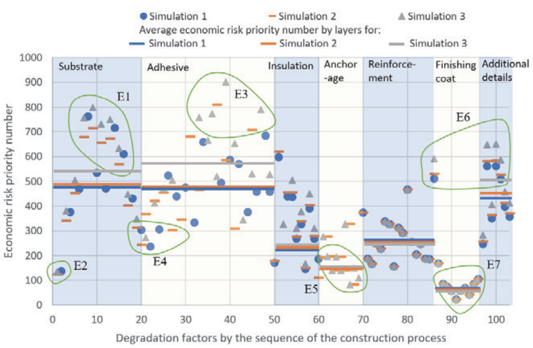


Figure 9. Economic risk priority number of the degradation factors by the sequence of the construction process

Group E3 involves the factors with high ERPN values in the layer of adhesive, which are relevant for simulation 2 and 3. Problems in simulation 2 occur as insufficient amount of adhesive applied (D3a), which is relevant for prohibiting air movement internally and has increased importance on the stability of the system. Additionally, the effect of exceeded working time (D7a) has high relevance. These degradation factors have relatively high detectability value as the shortcoming is covered with insulation plates immediately and are observable only during the application process. Simulation 3 is affected by lack of pressure on the installation plates during application (D8a) and no usage of notch towel (D5), leaving the possibility for air movement behind the system. Also, the drying out of the inorganic mixture due to high temperature (M11a) and dry curing conditions (M10a) are relevant.

Group E4 is a low relevance group which contains the freezing of adhesive due to a frozen external wall (S10a, S10b). As the degradation factors refer to existing buildings which are heated by the habitants, it is expected that after the application of insulation, the temperature will not fall into a critical freezing zone. The other factors concern unsuitable adhesive storage conditions (M1a, M1b), clots in the mixture due to an insufficient mixing process (M2b) and a low share of kneading water (M4a). Although these factors have high economic assessment value, the occurrence and detectability reduce the relevance of risk noticeably. The other low relevance group, E5, representing 8 shortcomings out of 10 in the layer of mechanical anchors, has low values in all categories.

The high ERPN values concern group E6, which represents four degradation factors of additional details in all simulations. Due to the high repair costs and occurrence value, the factors of insufficient shock resistance measures (X6), unfinished windowsills (X2) and fixed frame connections (X4) as well as problematic roof edge covers (X5) have relatively high economic priority.

3. Discussion

The developed economic relevance model makes use of decision making when the future costs of possible shortcomings and the construction quality is targeted. The developed model enables the economic aspects to be included in the construction process risk assessment of ETICS. If during resource allocation on quality control of ETICS only direct costs are considered, the focus would be set on the internal layers as they require replacement of the whole system and cause higher repair costs (see Figure 5). By adding an occurrence probability and detectability component, the focus can be set only for the limited factors with higher risk. The added components reduced the relevance of the degradation factors in the layers of insulation and mechanical anchors. When the components are observed in silos, then the probability of occurrence increased the risk in the layer of the substrate and in additionally added details, while the detectability of the failures increased the risk in the layer of adhesive and reinforcement.

In this model, the latency period has a relatively low effect on the results as it varies in a relatively small range – most of the shortcomings appear during the first three years. A similar observation is made by Neumann (2009), who stated that 80% of the shortcoming occur during the first five years and 2/3 occur in the first two years. According to the results of this study, 50% occur during the first 2-year period. Due to the short period, the interest rate has a relatively low impact on the results of this economic situation. However, the results of the latency period of the degradation factors can be interesting to various stakeholders of the project depending on their contractual agreement. If the contractual defect liability period is two years, then the financial risk is shifted from the contractor to the owner. Such degradation factors appeared more often in the layers of adhesive, insulation, anchorage and reinforcement as they have a longer latency period. These considerations enable decisions to be made on quality issues and the responsibilities of the parties on the contractual level.

Other studies consider the technical aspects in isolation and no comparative economic data is availible on the degradation signs. Several studies have investigated the durability aspects (Daniotti et al., 2012; Edis & Türkeri, 2012; Künzel et al., 2006) and the deteroriaration signs and linked them with most probable direct and indirect causes (Amaro et al., 2014). The construction process defects cannot often be directly related to the visible anomalies as they require destructive tests. The results of the occurrence value contribute to studies conducted with such a top-down approach which investigate the in-situ analysis and require destuctive tests to understand the origin of the problem. These studies often imply several shortcomings that might have been the causes and are related to the technical aspects.

The previous study on the technical influence of the degradation factors (Sulakatko & Vogdt, 2018) has emphasised the shortcomings in the layers of reinfocement and additional details as well as the works that influence the adhesion properties in the layers of substrate and adhesive of the purely bonded system. The average ERPN values in the layer of reinforcement are relatively low in this study. This shows that the resource allocation for quality insurance during the construction works must consider several variables.

The results of the analysis show higher relevance of the on-site construction process activities in the layers of substrate and adhesive as they often occur, are hard to detect and have a high financial impact if repair activity is required. High relevance can also be noticed for the often-occurring problems during construction works with windowsills and roof edge covers. The results of the study finds that the shortcomings in the finishing layer and by mechanical anchors have the lowest relevance and that 90% of the degradation factors appear during the five-year period after construction, while half of them are visible as early as the first two years.

The economic assessment model enables the enhancement of financial risk assessment of the on-site construction process of ETICS to highly relevant construction activities. The outcome supports decision makers in increasing the value of the construction works by reducing future repair costs.

Conclusions

The External Thermal Insulation Composite System (ETICS) can be used to modernize and increase the energy efficiency of existing and new buildings. However, the intensive on-site construction process aggravates the occurrence of systematic inadequacies. These inadequacies turn up as degradation signs and require additional resources for their elimination after the completion of the project. The financial relevance of construction activity is evaluated with the modified FMEA method, which considers the cost of repair as a severity variable of the on-site degradation factors. The model is simulated on three construction projects.

Acknowledgements

We would like to show our gratitude to the experts and participating construction company who have shared their experience and knowledge during this research.

Funding

This work was supported by the Estonian Ministry of Education and Research under Grant IUT-15 "Nearly-zero energy solutions and their implementation on deep renovation of buildings".

Author contributions

Virgo Sulakatko is the main author, he performed the research, collected data, conducted interviews and completed the analysis. Irene Lill supervised the activities in terms of methodology, framework and overall design of the research. Both authors contributed to discussion of results and recommendations, conclusions and the writing of the paper.

Disclosure statement

The authors declare no conflict of interests.

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APPENDIX

Table 5. Data for equation (1)

Sequence	ID	Layer	Factor	ETICS 1	ETICS 2	ETICS 3	OV	DV	LP	EAV (Sim1)	ERPN (Sim1)	EAV (Sim2)	ERPN (Sim2)	EAV (Sim3)	ERPN (Sim3)
1	S1a	S	Substrate is covered with grease or oil		x	x	1.00	1.20	2.00			101	121	113	135
2	S1b	S	Substrate is covered with grease or oil	x			1.00	1.40	1.63	98	137				
3	S2a	S	Substrate is covered with dust or dirt		x	x	2.40	1.40	2.00			101	339	113	378
4	S2b	S	Substrate is covered with dust or dirt	x			2.40	1.60	1.63	98	375				
5	S3a	S	Substrate is covered with biological growth		x	x	2.80	1.60	2.33			101	451	112	504
6	S3b	S	Substrate is covered with biological growth	x			3.00	1.60	1.88	98	468				
7	S4a	S	Substrate is covered with paint or other material which can chemically react with adhesive		x	x	2.40	2.80	2.17			101	678	113	756
8	S4b	S	Substrate is covered with paint or other material which can chemically react with adhesive	x			2.60	3.00	1.75	98	762				
9	S5a	S	Substrate is under required load-bearing capacity		x	x	2.20	3.20	1.00			101	714	113	797
10	S5b	S	Substrate is under required load-bearing capacity	x			1.60	3.40	0.83	98	534				
11	S6a	S	Substrate has large unevenness or has detached areas		x	x	3.60	1.80	2.17			101	653	113	729

End of Table 5

Sequence	ID	Layer	Factor	ETICS 1	ETICS 2	ETICS 3	OV	DV	LP	EAV (Sim1)	ERPN (Sim1)	EAV (Sim2)	ERPN (Sim2)	EAV (Sim3)	ERPN (Sim3)
12	S6b	S	Substrate has large unevenness or has detached areas	x			3.00	1.60	1.33	98	470				
13	S7a	S	Unsuitable surface (too smooth) which reduces adhesion properties		x	x	2.00	3.33	2.67			101	670	112	748
14	S7b	S	Unsuitable surface (too smooth) which reduces adhesion properties	x			2.00	3.67	1.88	98	716				
15	S8a	S	Substrate has very low humidity (inorganic adhesive)		x	x	2.25	2.50	1.88			101	568	113	634
16	S8b	S	Substrate has very low humidity (inorganic adhesive)	x			2.50	2.50	1.63	98	611				
17	S9a	S	Substrate is very wet (raining in prior to application of adhesive)		x	x	2.20	1.80	2.00			101	400	113	446
18	S9b	S	Substrate is very wet (raining in prior to application of adhesive)	x			2.20	2.00	1.50	98	430				
19	S10a	S	Substrate is frozen during the application (inorganic adhesive)		x	x	1.40	2.20	1.17			101	312	113	348
20	S10b	S	Substrate is frozen during the application (inorganic adhesive)	x			1.40	2.20	0.75	98	302				
21	M1a	D	Unsuitable mixture storage conditions		x	x	0.80	3.00	1.75			101	243	113	271
22	M1b	D	Unsuitable mixture storage conditions	x			0.80	3.00	1.25	98	235				
23	M2a	D	The mixing procedures do not remove clots		x	x	1.40	2.60	1.75			101	368	113	411
24	M2b	D	The mixing procedures do not remove clots	x			1.20	2.60	1.25	98	305				
25	M3a	D	High share of kneading water		x	x	1.40	3.00	3.50			100	421	112	469
26	M3b	D	High share of kneading water	x			1.80	3.00	3.17	97	523				
27	M4a	D	Low share of kneading water		x	x	1.50	3.00	2.67			101	453	112	505
28	M4b	D	Low share of kneading water	x			1.50	3.00	1.83	98	439				
29	D1a	D	Missing adhesive on the edges of insulation (polystyrene)		x		1.50	3.25	3.13			62	302		
30	D1b	D	Missing adhesive on the edges of insulation (polystyrene)	x			1.50	3.25	2.75	97	474				
31	D2a	D	Missing adhesive in the centre of insulation (polystyrene)		x		1.25	2.75	4.00			100	343		
32	D2b	D	Missing adhesive in the centre of insulation (polystyrene)	x			1.25	2.75	2.75	97	334				

Table 6. Data for equation (2)

Sequence	ID	Layer	Factor	ETICS 1	ETICS 2	ETICS 3	OV	DV	LP	EAV (Sim1)	ERPN (Sim1)	EAV (Sim2)	ERPN (Sim2)	EAV (Sim3)	ERPN (Sim3)
33	D3a	D	Insufficient adhesive surface area		x	x	2.75	2.50	6.00			99	680	110	758
34	D3b	D	Insufficient adhesive surface area	x			2.75	2.50	5.63	96	658				
35	D4	D	Adhesive is not rubbed into insulation plate (mineral wool)			x	2.00	3.00	5.50					111	664
36	D5	D	Adhesive is not treated with notch towel (mineral wool)			x	2.33	3.00	6.17					110	772
37	D7a	D	Working time of the adhesive is exceeded		x	x	1.80	2.60	5.38			99	464	111	518
38	D7b	D	Working time of the adhesive is exceeded	x			1.80	2.80	0.83	98	495				

End of Table 6

Sequence	ID	Layer	Factor	ETICS 1	ETICS 2	ETICS 3	OV	DV	LP	EAV (Sim1)	ERPN (Sim1)	EAV (Sim2)	ERPN (Sim2)	EAV (Sim3)	ERPN (Sim3)
39	D8a	D	Low pressure during application of insulation plates		x	x	2.67	3.00	2.00			101	807	113	901
40	D8b	D	Low pressure during application of insulation plates	x			2.00	3.00	1.50	98	587				
41	D9a	D	Large unevenness of the adhesive layer		x	x	1.67	3.50	3.25	0		100	585	112	653
42	D9b	D	Large unevenness of the adhesive layer	x			1.67	3.50	2.00	98	569				
43	M9a	D	Low temperature (freezing) during application and/or curing process		x	x	1.40	2.20	3.63			100	308	112	344
44	M9b	D	Low temperature (freezing) during application and/or curing process	x			1.60	2.40	1.38	98	376				
45	M10a	D	High temperature (hot) during curing process		x	x	1.80	2.60	1.50			101	474	113	528
46	M10b	D	High temperature (hot) during curing process	x			1.80	2.60	1.25	98	458				
47	M11a	D	Low humidity (dry) during curing process		x	x	2.33	3.00	2.00			101	706	113	788
48	M11b	D	Low humidity (dry) during curing process	x			2.33	3.00	1.67	98	684				
49	M8	D	Not recommended ingredients added to the mixture	x	x	x	1.80	2.60	1.63	98	457	101	473	113	528
50	I1	I	Polystyrene is exposed to UV-radiation for a extended period	x	x		1.25	1.40	2.75	97	170	101	176		
51	I2	I	Insulation plates are installed shortly after manufacturing (unfinished diffusion process	x	x		1.75	3.50	2.13	97	597	101	618		
52	I3a	I	Mineral wool insulation plates have very high relative humidity (are wet			x	1.20	2.40	1.00					113	326
53	I3b	I	Insulation plates which have very high relative humidity (wet)	x	x		1.50	3.00	2.25	97	438	101	454		
54	I4	I	Continuous gaps between substrate and insulation material	x	x	x	1.40	3.20	1.83	98	437	101	453	113	505
55	I5	I	Corners of neighbouring insulation plates are crossed or too close	x	x	x	2.25	1.25	6.75	95	268	98	277	110	309
56	I6	I	Corners of the openings have crossed joints	x	x	x	2.80	1.20	2.63	97	327	101	338	112	377
57	I7	I	Insulation plates joint width of neighbouring insulation plates is too wide	x	x	x	1.50	1.00	4.63	96	144	100	149	111	167
58	I8	I	Large height difference between neighbouring insulation plates	x	x	x	2.00	2.00	2.50	97	389	101	403	112	449
59	I9	I	Broken areas of the insulation plates are not filled with same material	x	x	x	2.25	1.25	6.13	95	268	99	278	110	310
60	I10	I	Missing or narrow fire reluctant areas	x	x		1.50	1.25	0.50	98	184	102	191		
61	A1	A	Increased diameter of drilled anchor hole		x	x	1.50	3.00	5.50			61	275	61	275
62	A10	A	Hole of the anchor is not cleaned		x	x	1.33	2.33	1.17			63	195	63	195
63	A5	A	Location of anchors is not as foreseen		x	x	1.67	1.33	1.67			62	139	62	139
64	A3	A	Decreased amount of anchors in the continuous areas		x	x	2.50	1.25	4.17			62	193	62	193
65	A8	A	Decreased amount of anchors in the corner areas		x	x	1.67	1.33	2.50			62	138	62	138
66	A9	A	Usage of unsuitable anchor type		x	x	2.20	2.40	3.00			62	327	62	327
67	A2	A	Decreased diameter of anchor plate		x	x	1.33	1.00	5.25			61	82	61	82
68	A6	A	Anchor plate is installed too deeply into insulation material		x	x	2.40	1.00	3.75			62	148	62	148

Table 7. Data for equation (3)

Sequence	ID	Layer	Factor	ETICS 1	ETICS 2	ETICS 3	OV	DV	LP	EAV (Sim1)	ERPN (Sim1)	EAV (Sim2)	ERPN (Sim2)	EAV (Sim3)	ERPN (Sim3)
69	A7	A	Anchor plate is placed too high on the surface of insulation material		x	x	1.75	1.00	0.83			63	110	63	110
70	R1	R	External layer of the insulation plate is too smooth, reduced adhesion	x	x		2.00	3.00	2.13	62	374	62	374		
71	M1c	R	Unsuitable material storage conditions	x	x	x	1.00	3.00	0.67	63	188	63	188	63	188
72	M2c	R	The mixing procedures do not remove clots	x	x	x	1.20	2.20	0.67	63	166	63	166	63	166
73	M3c	R	High share of kneading water	x	x	x	1.80	2.20	0.75	63	248	63	248	63	248
74	M4c	R	Low share of kneading water	x	x	x	1.40	2.60	1.25	63	228	63	228	63	228
75	R6	R	Thin mortar layer	x	x	x	2.75	2.00	4.63	61	338	61	338	61	338
76	R2	R	Decreased overlap of the mesh	x	x	x	1.75	3.00	2.13	62	327	62	327	62	327
77	R3	R	Folded mesh	x	x	x	1.00	2.50	1.75	62	156	62	156	62	156
78	R4	R	Missing diagonal mesh	x	x	x	2.00	2.50	1.38	63	313	63	313	63	313
79	R5	R	Mesh not filled with mortar, placed on the edge of the layer	x	x	x	2.00	2.33	2.00	62	291	62	291	62	291
80	R7	R	Layer is not applied in wet to wet conditions	x	x	x	2.50	3.00	2.38	62	466	62	466	62	466
81	R8	R	Usage of not compatible mesh	x	x	x	1.40	3.00	6.88	61	255	61	255	61	255
82	M9c	R	Low temperature (freezing) during application and/or curing process	x	x	x	1.80	1.80	0.75	63	203	63	203	63	203
83	M10c	R	High temperature (hot) curing conditions	x	x	x	2.20	1.80	3.00	62	245	62	245	62	245
84	M11c	R	Low humidity (dry) curing conditions	x	x	x	2.00	1.50	0.75	63	188	63	188	63	188
85	M12c	R	Usage of winter mixtures during unsuitable weather conditions	x	x	x	1.00	3.00	4.50	61	184	61	184	61	184
86	X6	X	Shock resistance solution is not used (i.e. no double reinforcement mesh, corner details with metal or additional protective plate installed)	x	x	x	2.60	2.00	0.50	98	511	102	529	114	590
87	F2	F	Reinforcement mixture or primary coat is not cured	x	x	x	2.00	3.00	0.75	28	169	28	169	28	169
88	F1	F	Missing primer if required	x	x	x	1.40	2.20	1.00	28	86	28	86	28	86
89	M1d	F	Unsuitable material storage conditions	x	x	x	1.00	2.60	0.50	28	73	28	73	28	73
90	M2d	F	The mixing procedures do not remove clots	x	x	x	1.00	2.00	0.33	28	56	28	56	28	56
91	M3d	F	High share of kneading water	x	x	x	0.50	1.67	3.17	28	23	28	23	28	23
92	F3	F	Thick render layer/ differences in thickness	x	x	x	0.67	3.00	0.83	28	56	28	56	28	56
93	F4	F	Thin render layer	x	x	x	1.50	1.67	3.33	28	69	28	69	28	69
94	M9d	F	Low temperature (freezing) during application and/or curing process	x	x	x	1.50	1.00	0.50	28	42	28	42	28	42
95	M10d	F	High temperature (hot) curing conditions	x	x	x	2.20	1.40	0.83	28	87	28	87	28	87
96	M11d	F	Low humidity (dry) curing conditions	x	x	x	2.50	1.50	0.83	28	105	28	105	28	105
97	X1	X	Structural expansion joint is not installed/ finished properly	x	x	x	1.40	1.80	2.38	97	245	101	254	112	283
98	X2	X	Windowsill is not appropriately finished (i.e. curved upwards, proper sealants)	x	x	x	3.60	1.60	2.38	97	561	101	580	112	648
99	X3	X	Unsolved rainwater drainage (i.e. drainpipe or drip profiles not used)	x	x	x	3.00	1.20	2.17	97	351	101	363	113	405
100	X4	X	Fixed frame connection is not finished accurately (i.e. missing sealants)	x	x	x	3.20	1.80	1.88	98	562	101	582	113	649
101	X5	X	Roof edge covers are not installed correctly (i.e. vertical detail too short)	x	x	x	2.60	2.00	1.88	98	507	101	525	113	586
102	X7	X	Unfinished penetrations through the system (i.e. fixed without sealants)	x	x	x	3.40	1.20	2.50	97	397	101	411	112	458
103	X8	X	Unsuitable plinth detail solutions (i.e. incorrect fixing, overlapping of details)	x	x	x	2.60	1.40	1.50	98	356	101	368	113	411

Appendix 5

PUBLICATION III

Publication III

Sulakatko, V. (2018). Modelling the Technical-Economic Relevance of the ETICS Construction Process. Buildings, 8 (11).10.3390/buildings8110155.

buildings

MDPI

Article

Modelling the Technical–Economic Relevance of the ETICS Construction Process

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Received: 13 October 2018; Accepted: 3 November 2018; Published: 9 November 2018

Abstract: The increased number of energy efficiency requirements of the European Union has increased the renovation rate of apartment buildings. The external thermal insulation composite system (ETICS) is often used to upgrade the façade. However, the construction process shortcomings very often cause defects shortly after completion. This paper develops a technical–economic relevance assessment model of the onsite degradation factors for better quality assurance in an SME. The model quantifies the technical significance of the degradation factors along with the future repair costs. The technical severity of 103 factors is evaluated by 12 experts, and the data is validated with the Friedman's test. The occurrence ratio, detectability, and latency period are foreseen by five experts and validated with the Delphi technique. The results of the three sample simulations emphasize the activities during substrate preparation and application of adhesive as well as a base coat with reinforcement mesh. The application of a finishing coat and installation of insulation plates have less relevance. It is recommended to upskill the craftsmen in regard to working with mixtures as the shortcomings are covered simultaneously and the failure detection period is short. The measures to protect against external weather effects are recommended due to their relatively high impact. Half of the shortcomings appear during the first two years.

Keywords: construction management; construction technology; ETICS; risk management

1. Introduction

Reducing the energy consumption of the built environment is a topic that has been tackled by the European Commission in recent decades [1,2]. The increased number of energy efficiency requirements has increased the refurbishment rate of apartment buildings covered with an external thermal insulation composite system (ETICS) [3,4]. In Germany, Institut für Bauforschung [5] investigated the dwellings which did not achieve the expected energy efficiency expectations after refurbishment. The study found that the construction process activities are responsible for 66% of the cases of failure. Neumann [6], on the other hand, assumes that three-quarters of the failures due to on-site construction activities are avoidable. Defects caused during the construction process affect the performance of the system and incur financial consequences. As there are many requirements to be followed during the construction process, it is rational to focus on the activities which occur most often, are harder to detect, are technically more relevant, and will cause high repair costs in the future.

The results of the studies on technical [7] and economic relevance will be presented separately. The results of these individual studies have diverse recommendations due to the different components involved in the evaluation models. A single united model is essential to combine the perspectives and provide recommendations to the industry. This paper develops a common technical–economic relevance (TER) model which enables the onsite construction process activities of ETICS to be prioritized, taking into account a combination of aspects. The systematized framework quantifies and merges the qualitative technical experience of experts and time-dependent economic data.

The onsite activities of ETICS influence the deterioration in each stage of the application process. As each layer of the system has a different technical purpose, the significance to the system's performance is diverse. Regulation No. 305/2011 (Construction Products Regulation) [8] of the European Parliament and the European Council has set the general guidelines for building products, while the façade system-specific guidelines are presented in the European Technical Approval Guidelines for External Thermal Insulation Composite Systems with Rendering (ETAG 004) [9]. The documents describe the essential requirements that construction products and buildings need to meet during their economically reasonable working life. Much research in the field of ETICS observes the quality aspects in isolation, making a rational relevance comparison impossible. The case studies of deteriorations have been diagnosed in several books [6,10,11], as well as studied in the controlled environment laboratory [12–14]. These and many other studies reveal a number of possible causes which should be compared to a single system.

Skitmore and Marston [15] and Woodward [16] have argued that construction quality is correlated to its cost. The elimination of inadequacies during the construction process takes fewer resources and less effort in comparison to future repair activities. The developed economic relevance model developed in another research paper, based on the method of failure mode effects analysis (FMEA), evaluates the onsite inadequacies while considering their repair costs, occurrence probability, and detectability during the application process. The approach differs from the traditional FMEA model, as economic severity replaces technical severity. A similar approach has been used by Shafiee et al. [17], Rhee and Ishii [18], and Carmignani [19] to highlight the financial impact of the failures. The need to include other relevant components of the traditional risk assessment model is emphasized by Bowles [20]. He argues that the economic aspect is underrated and should be considered during decision-making. The FMEA model has been criticized due to the multiplication of variables on the equal scale by Pillay [21], Bowles [20], and Carmignani [19]. The main criticism concerns the need for weighting factors in the calculation, as detectability and occurrence are not as relevant and their impact should be reduced. Carmignani [19] and Bowles [20] additionally point out the inaccuracy of predicted future costs. It can be acquiesced that the costs may change due to economic and political as well as technological alterations. However, the developed method enables reapplication as relevant alterations occur.

This paper combines the four factors (technical severity, financial impact, occurrence, and detectability) into a merged assessment model. The interpretation of the results enables the quality to be improved through resource allocation during the construction process as the focus is set on highly relevant activities. This paper describes the framework of the model and the interaction of variables, as well as a selection of degradation factors for the simulations. The received weighted technical severity value (SV) and the economic risk priority number (ERPN) are visualized on a two-dimensional risk matrix to set the priorities of on-site activities. The model is tested on three simulations and the results are discussed.

Scope and Limitations

Construction products are rapidly improving as new construction technology emerges. The model is developed with the aim to quantify the relevance of onsite shortcomings of ETICS of existing dwellings. Therefore, the data collected for the simulation model concerns systems with the following characteristics:

- the subject is an existing multiapartment building;
- external walls are made out of masonry or prefabricated concrete panels;
- the fixing method is either purely bonded with adhesive or mechanically fixed with anchors and supplementary adhesive;
- reinforcement consists of base coat and fiberglass mesh;

- the thermal insulation product is made out of mineral wool or expanded polystyrene with a thickness from 150 mm to 250 mm;
- the study concerns the region of Estonia, which lies in zone Dfb (warm summer, fully humid, snow climate) according to the Köppen–Geiger map.

The simulations in this study concern three different project-based cost scenarios with the characteristics shown in Table 1.

Table 1. Characteristics of the simulations.

Simulation No.	ETICS Type	Insulation Type	Insulation Thickness	Fixing Method
Simulation 1	ETICS 1	Polystyrene	200 mm	Purely bonded kit
Simulation 2	ETICS 2	Polystyrene	200 mm	Mechanically fixed kit with supplementary adhesive
Simulation 3	ETICS 3	Mineral wool	200 mm	Mechanically fixed kit with supplementary adhesive

2. Materials and Methods

The technical–economic relevance (TER) model of ETICS is a complex system, which quantifies the technical severity as well as the future costs incurred by the shortcomings and considers the occurrence possibility along with detectability during the construction works. The framework of the model (Figure 1) visualizes the simplified interaction of the components included in the model, while the research design (Figure 2) visualizes the process of the model. This paper represents a further development in the research on technical severity [7] and economic risk assessment and approaches both aspects in a unified TER model.

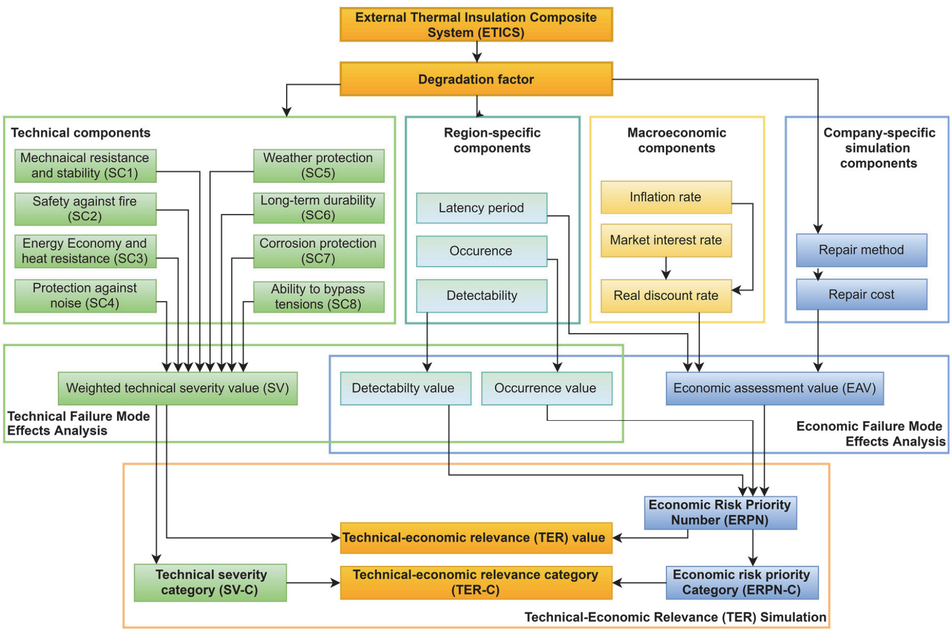


Figure 1. The framework of the technical–economic relevance (TER) model.

The research design is divided into eight phases, which are marked as grey areas in Figure 2. The model can be followed by individual companies to calculate firm-specific risks in the context of economic changes, seasonal influences, and other macroeconomic aspects.

Firstly, the scope of the system as well as specific limitations are to be set (phase 1). Then, the degradation factors are to be selected and described as a questionnaire (phase 2). This is followed by the selection of the experts (phase 3). To consider the economic aspects, the macroeconomic data needs to be extracted to discount the future costs and to specify the repair method (phase 4). The data collection and analysis is divided into two evaluations due to the difference in the nature of the data. The evaluation of technical aspects requires in-depth knowledge and understanding of the façade system (phase 5). The occurrence ratio, detectability, and latency period of the shortcoming is more region-, company-, and craftsmen-specific and concerns the forecasting as well as practical observations (phase 6). Historical cost data is company-specific and is extracted from similar construction projects described in the system's scope (phase 7). As all the data has been acquired (phase 8), the SV and ERPN position each degradation factor into a risk category and their TER value is calculated for ranking. This enables analysis of the results and the development of recommendations.

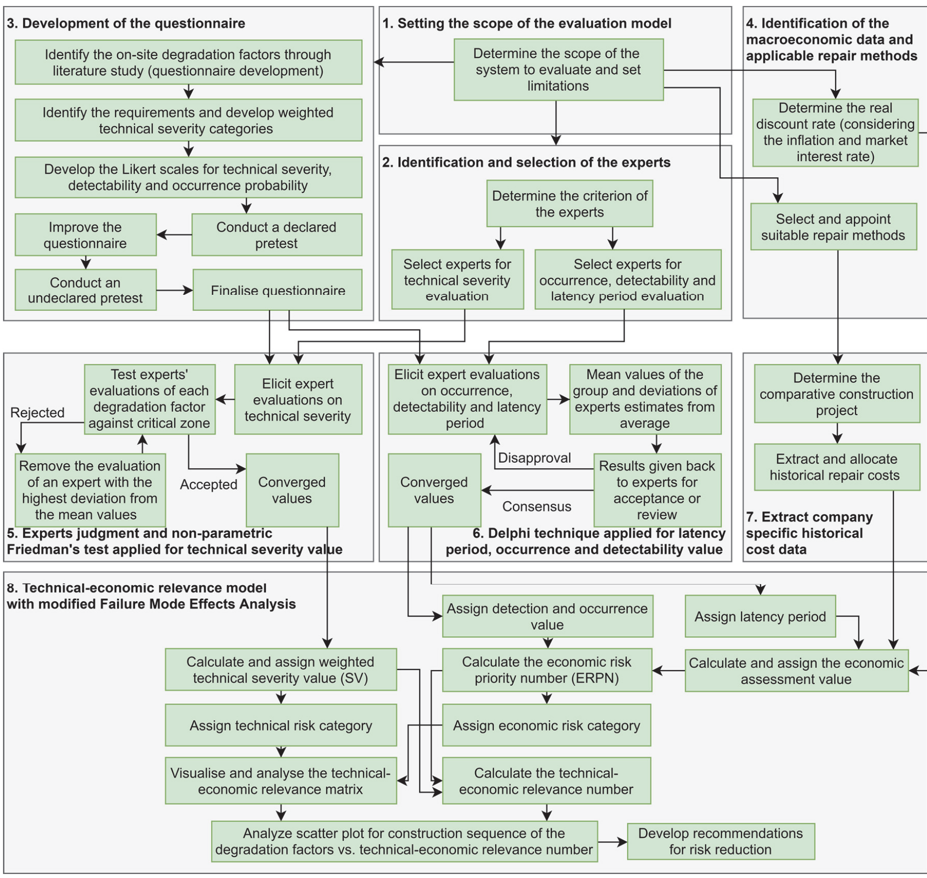


Figure 2. The research design of the technical–economic relevance (TER) model.

The subchapter of the research methods provides an overview of the methodology for the selection of degradation factors (Section 2.1) and experts as well as the construction company for historical data extraction (Section 2.2). The concepts concerning the SV are discussed in Section 2.3. The region-specific data (probability of the occurrence, detectability, and latency period) is discussed in Section 2.4, and the calculation of the ERPN is provided in Section 2.5. The final section presents the aggregation of all of the components as well as the categorization of the risk.

2.1. Onsite Degradation Factors of ETICS

The general requirements for ETICS are set by the European Technical Approval Guidance ETAG 004 [9] and are applicable for the material producers. Based on these requirements, the material producer provides installation guidelines and limitations according to their system specifications. These documents describe the set of requirements that the onsite activities must meet. During the onsite construction process, there are specific activities which are needed to achieve the finished end product. The list of degradation factors was developed through two stages—literature study and verification by two experts.

The list of shortcomings was formulated from descriptive instructions, recommendations, harmonized standards and set requirements [9,22–26], research regarding simulations or material studies conducted in laboratory conditions [12–14,27–51], field research [3–5,34,52–64], and books on the topic [6,10,11]. The selected factors were verified by two experts, who had more than 12 years' experience with ETICS. The reviews were conducted individually and independently, while the results of other evaluations were not revealed. One expert who verified the list was located in Germany and had a doctoral degree, while the second was located in Estonia and had a master's degree in the field of construction. Eleven irrelevant factors were removed from the further analysis, and the wording of 16 shortcomings was rephrased to reduce the illegibility and the suitability of the systems checked. The final list of selected degradation factors is presented in Appendix A.

2.2. Identification and Selection of the Experts and Characteristics of the Construction Company

There is no quantified data available on the research subject. Therefore, the expert's judgement was used in this study to collect subjective data. The selection of experts plays an essential role in the quality of the data [65]. The criteria for the selection of the experts were their in-depth knowledge and understanding of technical considerations of ETICS as well as practical onsite experience. According to Olson [66], variations across reviewers' backgrounds are allowed. In his study in the construction industry, Hallowell et al. [67] suggested that the identification of experts could be conducted through the membership of a nationally recognized committee or by the participation of similar studies. The expert should meet at least four of the following requirements:

- At least five years of professional experience in the construction industry;
- Tertiary education degree in the field of civil engineering or other related fields;
- Professional registration in the field of construction;
- Member or chair of a nationally recognized committee for ETICS;
- Writer or editor of a book or book chapter on the topic;
- A faculty member at an accredited institution of higher learning;
- Invited to present at a conference on the topic;
- The primary or secondary writer of at least three peer-reviewed journal articles.

As the model is developed for usage in small and medium enterprises (SME), it is expected that the number of experts will remain small. The most suitable number of panellists has not been determined in the literature. The size of the group depends on the availability of the experts, available resources and research topic [68]. In other research in the construction industry, a small number of experts is used in various studies. Studies have included 3 to 93 panellists in the construction industry [68]. Hallowell et al. [67] proposed a panel size of between 8 and 12 experts, while Rowe et al. [69] suggested including 5 or more experts on the panel and pointed out that there are "no clear distinctions in panel accuracy" when the panel size varies from 5 to 11 experts. Hence, for the user of the model, it is suggested to include at least 5 experts. Figure 3 visualizes the demographics of the experts involved in this study.

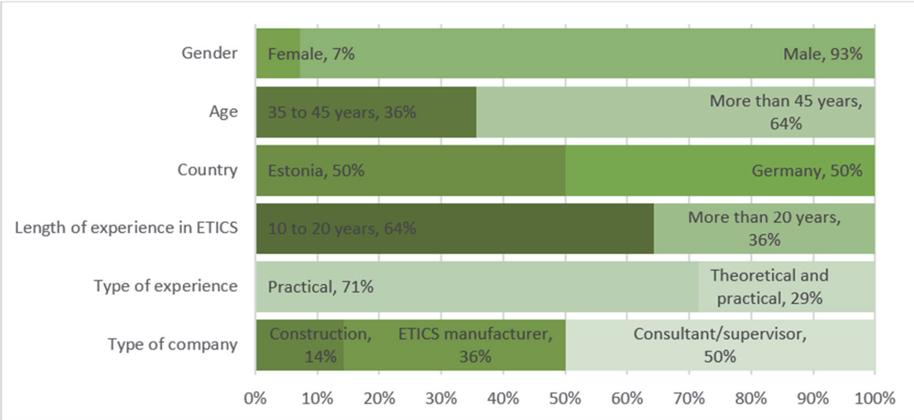


Figure 3. Demographics of the experts included in various areas of research.

For the simulations of the model, the historical cost data of a construction company was used. The construction company is located in Estonia and had specialized in façade construction for more than 15 years by the time the data was collected. The estimator who provided the data has more than 15 years' experience in the field of ETICS and has had tertiary education. For the user of the model, it is recommended to use company-specific cost data and extract the costs from recent construction projects.

2.3. *Weighted Technical Severity Value*

For the building products used in the European Union, the general international technical requirement is set by the Regulation (EU) No 305/2011 [8] (also Construction Products Regulation or CPR), which is the basis for the ETICS-specific guideline ETAG 004 [9]. The Construction Products Regulation presumes that buildings and construction products meet the performance requirements during their economically reasonable working life and describes seven essential requirements for the construction products.

"Mechanical resistance and stability" (SC1), "safety in case of fire" (SC2), "energy economy and heat retention" (SC3), and "protection against noise" (SC4) are considered in this study as described in the regulation. "Sustainable use of natural resources" is explained in ETAG 004 as measures of the "aspects of durability and serviceability", which concern durability in several aspects which are differentiated in this study. The system is required to protect against short-term weather effects ("humidity and weather protection" (SC5)), deliver its functions during the whole service life ("long-term durability" (SC6)), and be resistant to corrosion ("corrosion protection" (SC7)). "Safety in use" considers the resistance to combined stresses caused by normal loads. For clarity, in this research, the term "ability to bypass tensions" (SC8) is used. "Hygiene, health, and environment" considers the effect on the indoor and outdoor environment as well as pollution due to the release of dangerous substances, which is not seen as a separate severity category in this façade construction technology-related study.

Each degradation factor affects the performance of each severity category, which influences the total performance of the façade. Aurnhammer [70] has estimated technical defects concerning the diminishing of the value to the users. In the case of a shortcoming in any segment, the final resulting value decreases. The degradation severity is evaluated with a weighted impact method, in which all categories sum up to 100%, describing the total failure in each category. Based on the weighting method developed by Aurnhammer [70], the adjusted distribution (Figure 4) provides an evaluation model to calculate the SV.

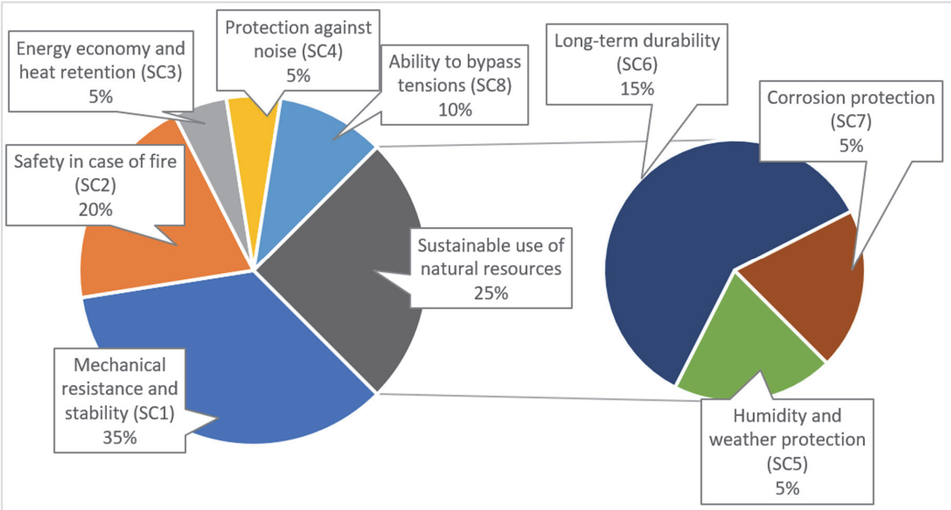


Figure 4. The weight distribution of the severity categories [7].

For the severity evaluation, the 6-point Likert scale is used to include the value of zero, which simplifies the interpretation of the cases where no influence is foreseen. The SV for each expert is calculated with Equation (1). The mean SV of all experts is the input value for TER calculation.

$$SV_{DF,e} = \sum\left(\frac{SR_{DF,SC,e}}{SR_{SC,max}} \times T_{SC}\right), \quad (1)$$

where

$SV_{DF,e}$ is the weighted technical severity value (SV) of an expert;
$SR_{DF,SC,e}$ is the individual rating of an expert for a severity category;
$SR_{SC,max}$ is the maximum rating value for the severity category;
T_{SC} is the weight of the severity category according to Figure 4.

The experts' judgments on technical severity were collected in 2016. Twelve experts out of the identified 14 accepted the invitation to participate in this study. Half of them were located in Germany and the other half in Estonia. Nine of the participants had practical experience and three of them also had theoretical experience. Eight experts had more than ten years of experience in the field, while four had more than 20 years of experience. Six participants worked as consultants or supervisors, four of them as technical specialists for a product manufacturer, and one in the construction company. The validity of severity values based on an expert's judgement was tested with the nonparametric Friedman's test, which increases the credibility of quantification of subjective evaluations [71,72]. The Friedman's test is used for each degradation factor separately to detect expert values which are in the critical zone. The 103 degradation factors concerned 991 individual evaluations. Fifty-three degradation factors received positive Friedman test results in the first analysis. Eighty-two individual evaluations were in the critical zone and a maximum of four rounds were applied. After the Friedman's test, the datasets concerned 4 to 12 experimental units.

2.4. Detectability, Occurrence, and Latency Period

For each degradation factor, the developed model requires data regarding detectability and occurrence probability, as well as the latency period for the discounting of repair costs. The latency period is a time range between the occurrence of the on-site shortcoming and the time when the degradation has evolved and requires repair activities. The occurrence probability measures how often the shortcomings occur, and detectability measures how difficult it is to notice the shortcoming during the construction works. As this study aims to identify the situation in Estonia, the Estonian experts were asked to participate in the region-specific data collection. Five of the seven Estonian experts agreed to participate in the survey conducted in 2018. All of them had between 10 and 20 years of practical experience in the field and tertiary education.

For the evaluation of detectability and occurrence probability, a 5-point Likert scale was used. The latency period was detected with the accuracy of one year. The data was collected using the Delphi technique, where independent and anonymous expert judgements are combined through mathematical aggregation [73]. The experts were asked to provide their evaluation individually and anonymously to each other. The responses from all experts were summarized and mean values calculated. The collective mean results were sent to all experts who were then asked to revise their evaluation or agree/disagree with the collective result. Three participants agreed with the collective results. Two experts reviewed the group results after a reminding phone call and stated their agreement with the consensus. Hallowell et al. [67] have described the "bandwagon effect", where decision-makers may feel pressure to confirm the opinion of a group. Due to the fast agreement with the consensus and to investigate whether there was the described effect, the team of experts was brought physically together. The highest and lowest evaluations were discussed with the group to check whether there were hidden assumptions. Positively, the consensus was not changed after the meeting. The primary reason was that the individual evaluations depend highly on the skills and experience of the expert and the results may vary. The data collection process was conducted in 2018. A more specific description of the method as well as the results are presented in other papers by the author [7].

2.5. Economic Risk Priority Number

The outcome of the economic relevance calculation for each degradation factor is the ERPN, calculated with Equation (2):

$$ERPN_{DF} = EAV_{DF} \times OV_{DF} \times DV_{DF}, \tag{2}$$

where

$ERPN_{DF}$ is the economic risk priority number (ERPN);
EAV_{DF} is the economic assessment value;
DV_{DF} is detectability;
OV_{DF} is the likelihood of occurrence.

An economic assessment value is developed to quantify future repair costs of specific degradation factors. In regard to the life cycle costing method, which reflects the expenses in each phase of the building [74], the current model focuses only on the future repair costs of the shortcoming of a construction process activity. The discounted repair costs are leveraged with the construction cost index for new residential buildings provided by Eurostat to maintain comparability during economic fluctuations. As the simulations in this model are based on the situation of Estonia, the construction cost index for quarter 4 in 2017 was 116.6% [75], considering the year 2010 as the reference year. The economic assessment value is calculated with Equation (3):

$$EAV_{DF} = \frac{NPV_{DF}}{CCI}, \tag{3}$$

where

EAV_{DF} is the economic assessment value;
NPV_{DF} is the discounted repair costs of a degradation factor;
CCI is the construction cost index.

The repair costs are the time-relevant component and are calculated with the net present value (NPV) method as shown in Equation (4):

$$NPV_{DF} = \frac{C_R}{(1+R_r)^{LP_{DF}}}, \quad (4)$$

where

NPV_{DF} is the net present value of the repair costs for a degradation factor;
R_r is the real discount rate per annum;
LP_{DF} is the latency period of a degradation factor;
C_R is the repair cost of the selected repair method.

The economic relevance model focuses on the features of the Estonian market. The real interest rate of 0.52% considers the inflation of 3.73% [76] and the average 5- to 10-year loan interest rate for entrepreneurs, which is 4.25% [77].

Professionals in the field [3,6,10,11,23,78] have thoroughly described the repair methods which are reliable to use for ETICS. To ensure comparability, the cost calculations examine the area of 1 m^2. The usage of industry data has provided valuable and more exact results in other studies [79]. Therefore, the cost data for the simulations is provided by an experienced professional from one active construction company and is based on the costs of projects simultaneously under construction from September 2017 until January 2018 in Estonia. The cost difference ratio to the initial construction cost of simulation 1 is shown in Table 2.

Table 2. The comparative ratio of initial construction and repair costs.

Description of Construction Work	Simulation 1	Simulation 2	Simulation 3
The initial construction ETICS	1.00	1.08	1.30
Replacement of insulation	1.74	1.80	2.01
Replacement of reinforcement layer	1.11	1.11	1.11
Replacement of finishing layer	0.50	0.50	0.50

2.6. Technical–Economic Relevance Value of the Degradation Factors

The discussed ERPN and SV are to be considered in one model. The traditional risk matrix concerns the likelihood of occurrence and consequence on the x- and y-axis. In this study, the consequence concerns the weighted technical severity impact of a degradation factor. However, there are more components considered on the other axis. It concerns the occurrence, detectability, and economic impact, which are combined into an ERPN. The risk matrix (Figure 5) positions each degradation factor in a risk category. The positioning of the matrix is in the Cartesian coordinate system, and the numerical values correspond to risk levels—a higher score means increased risk. This work is based on a 5 × 5 cell matrix, having 25 risk cells, as often used in research [80,81]. The 25 risk cell matrix is divided into three risk categories. The categories are described as follows: "low" is acceptable, no action required; "medium" is tolerable, additional action required; "high" is not acceptable, immediate action required.

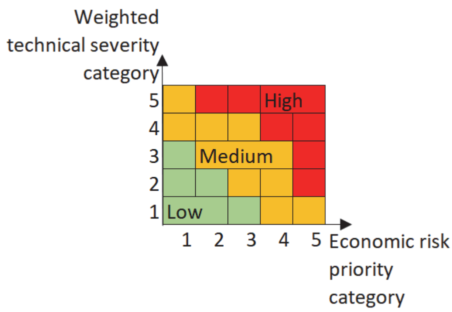


Figure 5. Relevance matrix.

As there are three risk categories, an additional ranking within a single risk category is required to prioritize the degradation factors to each other. Therefore, the degradation factor is also described with the TER value for further analysis with Equation (5).

$$TER_{DF} = SV_{DF} \times ERPN_{DF}, \tag{5}$$

where

TER_{DF} is the technical–economic relevance (TER) number;
SV_{DF} is the weighted technical severity value (SV);
$ERPN_{DF}$ is the economic risk priority number (ERPN).

The ERPN and SV are classified into five categories. Category 5 represents the highest economic or technical relevance, and category 1 the lowest. The highest value is the maximum value received during the evaluations, and other categories are distributed equally. For the conducted simulations, the maximum ERPN is 910.2, and the SV is 0.633. The evenly distributed category ranges are shown in Table 3.

Table 3. Categorization of the economic risk priority number (ERPN) and weighted technical severity values (SV).

Category	Risk Description	ERPN	SV
5	very high	$728.2 < ERPN_{DF} < 910.2$	$0.506 < SV_{DF} < 0.633$
4	high	$546.1 < ERPN_{DF} < 728.1$	$0.380 < SV_{DF} < 0.505$
3	medium	$364.2 < ERPN_{DF} < 546.1$	$0.253 < SV_{DF} < 0.379$
2	low	$182.0 < ERPN_{DF} < 364.1$	$0.127 < SV_{DF} < 0.252$
1	very low	$ERPN_{DF} < 182.0$	$SV_{DF} < 0.126$

3. The Technical–Economic Relevance of the Degradation Factors

The input values for the TER simulation are the SV and the ERPN, whose average impact by layers is shown in Figure 6. Higher value means higher relevance. The comparison shows which component influences the outcome and in which direction. As the components are described in more detail in other papers, the influence of the components is described only in layers in this paper.

The average SV is very high in the layer of reinforcement for all simulations. Simulation 1 has high values in the same range for the substrate and adhesive layers. The increased relevance of simulation 1 is caused by the fixing method (purely bonded), which emphasizes the degradation factors that decrease adherence properties. The lowest average SV is for a layer of insulation. In regard to the SV, it must be noted that the standard deviation is relatively high, meaning that the risk categorization should provide relevant information for better decision-making.

Economic relevance is highest in the substrate, adhesive, and additional details' layers. The main cause is the high repair costs, as the replacement of the whole system is considered. The detectability increased the relevance in the adhesive and reinforcement layers. These defects are covered at the same time as they occur, and problems can be identified only during the brief application period. The occurrence value was highest in the additional details' layer, followed by the substrate layer.

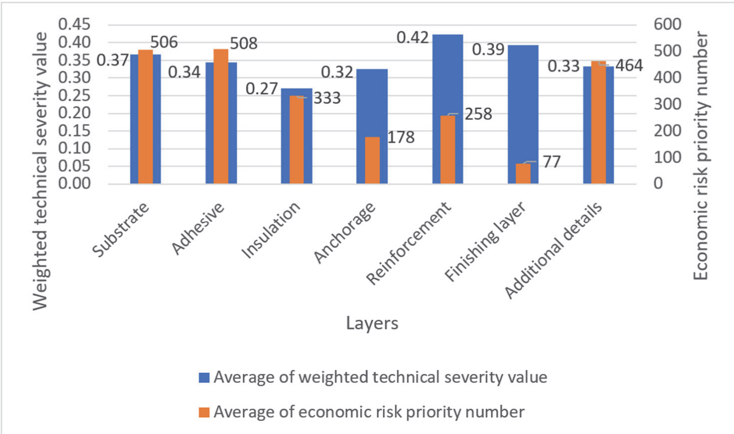


Figure 6. Average of the weighted technical severity value (SV) and economic risk priority number (ERPN) by layers.

The categorization distributes the degradation factors of the simulations into three risk categories, which are required to focus on the more relevant shortcomings. Figure 7 shows the share of degradation factors and their count in numbers. The visualization shows that the high category concerns 9% to 17% (7 to 12 factors) of the degradation factors, the medium category 65% to 74% (47 to 55 factors), and the low category 13% to 18% (9 to 15 factors).

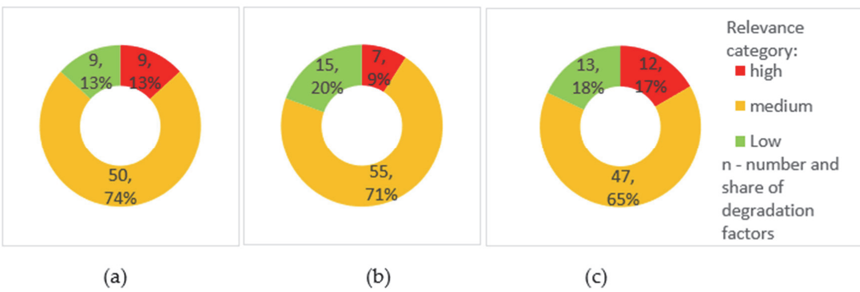
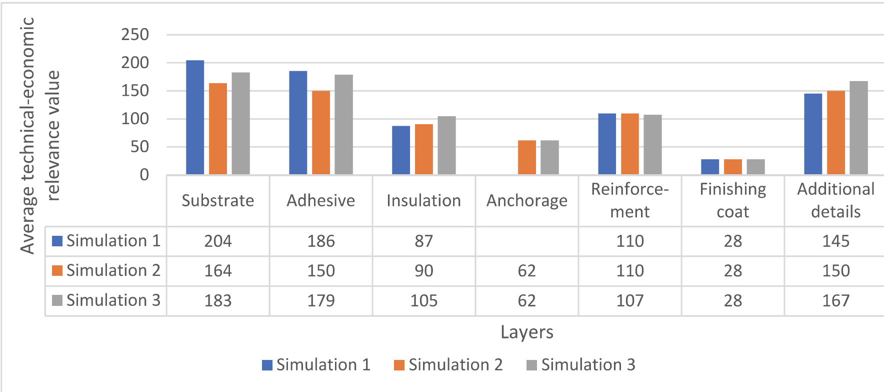


Figure 7. Number and share of degradation factors in risk categories for (**a**) simulation 1, (**b**) simulation 2, and (**c**) simulation 3.

For the analysis of the degradation factors within a single risk category, the product of the two variables, the TER value, is used. Figure 8 compares the average TER values of the simulations by layers. There are two main reasons behind the difference in values between the simulations in the substrate, adhesive, and additional details' layers. Simulation 1 describes the purely bonded ETICS with polystyrene as the insulation material, meaning that the adhesive layer has a higher significance for ensuring mechanical stability, thus increasing the SV. Simulation 3 refers to the ETICS with mineral wool, fixed with mechanical anchors and additional adhesive. The higher repair costs of the inner layers, where the whole system is to be replaced, increases the average ERPN. Simulation 2 has the lowest ERPN due to the lower cost of polystyrene plates, which are fixed with mechanical anchors and supplementary adhesive.



	Substrate	Adhesive	Insulation	Anchorage	Reinforce-ment	Finishing coat	Additional details
Simulation 1	204	186	87		110	28	145
Simulation 2	164	150	90	62	110	28	150
Simulation 3	183	179	105	62	107	28	167

Figure 8. Average technical–economic relevance (TER) value of the simulations by layers.

The TER model positions the degradation factors on the risk matrix as seen in Figure 9. For further analysis, the categories are discussed in the following groups:

- SV in category 5, ERPN in categories 2 to 5 (Risk1);
- ERPN value in category 5, SV in categories 2 to 5 (Risk2);
- ERPN and SV in category 4 (Risk3).
- Medium risk category
- Low risk category

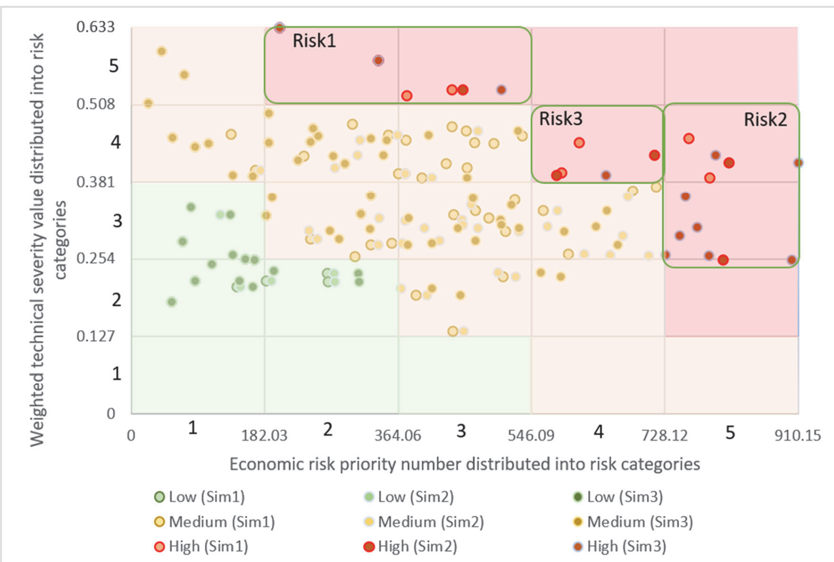


Figure 9. The positioning of the degradation factors' risk categories on the risk matrix.

"Risk1" is the group with the highest SV and concerns three unique degradation factors relevant for all simulations and one degradation factor relevant for simulation 1. The freezing of adhesive during the curing process (M9b), relevant for simulation 1, has a strong influence on the adhesion properties as the system is purely bonded. Other shortcomings relevant for all simulations concern the layer of reinforcement and insulation—continuous gaps between the substrate and adhesive which enable airflow in the system (I4), thin reinforcement mortar thickness (R6), and freezing of the reinforcement layer (M9c).

"Risk2" describes the degradation factors with the highest ERPN category and concerns eight shortcomings. All shortcomings in this group belong to the substrate and adhesive layers. Only one degradation factor belongs to simulation 1—substrate covered with old paint (S4b). All other factors belong to simulation 3, which is the expected result due to the higher repair cost of the mineral wool. The highest values have degradation factors which describe the low load-bearing capacity (S5a), coverage of the substrate with old or existing paint (S4a), and an insufficient amount of adhesive (D3a). The insufficient amount of adhesive received high values in the technical severity category of safety against fire, which is reduced due to possible airflow in the system. The other relevant factors influence mainly the stability of the system influenced by fixation—unleveraged adhesive on the mineral wool (D5), dry curing conditions of the cement-based adhesive (M11a), usage of unsuitable adhesive (S7a), and not pre-processed detached areas (S6a) are the other relevant shortcomings in this group.

Group "Risk3" describes the shortcomings in category 4 for both components. A relevant degradation factor for all simulations is the improperly finished windowsills, enabling moisture to penetrate into the system (X2). Other risks concern simulation 1 and simulation 2. They describe the works that decrease the adhesion properties—low humidity of the substrate (S8b), insufficient adhesive (D3b), problematic load-bearing capacity of the substrate (S5a), and reduced area of adhesive due to a lack of pressure applied during the attachment of insulation plates (D8b).

The medium-risk category has the largest amount of degradation factors. The degradation factors in the substrate, adhesive, and additional details' layers received the highest TER values. The highly relevant shortcomings in the substrate layer concern the preparation of the substrate surface—cleaning from biological growth (S3b), dust (S2b), and old paint (S4a), as well as problematic load-bearing capacity (S5b) and detached and unfilled areas of the surface (S6a). Additionally, the usage of an unsuitable adhesive type (S72, S7b) is relevant. The mixture preparation and curing conditions received higher TER values. Relevant are the low-humidity weather factors of the substrate (S8a), high temperature (M10b), and low relative humidity (M11a). For the application process, the exceeded working time of the mixture (D7a, D7b), high share of kneading water (M3b), and additional unsuitable ingredients (M8) are noted. The occasion when the adhesive is not applied on the border of the insulation plates (D1b) is relevant for simulations 1 and 2. The shortcomings during the application of additional details concern moisture penetration into the system through problematic fixed frame connections (X4) and penetrations into the system due to objects attached on the façade (X7).

The low-risk category concerns mainly the shortcomings in the layers of the finishing coat, insulation, and mechanical anchors. In the finishing layer, low relevance is set for the increased and decreased thickness of the applied mortar (F3, F4) and missing primer (F1). In the mechanical anchors layer, the highly or deeply placed anchor plates (A7, A6), wrong placement of the anchors in comparison to the manufacturer's recommendations (A5), as well as uncleaned anchor holes (A10) are noted as irrelevant. The shortcomings during the application of insulation plates show that the increased width of the neighbouring polystyrene insulation plates (I7), crossed joints (I5), broken and not filled polystyrene plates (I9), and missing fire-retardant areas if required (I10) are the least problematic (I10). The reason for their low values lies in the ERPN, as the defects are easily detectable and do not occur very often.

For further analysis, the TER values of the simulations are positioned in accordance with their sequence in the construction process in Figure 10. The circles around the degradation factors show their belonging to the risk category. The horizontal lines show the average TER values by layers; the groups with a green line are discussed more specifically. The figure shows that construction works have the highest relevance for simulation 1 in the substrate and adhesive layers, while in other layers, the impact is relatively similar to other simulations. This difference is mainly due to the fixation type, which increases the technical risk. The lowest risk can be noted for simulation 2, which concerns the insulation plates made out of polystyrene and fixed with mechanical anchors and supplementary adhesive. Simulation 3 is in between, with the exception of the work concerning additional details, which is marked as group TE9. Simulation 3 has a comparable average technical risk to simulation 2, but increased economic impact due to the higher cost of mineral wool as the insulation material.

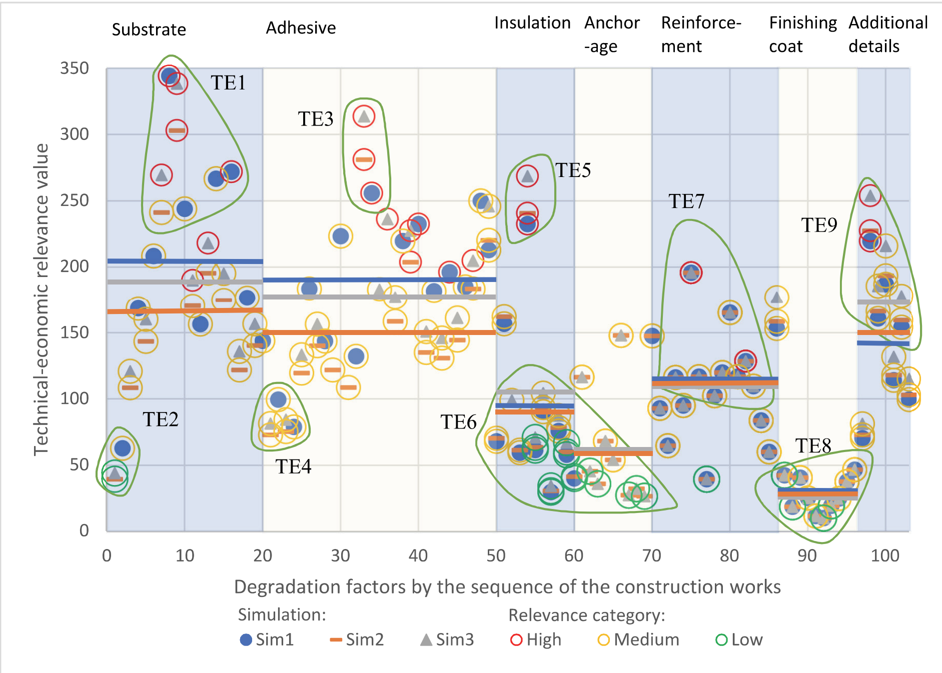


Figure 10. Technical–economic relevance (TER) values and risk categories of the degradation factors by the sequence of construction works.

The increased deviation between simulations is noticed within the substrate layer (group "TE1"). The group includes eight degradation factors in the substrate layer, of which four concern simulation 1. The common factors are the occasions when the substrate is covered with old paint and it reacts with adhesive (S4a, S4b) or is under the load-bearing capacity (S5a, S5b). Other highly relevant shortcomings are the very low humidity of the substrate (S8b), which is a risk in the curing process mainly for inorganic mixtures and unsuitable adhesive types (S7b). The low-relevance group "TE2" contains the shortcomings which concern the substrate coverage with oil (S1a, S1b). Although the factors of substrate covered with old paint (S4a and S4b) and substrate covered with dust or dirt (S1a and S1b) have the same technical effect on the system, the ERPN of the low relevance group is decreased substantially due to good detectability and low occurrence probability, which reduce the relevance value by more than five times.

The high relevance group "TE3" brings together the factors in the adhesive layer, concerning the application of insufficient adhesive (D3a, D3b) as well as missing adhesive in the centre (D2a) as insulation plates made out of polystyrene are applied. The differentiation from the average is caused by a high occurrence value. The low relevance group "TE4" describes wrong material storage conditions (M1a, M1b) and an insufficient mixing procedure which leaves clots in the mixture (M2a, M2b). In contrast to "TE3", the high deviation is due to a very low occurrence value. For the same reason, the group "TE5" differentiates from the average. The technical severity of the degradation factor from "TE5", which describes continuous gaps in the system due to the installation application (I4), is highly influenced by the effect of fire protection as the requirement is highly influenced by airflow within the system.

The groups "TE6" and "TE8" include a number of factors which have a negative deviation from the trendline. The groups include the majority of degradation factors in the insulation, mechanical anchors, and finishing layers. The degradation factors in the reinforcement layer (group "TE7") have a positive deviation, but the values remain in the middle area compared to all factors. The degradation factors that occur during the installation of additional details (group "TE9") received relatively high values. Problematic are the windowsills (X2) and fixed frame connections (X4), as well as unfinished penetrations through the system when objects are added on the surface of the system (X7). The value of the failures in this group is increased due to the high occurrence rate.

4. Implications of the Latency Period on the Decision-Making Process

The stakeholders in the construction process should reduce the occurrence of degradation factors for a better overall outcome. However, the economic reasonability of resource allocation is influenced by the contractual defect liability period, which is, by law, two years in many cases.

The latency distribution of the degradation factors shows that the majority of shortcomings appear after the two years of construction for the systems attached to mechanical anchors (simulations 1 and 2), while the majority of the shortcomings for the purely bonded system appear during the first 2 years (simulation 3). Figure 11 presents the distribution of the shortcomings according to the latency period. Simulations 1 and 2 have more degradation factors with the high- and medium-risk categories, which appear after the latency period of two years.

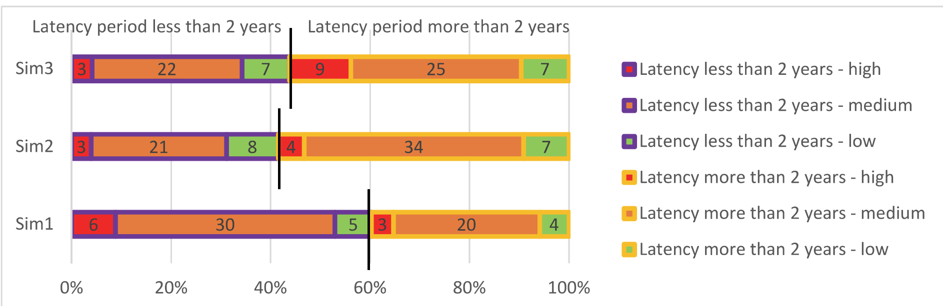
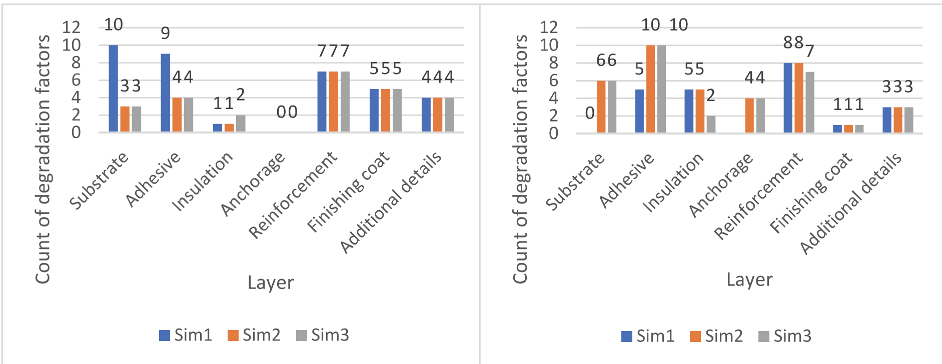


Figure 11. Count and share of degradation factors distributed by the 2-year latency period and risk category.

In order to take a closer look, the high- and medium-risk category degradation factors have been differentiated by layers and a 2-year liability period in Figure 12. The latency period of the shortcomings in the substrate and adhesive layers for the purely bonded system (simulation 1) differentiate from the other simulations—19 factors out of 24 appear during the first two years after construction. This means that the adhesion properties are more relevant to the contractor and problems show visible signs of deterioration during the short period after application. Additionally, in the finishing layer, five of six relevant shortcomings appear during the two-year period in all simulations. These defects are technically less relevant, but are visibly detectable and occur quite often. Especially in these layers, the legal liability is covered by the contractor.



(**a**) (**b**)

Figure 12. Distribution of the high- and medium-risk category degradation factors by layer and by latency period of (**a**) less than two years and (**b**) equal to or more than two years.

5. Conclusions and Suggestions

The increased number of energy efficiency requirements have increased the refurbishment rate of apartment buildings covered with an external thermal insulation composite system (ETICS). The majority of visible defects in the years following completion are caused by shortcomings during the construction process. To avoid failures, quality control should focus on the factors which have increased technical relevance as well as financial impact.

The technical–economic relevance (TER) model expands the traditional FMEA approach by adding the impact of future costs caused by the shortcomings of technical severity, detectability, and occurrence of the failure. The model evaluates and differentiates the significant onsite construction activities in terms of system type for more rational resource allocation and is also suitable for small- and medium-sized enterprises. The model was tested on three simulations which quantify the onsite degradation factors of ETICS.

In this study, 103 degradation factors were evaluated through expert judgment. The data was validated with the Delphi technique and nonparametric Friedman's test. Cost data for three simulations was received from one active company from the industry. The results emphasize the relevance of onsite activities during substrate preparation and the application of adhesive and a base coat with reinforcement mesh. Less relevance is assigned to the activities during the application of a finishing coat and installation of insulation plates.

According to the results of this study, the following onsite aspects should be considered to increase the quality of the façade system:

1. The shortcomings during the preparation of the substrate and application of adhesive have a very high impact on the technical severity as well as a fatal outcome on the system as the critical limit is exceeded. The possible high cost of replacement should be replaced by an increase in the quality and more careful inspection during the application process. The majority of the shortcomings of the purely bonded system appear in the two years following construction.
2. The frequently occurring and systematic problems occur due to the installation of additional details, such as windowsills, connections between fixed frames and ETICS, and other penetrations through the system. These defects cause significant technical degradation as well as having high repair costs. It is suggested to reduce the moisture penetration into the systems.
3. The weather-related degradation factors are relevant for most of the layers which concern mixtures. Freezing or drying out of the mixtures, as well as high humidity remaining in the system, have a relatively high impact on the technical outcome. Good climate through coating as well as temperature and humidity control are highly recommended.
4. During the application of the adhesive and reinforcement layers, the shortcomings will be covered simultaneously, which makes it difficult to detect and repair the mistakes during the process. The habits and working methods of individual artisans have a high impact as the activities are repeated. To avoid the shortcomings in these layers, the upscaling of skills and work methods is highly suggested.

The simulations have provided logical results and are relevant to the decision-making process. For more specific modelling, a sublevel of onsite activities could be applied in future studies. For example, the mixtures can be differentiated by their nature and ingredients, which are only partially observed in this research. The construction process shortcomings have different severity impacts on various mixture types. Additionally, the additional details in this study are only generally described. It would be worthwhile to select specific solutions for additional details and develop their degradation factors in a more specific manner.

Funding: This work was supported by institutional research funding of the Estonian Ministry of Education and Research IUT1−15: "Nearly-zero energy solutions and their implementation on deep renovation of buildings".

Acknowledgments: The author would like to show their gratitude to the experts from Germany and Estonia, as well as the participating construction companies who shared their experience and knowledge during this research.

Conflicts of Interest: The author declares no conflict of interest.

Appendix A

Table A1. Data (1).

Sequence	ID	Layer	Factor	SV	SV-C	ERPN (Sim1)	ERPN-C (Sim1)	TER (Sim1)	TER-C (Sim1)	ERPN (Sim2)	ERPN-C (Sim2)	TER (Sim2)	TER-C (Sim2)	ERPN (Sim3)	ERPN-C (Sim3)	TER (Sim3)	TER-C (Sim3)
1	S1a	S	Substrate is covered with grease or oil	0.327	3					121	1	40	Low	135	1	44	Low
2	S1b	S	Substrate is covered with grease or oil	0.460	4	137	1	63	Med.								
3	S2a	S	Substrate is covered with dust or dirt	0.320	3					339	2	109	Med.	378	3	121	Med.
4	S2b	S	Substrate is covered with dust or dirt	0.449	4	375	3	169	Med.								
5	S3a	S	Substrate is covered with biological growth	0.318	3					451	3	144	Med.	504	3	160	Med.
6	S3b	S	Substrate is covered with biological growth	0.445	4	468	3	209	Med.								
7	S4a	S	Substrate is covered with paint or other material which can chemically react with adhesive	0.356	3					678	4	241	Med.	756	5	269	High
8	S4b	S	Substrate is covered with paint or other material which can chemically react with adhesive	0.452	4	762	5	344	High								
9	S5a	S	Substrate is under the required load-bearing capacity	0.425	4					714	4	303	High	797	5	338	High
10	S5b	S	Substrate is under the required load-bearing capacity	0.457	4	534	3	244	Med.								
11	S6a	S	Substrate has large unevenness or has detached areas	0.261	3					653	4	170	Med.	729	5	190	High
12	S6b	S	Substrate has large unevenness or has detached areas	0.333	3	470	3	157	Med.								
13	S7a	S	Unsuitable surface (too smooth) which reduces adhesion properties	0.292	3					670	4	196	Med.	748	5	218	High
14	S7b	S	Unsuitable surface (too smooth) which reduces adhesion properties	0.373	3	716	4	267	Med.								
15	S8a	S	Substrate has very low humidity (inorganic adhesive)	0.308	3					568	4	175	Med.	634	4	195	Med.
16	S8b	S	Substrate has very low humidity (inorganic adhesive)	0.445	4	611	4	272	High								
17	S9a	S	Substrate is very wet (raining prior to application of adhesive)	0.305	3					400	3	122	Med.	446	3	136	Med.
18	S9b	S	Substrate is very wet (raining prior to application of adhesive)	0.411	4	430	3	177	Med.								
19	S10a	S	Substrate is frozen during the application (inorganic adhesive)	0.450	4					312	2	140	Med.	348	2	157	Med.
20	S10b	S	Substrate is frozen during the application (inorganic adhesive)	0.476	4	302	2	144	Med.								
21	M1a	D	Unsuitable mixture storage conditions	0.301	3					243	2	73	Med.	271	2	82	Med.

Table A2. Data (2).

Sequence	ID	Layer	Factor	SV	SV-C	ERPN (Sim1)	ERPN-C (Sim1)	TER (Sim1)	TER-C (Sim1)	ERPN (Sim2)	ERPN-C (Sim2)	TER (Sim2)	TER-C (Sim2)	ERPN (Sim3)	ERPN-C (Sim3)	TER (Sim3)	TER-C (Sim3)
22	M1b	D	Unsuitable mixture storage conditions	0.424	4	235	2	100	Med.								
23	M2a	D	The mixing procedures do not remove clots	0.206	2					368	3	76	Med.	411	3	84	Med.
24	M2b	D	The mixing procedures do not remove clots	0.259	3	305	2	79	Med.								
25	M3a	D	High share of kneading water	0.284	3					421	3	120	Med.	469	3	134	Med.
26	M3b	D	High share of kneading water	0.351	3	523	3	184	Med.								
27	M4a	D	Low share of kneading water	0.310	3					453	3	140	Med.	505	3	157	Med.
28	M4b	D	Low share of kneading water	0.327	3	439	3	144	Med.								
29	D1a	D	Missing adhesive on the edges of insulation (polystyrene)	0.404	4					302	2	122	Med.				
30	D1b	D	Missing adhesive on the edges of insulation (polystyrene)	0.472	4	474	3	223	Med.								
31	D2a	D	Missing adhesive in the center of insulation (polystyrene)	0.317	3					343	2	109	Med.				
32	D2b	D	Missing adhesive in the center of insulation (polystyrene)	0.396	4	334	2	132	Med.								
33	D3a	D	Insufficient adhesive surface area	0.414	4					680	4	281	High	758	5	314	High
34	D3b	D	Insufficient adhesive surface area	0.389	4	658	4	256	High								
35	D4	D	Adhesive is not rubbed into the insulation plate (mineral wool)	0.276	3									664	4	183	Med.
36	D5	D	Adhesive is not treated with notch towel (mineral wool)	0.306	3									772	5	236	High
37	D7a	D	Working time of the adhesive is exceeded	0.342	3					464	3	159	Med.	518	3	177	Med.
38	D7b	D	Working time of the adhesive is exceeded	0.445	4	495	3	220	Med.								
39	D8a	D	Low pressure during the application of insulation plates	0.253	2					807	5	204	High	901	5	228	High
40	D8b	D	Low pressure during the application of insulation plates	0.397	4	587	4	233	High								
41	D9a	D	Large unevenness of the adhesive layer	0.231	2					585	4	135	Med.	653	4	151	Med.
42	D9b	D	Large unevenness of the adhesive layer	0.320	3	569	4	182	Med.								
43	M9a	D	Low temperature (freezing) during application and/or curing process	0.425	4					308	2	131	Med.	344	2	146	Med.
44	M9b	D	Low temperature (freezing) during application and/or curing process	0.523	5	376	3	196	High								
45	M10a	D	High temperature (hot) during the curing process	0.305	3					474	3	144	Med.	528	3	161	Med.
46	M10b	D	High temperature (hot) during the curing process	0.405	4	458	3	185	Med.								
47	M11a	D	Low humidity (dry) during the curing process	0.260	3					706	4	184	Med.	788	5	205	High

Table A3. Data (3).

Sequence	ID	Layer	Factor	SV	SV-C	ERPN (Sim1)	ERPN-C (Sim1)	TER (Sim1)	TER-C (Sim1)	ERPN (Sim2)	ERPN-C (Sim2)	TER (Sim2)	TER-C (Sim2)	ERPN (Sim3)	ERPN-C (Sim3)	TER (Sim3)	TER-C (Sim3)
48	M11b	D	Low humidity (dry) during the curing process	0.366	3	684	4	250	Med.								
49	M8	D	Not recommended ingredients added to the mixture	0.466	4	457	3	213	Med.	473	3	220	Med.	528	3	246	Med.
50	I1	I	Polystyrene is exposed to UV radiation for an extended period	0.401	4	170	1	68	Med.	176	1	71	Med.				
51	I2	I	Insulation plates installed shortly after manufacturing (unfinished diffusion)	0.263	3	597	4	157	Med.	618	4	162	Med.				
52	I3a	I	Mineral wool insulation plates have very high relative humidity (wet)	0.304	3									326	2	99	Med.
53	I3b	I	Insulation plates have very high relative humidity (wet)	0.136	2	438	3	60	Med.	454	3	62	Med.				
54	I4	I	Continuous gaps between the substrate and insulation material	0.532	5	437	3	233	High	453	3	241	High	505	3	269	High
55	I5	I	Corners of neighboring insulation plates are crossed or too close	0.230	2	268	2	62	Low	277	2	64	Low	309	2	71	Low
56	I6	I	Corners of the openings have crossed joints	0.277	3	327	2	91	Med.	338	2	94	Med.	377	3	105	Med.
57	I7	I	Insulation plates' joint width of neighboring insulation plates is too wide	0.208	2	144	1	30	Low	149	1	31	Low	167	1	35	Low
58	I8	I	Large height difference between neighboring insulation plates	0.195	2	389	3	76	Med.	403	3	79	Med.	449	3	88	Med.
59	I9	I	Broken areas of the insulation plates are not filled with the same material	0.217	2	268	2	58	Low	278	2	60	Low	310	2	67	Low
60	I10	I	Missing or narrow fire-retardant areas	0.218	2	184	2	40	Low	191	2	42	Low				
61	A1	A	Increased diameter of the drilled anchor hole	0.423	4					275	2	117	Med.	275	2	117	Med.
62	A10	A	Hole of the anchor is not cleaned	0.235	2					195	2	46	Low	195	2	46	Low
63	A5	A	Location of anchors is not as foreseen	0.261	3					139	1	36	Low	139	1	36	Low
64	A3	A	Decreased amount of anchors in the continuous areas	0.355	3					193	2	68	Med.	193	2	68	Med.
65	A8	A	Decreased amount of anchors in the corner areas	0.392	4					138	1	54	Med.	138	1	54	Med.
66	A9	A	Usage of unsuitable anchor type	0.452	4					327	2	148	Med.	327	2	148	Med.
67	A2	A	Decreased diameter of the anchor plate	0.338	3					82	1	28	Low	82	1	28	Low
68	A6	A	Anchor plate is installed too deeply into the insulation material	0.219	2					148	1	32	Low	148	1	32	Low
69	A7	A	Anchor plate is placed too high on the surface of the insulation material	0.246	2					110	1	27	Low	110	1	27	Low
70	R1	R	External layer of the insulation plate is too smooth, reducing adhesion	0.395	4	374	3	148	Med.	374	3	148	Med.				

Table A4. Data (4).

Sequence	ID	Layer	Factor	SV	SV-C	ERPN (Sim1)	ERPN-C (Sim1)	TER (Sim1)	TER-C (Sim1)	ERPN (Sim2)	ERPN-C (Sim2)	TER (Sim2)	TER-C (Sim2)	ERPN (Sim3)	ERPN-C (Sim3)	TER (Sim3)	TER-C (Sim3)
71	M1c	R	Unsuitable material storage conditions	0.494	4	188	2	93	Med.	188	2	93	Med.	188	2	93	Med.
72	M2c	R	The mixing procedures do not remove clots	0.391	4	166	1	65	Med.	166	1	65	Med.	166	1	65	Med.
73	M3c	R	High share of kneading water	0.469	4	248	2	116	Med.	248	2	116	Med.	248	2	116	Med.
74	M4c	R	Low share of kneading water	0.418	4	228	2	95	Med.	228	2	95	Med.	228	2	95	Med.
75	R6	R	Thin mortar layer	0.580	5	338	2	196	High	338	2	196	High	338	2	196	High
76	R2	R	Decreased overlap of the mesh	0.358	3	327	2	117	Med.	327	2	117	Med.	327	2	117	Med.
77	R3	R	Folded mesh	0.254	3	156	1	40	Low	156	1	40	Low	156	1	40	Low
78	R4	R	Missing diagonal mesh	0.328	3	313	2	103	Med.	313	2	103	Med.	313	2	103	Med.
79	R5	R	Mesh not filled with mortar, placed on the edge of the layer	0.413	4	291	2	120	Med.	291	2	120	Med.	291	2	120	Med.
80	R7	R	Layer is not applied in wet-to-wet conditions	0.354	3	466	3	165	Med.	466	3	165	Med.	466	3	165	Med.
81	R8	R	Usage of incompatible mesh	0.458	4	255	2	117	Med.	255	2	117	Med.	255	2	117	Med.
82	M9c	R	Low temperature (freezing) during application and/or curing process	0.633	5	203	2	129	High	203	2	129	High	203	2	129	High
83	M10c	R	High temperature (hot) curing conditions	0.447	4	245	2	110	Med.	245	2	110	Med.	245	2	110	Med.
84	M11c	R	Low humidity (dry) curing conditions	0.446	4	188	2	84	Med.	188	2	84	Med.	188	2	84	Med.
85	M12c	R	Usage of winter mixtures during unsuitable weather conditions	0.326	3	184	2	60	Med.	184	2	60	Med.	184	2	60	Med.
86	X6	X	Shock resistance solution is not used (i.e., no double reinforcement mesh, corner details with metal or additional protective plate installed)	0.300	3	511	3	153	Med.	529	3	159	Med.	590	4	177	Med.
87	F2	F	Reinforcement mixture or primary coat is not cured	0.252	2	169	1	43	Low	169	1	43	Low	169	1	43	Low
88	F1	F	Missing primer if required	0.219	2	86	1	19	Low	86	1	19	Low	86	1	19	Low
89	M1d	F	Unsuitable material storage conditions	0.557	5	73	1	41	Med.	73	1	41	Med.	73	1	41	Med.
90	M2d	F	The mixing procedures do not remove clots	0.454	4	56	1	26	Med.	56	1	26	Med.	56	1	26	Med.
91	M3d	F	High share of kneading water	0.510	5	23	1	12	Med.	23	1	12	Med.	23	1	12	Med.
92	F3	F	Thick render layer/differences in thickness	0.183	2	56	1	10	Low	56	1	10	Low	56	1	10	Low
93	F4	F	Thin render layer	0.283	3	69	1	20	Low	69	1	20	Low	69	1	20	Low
94	M9d	F	Low temperature (freezing) during application and/or curing process	0.595	5	42	1	25	Med.	42	1	25	Med.	42	1	25	Med.

Table A5. Data (5).

Sequence	ID	Layer	Factor	SV	SV-C	ERPN (Sim1)	ERPN-C (Sim1)	TER (Sim1)	TER-C (Sim1)	ERPN (Sim2)	ERPN-C (Sim2)	TER (Sim2)	TER-C (Sim2)	ERPN (Sim3)	ERPN-C (Sim3)	TER (Sim3)	TER-C (Sim3)
95	M10d	F	High temperature (hot) curing conditions	0.439	4	87	1	38	Med.	87	1	38	Med.	87	1	38	Med.
96	M11d	F	Low humidity (dry) curing conditions	0.445	4	105	1	47	Med.	105	1	47	Med.	105	1	47	Med.
97	X1	X	Structural expansion joint is not installed/finished properly	0.288	3	245	2	71	Med.	254	2	73	Med.	283	2	81	Med.
98	X2	X	Windowsill is not appropriately finished (i.e., curved upwards, proper sealants)	0.392	4	561	4	220	High	580	4	228	High	648	4	254	High
99	X3	X	Unsolved rainwater drainage (i.e., drainpipe or drip profiles not used)	0.459	4	351	2	161	Med.	363	2	166	Med.	405	3	186	Med.
100	X4	X	Fixed frame connection is not finished accurately (i.e., missing sealants)	0.333	3	562	4	187	Med.	582	4	194	Med.	649	4	216	Med.
101	X5	X	Roof edge covers are not installed correctly (i.e., vertical detail too short)	0.225	2	507	3	114	Med.	525	3	118	Med.	586	4	132	Med.
102	X7	X	Unfinished penetrations through the system (i.e., fixed without sealants)	0.389	4	397	3	154	Med.	411	3	160	Med.	458	3	178	Med.
103	X8	X	Unsuitable plinth detail solutions (i.e., incorrect fixing, overlapping of details)	0.280	3	356	2	100	Med.	368	3	103	Med.	411	3	115	Med.

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