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Methodological framework to assess the significance of External Thermal Insulation Composite System (ETICS) on-site activities

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Abstract

European climate strategy foresees measures to increase energy efficiency, competitiveness and the energy security of Europe by decreasing energy consumption. As buildings are responsible for 40% of the total energy consumption in the European Union, the Energy Performance of Buildings Directive sets energy consumption reduction targets for the member states. The rapidly increasing market for energy efficient buildings favours External Thermal Insulation Composite System (ETICS) usage in Europe. From the consumers' perspective the use of this façade system provides high thermal resistance and can be applied externally relatively fast with simple work methods.
The façade system and each component of it need to meet specific technical performance criteria. The on-site construction process has the ability to modify technical performances with minor actions like mixing time, kneading water, insulation fixation, weather conditions, material moisture level and curing time. Minor deviations during construction can cause a variety of adverse consequences which lead to deterioration and reduced energy efficiency. The current paper proposes a methodology to rank the on-site degradation factors and provide a risk priority number. Based on the technical requirements set for building products, the significance of the collected degradation factors can be ranked by experts and the results ranked using a modified form of Failure Mode Effects Analysis (FMEA). The methodology provides a significance assessment tool to identify degradation factors in the construction phase.

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Keywords: External Thermal Insulation Composite System; ETICS; Construction Technology; FMEA

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1. Introduction

The rapidly increasing demand for high energy efficiency buildings favours the use of ETICS in Europe. It is one of the options for existing and new buildings to improve thermal resistance and provide a protective shell to the exterior wall. Although the system has many advantages, the outcome and long-term performance characteristics can be influenced during the construction phase. The causes of degradation can lie in poor design, unsuitable building materials or construction technology inadequacies. These problems have caught the researchers' attention. However, different aspects which lead to decreased technical performance have been studied in isolation, and there is no existing knowledge concerning which processes of on-site construction activities have greater impacts on the lifetime of the façade.

The study proposes a methodology to rank the construction technology activities. The intention is to rate the relevance of each Degradation Factor (DF) according to its technical significance, the probability of occurrence and possibility of detection. By revealing the effect of on-site activities, it would be possible to avoid mistakes during the construction process which lead to failure of the building envelope. The developed tool enables clients, supervisors, and builders to focus their attention on the most relevant on-site activities to increase the long-term economic and social benefits.

2. Framework development procedure

The proposed framework relates specific technical requirements of ETICS to on-site DFs, enabling the severity and relevance of on-site activities to be determined. The influence of each essential technical requirement is prioritized and defined as an element of a problem tree with a weighted impact. Besides technical severity, the risk is altered by the frequency of occurrence and the possibility of detecting the shortcoming during the construction phase. To combine and analyze the modifiers, a Failure Mode Effects Analysis (FMEA) is applied with non-parametric testing. To test the methodology, the ratings from three experts are collected and analyzed. The results enable the relevance of selected DFs to be identified and ranked.

3. Requirements set for the system

On-site construction technology is guided by compulsory technical requirements which are set for the system's performance or for the construction process. Previous work by the authors [1] has revealed that there are three main types of regulations that cover the on-site construction process: legal acts; national, EU and harmonized standards and commonly used producers' certificates and descriptive guidelines. The quality of on-site process activities cannot be measured on the basis of the compulsory legislative materials for the construction process, as they are too general. However, there are requirements set for the building and for building products. The European Council Directive 89/106/EEC [2] presumes that construction products meet the performance requirements during their service life. The following six essential requirement groups are set for the products: "mechanical resistance and stability", "safety in case of fire", "energy economy and heat retention", "protection against noise", "hygiene, health and environment" and "safety in use" [2]. Based on these general requirements, the European Organisation for Technical Approvals has published specific guidelines in ETAG 004 [3] for construction product manufacturers of ETICS, which set specific and measurable performance requirements for the system and its components. In addition to the essential requirements identified above, corrosion protection and ability to bypass tensions are stated as critical functions of the facade system for building renovation [4]. In this research, the evaluation of essential requirements is described based on these eight categories.

3.1. Mechanical resistance and Stability

Mechanical resistance and stability (i) is one of the most important functions of the building. The load bearing construction and the system itself need to bear the dead load of ETICS, be resistant to wind suction and pressure, able to bear stresses caused by material shrinkage occurring in the drying-out phase and to resist mechanical impact [4].

The system needs to be resistant to stresses occurring due to natural weathering factors like daily and yearly temperature and humidity changes, solar radiation and freeze-thaw cycles [5].

3.2. Humidity and weather protection

Humidity and weather protection (ii) is one of the functions of the external shell of the building. The applied system needs to be resistant to condensation, wind driven rain and splashing water. The requirements are set for water absorption and water vapour permeability [3].

3.3. Noise protection

The requirements for external noise protection (iii) depend on the type of building. The load bearing construction and ETICS influence the noise resistance of the external wall. Although there are no requirements set for ETICS [3], the more exact calculations take into account the influence of anchors, area of adhesive, materials properties and resonance frequency.

3.4. Safety in case of fire

Safety in case of fire (iv) is regulated with material properties. In the case of an outbreak of fire, the facade needs to hold load bearing capacity for a specific time and limit the spread of fire and smoke. Material properties are specified with flammability, smoke emission and dripping of burning material. The performance levels are specified in national regulations and laws. The construction areas should be separated into sections to stop the spread of fire. These are built with non-flammable materials (i.e. mineral wool).

3.5. Thermal resistance

Thermal resistance (v) is one of the most important parameters for the owner of the building. The thermal conductivity can be proven with calculations and simulations during the design phase and is based on the properties of the structure and the construction materials. Additionally, construction quality affects the thermal performance of the system. This can be determined with thermal cameras after construction.

3.6. Long term durability

It is expected that the installed façade has long term durability (vi). Specific construction product requirements are set for the reinforcement layer (usually glass fibre mesh), bond strength after aging, anchors' resistance to aging and the movement of dowel heads due to hygrothermal stresses in render. Additionally, watertightness is considered with respect to hygrothermal and freeze/thaw cycles.

3.7. Ability to bypass tensions

Ability to bypass tensions (vii) is one of the main functions of the reinforcement layer but is also relevant in other layers. The building must be designed in a way that structural movements do not cause cracking. As the structure of the building has internal movements, the façade system must also be able to resist cracking. The joints and connections between different materials need to be designed and applied to withstand the forces that occur.

3.8. Corrosion protection

The facade system should prevent the corrosion (viii) of load bearing structures. The main factor is the humidity level in the system. The corrosion process is stopped if the relative humidity is below the critical level (80%) [4]. The drying out period has a significant influence as the moisture can remain in the system for years after ETICS is installed.

3.9. Problem tree

These eight essential functions of ETICS described above are influenced by different on-site construction activities during the installation process. Each requirement category has an impact on the overall quality of the façade and any shortcomings have an influence on the system’s performance. To evaluate the degradation severity, an impact evaluation is proposed for each category. Aurnhammer [6] has evaluated technical defects with respect to the value received by the users [6]. All categories sum up to 100%. In case of defects in any segment, the final resulting value decreases [7]. As Aurnhammer’s method includes several factors which are irrelevant for this research, a modification is proposed. The developed method aims to provide an objective evaluation to calculate the diminished value to the user.

The adjusted problem tree shown in Figure 1 evaluates the importance of each degradation class to provide a common impact evaluation.

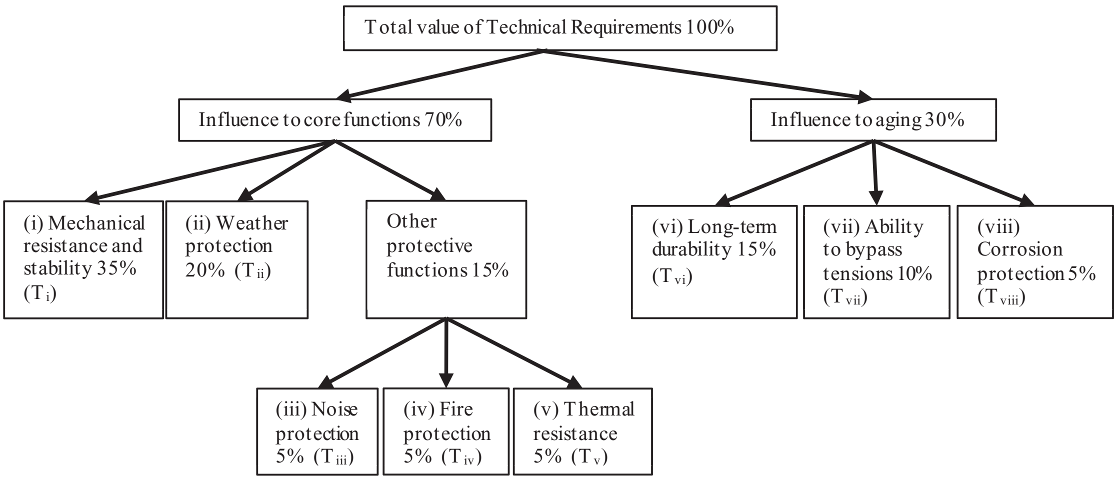

Fig. 1. Technical Requirement Problem Tree.

4. Identifying the Degradation Factors

ETICS and its components have to meet the specific requirements. Each requirement has specific factors which influence the outcome of the product. As the construction process influences material properties, it is necessary to understand how it would be possible to change the characteristics of the outcome. For the identification of significant on-site construction activities, the Degradation Factors (DFs) are collected.

The list of DFs is compiled using product manufacturers’ recommendations, material studies made in the laboratory, field studies which have identified the causes of visible degradations, books on the topic and a field study conducted by the author to reveal construction technology variations. The combination of this data and identification of influencing factors creates the basis for this research. Some of the examples of the results are discussed in the following section.

In an on-site investigation conducted by the first author, different phases of the construction process were observed. An observation list for construction technology-related activities was composed using product manufacturers’ recommendations. Five sample facades were selected, and each façade type was observed four times as different layers were attached. The results improved the selection of DFs for further studies and showed that the habits of construction workers have a considerable impact on the quality. The results of the study will be published in a separate paper.

Based on the extensive literature review and field studies, potential causes of failures and their primary effect on the system is described. The DFs are categorized according to the layers of the system: substrate, adhesive, insulation, mechanical anchors, reinforcement and finishing coat. In addition to the named six categories, mixtures are divided by mixture type and described in a seventh category. As an example, the potential causes of failure of mechanical anchors during construction are presented in Table 1.

For example, ID A7 describes an instance where the anchor plate is placed too high due to decreased depth of the anchor hole or poor application. The exterior side of the plates should be at the same level as the insulation plate to avoid their visibility after render is attached. In the case that the plate lies at a higher level, the resulting decreased render thickness will dry out faster in comparison to other areas. During repeated wetting and drying out periods the tone of the areas will be lighter and the durability will decrease to 10 years as the hygrothermal tests have shown [4].

Table 1. Degradation Factors of mechanical anchor installation

ID	Potential Cause of Failure	Potential Effect of Failure
A1	Increased diameter of drilled anchor hole	Decreased resistance to wind load
A2	Decreased diameter of anchor plate	Decreased resistance to wind load
A3	Decreased amount of anchors	Decreased resistance to wind load
A4	Increased amount of anchors	Reduced thermal resistance
A5	Location is not as foreseen	Decreased resistance to wind load
A6	Anchor plate is installed too deeply into insulation material	Increased render thickness will dry out longer in comparison to other areas. Decreased freeze-thaw resistance.
A7	Anchor plate is placed too high	Decreased render thickness will dry out faster in comparison to thicker areas influencing the freeze-thaw resistance and durability.
A8	Amount of anchors is not increased in the corners of the building	Decreased resistance to wind load
A9	Unsuitable anchor type	Decreased resistance to wind load
A10	Hole of the anchor is not cleaned	Reduced frictional strength between cavity wall and the anchor

The literature analysis with a field study has revealed 75 on-site activities which cause technical problems. To understand the severity rating of the DFs, the limitations described in the following subsection were set.

5. Risk Priority number of Degradation Factors

The proposed system is based on the essential technical performance requirements. It is assumed that, if the performance of the system does not meet the desired characteristics, a failure occurs in the system. To classify and rate the significance of each failure, the risk assessment methodology Failure Mode Effects Analysis (FMEA) is used. FMEA is used mainly in production, but is also applicable in the construction industry in order to identify failures and manage risks [12-14]. The proposed risk management tool enables the identification, quantification, prioritization and evaluation of risk. The aim is to analyze and reduce risk and improve reliability during the construction process and it is assumed that material properties are without defects.

In order to use the tool effectively, a spreadsheet to collect expert evaluation is composed and presented in Table 2. Each DF is described with Potential Cause of Failure and Potential Effect of Failure as outlined in the previous section. The rating system consists of the experts' evaluation of Severity to System Performance, Likelihood of Occurrence and Detectability Rate. After the assessment by the experts the following calculation results in the Risk Priority Number.

$$RPN_{DF,e} = SV_{DF,e} \times OV_{DF,e} \times DV_{DF,e} \tag{1}$$

$RPN_{DF,e}$	Risk Priority Number
$SV_{DF,e}$	Severity Value
$OV_{DF,e}$	Likelihood of Occurrence Value
$DV_{DF,e}$	Detectability Value

The Risk Priority Number for each DF ($RPN_{DF,e}$) is calculated by multiplying the Severity Value ($SV_{DF,e}$) by the Value for Likelihood of Occurrence ($OV_{DF,e}$) and the Detectability Value ($DV_{DF,e}$).

Potential Cause of Failure indicates specific factors which might activate the degradation process. Potential Effect of Failure describes the consequences which can happen and can have more effects to the system than described.

Table 2. An excerpt from proposed Failure Mode Effects Analysis.

ID	Potential Cause of Failure - Degradation Factor (DF)	Potential Effect of Failure (E)	Severity to System Performance (SR)	Likelihood of Occurrence (O)	Detectability (D)	Risk Priority Number (RPN)
A1	Increased diameter of drilled anchor hole	Decreased resistance to wind load	(Evaluated by Experts) (SV)	(Evaluated by Experts) (OV)	(Evaluated by Experts) (DV)	(Calculated)
A2	Decreased diameter of anchor plate	Decreased resistance to wind load	(Evaluated by Experts) (SV)	(Evaluated by Experts) (OV)	(Evaluated by Experts) (DV)	(Calculated)

5.1. Severity to System Performance

Severity to System Performance, Likelihood of Occurrence and Detectability is evaluated by the experts. Severity to System Performance rates the severity of each failure to Specific Requirement described in Section 2. The rating scale is shown in Table 3. The highest rating is assigned if the failure has a very great effect on the requirement, causing total failure. A score of zero is given when the failure has no effect on the requirement.

Table 3. Severity to the system

Characteristic	Description	Ranking (SR)
Very high	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

Severity Value rated by each expert ($SV_{DF,e}$) is evaluated in eight requirement categories as described in Subsection 2.9. Maximum severity arises when all evaluations are rated with the maximum grade and calculated as shown in Equation 2.

$$SV_{DF,e} = \sum \left(\frac{SR_{DF,n,e}}{SR_{\max,e}} \times T_n \right) \tag{2}$$

$SV_{DF,,e}$	Severity Value evaluated by expert
$SR_{DF,,e}$	Degradation Factor rating of the expert for Performance Requirement n
R_{max}	Maximum rating for Performance Requirement n
T_n	Technical Category share value (see Figure 1)

5.2. Likelihood of Occurrence

Likelihood of Occurrence rates the incident frequency during the construction process. The rating scale is shown in Table 4. The highest rating (OR) is given when the DF is occurring more often. Zero is assigned if the factor is not relevant and should not be evaluated. To calculate RPN the influence coefficient OV is used.

Table 4. Likelihood of Occurrence

Characteristic	Ranking (OR)	RPN Influence Value (OV)
Failure occurs often	3	1,3
Occasional failures	2	1,2
Failure is unlikely	1	1,1
Is not relevant	0	0

5.3. Detectability

Detectability rates the possibility that the fault could be detected during the construction process as shown in Table 5. The highest risk is when casual observations can not detect the potential failure and additional tests should be executed. Rating two is assigned if the factor can be detected only during the application of the layer. Rating one is the best possible detection option and describes the situation when it is possible to detect the fault after (or before) the layer is attached and the time for inspection is greatest. To calculate RPN the coefficient DV is used.

Table 5. Detectability

Characteristic	Description of detection option	Ranking (DR)	RPN Influence Value (DV)
Not possible	A potential cause of failure cannot be detected visually. Additional tests need to be used.	3	1,3
During application	Potential cause of failure can be detected visually before completion of the layer, during the application process or markings on the material packaging/ certificate need to be verified	2	1,2
After completion of the layer	Can be detected after completion of the layer	1	1,1
Not ratable failure	The failure is not relevant.	0	0

5.4. Nonparametric Analysis with Friedman's Test

To test the difference between experts' ratings a non-parametric Friedman test is used [15]. It enables the comparison of more than two related groups and is suitable for ordinal data [16]. The test is used for each Degradation Factor separately to detect expert values which are in the critical zone. The blocks are the requirement categories, which are ranked together, and the columns are the evaluations of experts which are compared. If the calculated Friedman rank is in the rejection region, the Expert Ratings with the most extreme column values are eliminated.

5.5. Common Risk Priority Number

Common Risk Priority Number for each Degradation Factor ($CRPN_{DF}$) is calculated with the mean value of the valid Risk Priority Numbers (RPN_e). The calculation is shown in Equation 3.

$$CRPN_{DF} = \frac{\sum RPN_e}{n_{DF}} \tag{3}$$

$CRPN_{DF}$	Common Risk Priority Number
RPN_e	Risk Priority Number
n_{DF}	Number of valid Priority Rating Values

The analysis of DFs is revealing the Common Risk Priority Number, allowing to prioritize the relevance of on-site shortcomings.

6. Limitations

The durability of a building element is influenced by several factors: component quality, design level, indoor and outdoor environment, in-use conditions, maintenance level and execution. During long-term degradation, many factors have an influence at the same time, and their synergy can change the pathology [8]. The research aims to isolate the impact of construction execution, and some limitations need to be set to evaluate possible effects.

A large amount (ca 70%) of the European housing stock was built before 1980 [9] and the structure of apartment buildings is mainly made from precast concrete or brick, which is the substrate material for ETICS. Therefore the research is limited to these two external wall types.

The insulation can be fastened with adhesive, adhesive and mechanical anchors, mechanical anchors and a rail mounting [4]. As mainly adhesive or adhesive with mechanical anchors are used, the research is limited to these two fastening methods.

For the reconstructed façades, polystyrene and mineral wool are mainly used. Both types of materials are examined in the study. The thickness of insulation has been thinner in the past. The increased energy efficiency requirements increase the use of thicker insulation layers [10]. To provide a sufficient amount of sample buildings for a situation analysis regarding degradations, the thickness is limited to 150mm to 200mm. It is probable that the thicknesses will increase in the future. To provide reliable data for the future, an evaluation of the increased insulation thickness is asked from the experts.

The mixtures of ETICS can be separated by the binder type as this influences the weather resistance and affects the material characteristics. Thin layer rendering systems can be organically or inorganically (mineral) bound. Mineral plasters are composed of inorganic binder (cement, silicate) and have thicknesses from 5mm to 10 mm [4]. Organically bound plasters include organic binders like resin with silicon, acryl or similar compounds. As the usage of minerally bound plasters is declining, only organically bound plasters are observed if a distinction is required.

Freezing cycles, humidity and temperature in different regions of the world can influence the outcome. The variation of climate conditions must be compared previously. One of the possibility is to use Köppen-Geiger Map, which classifies geographic regions and is one of the most commonly referred climate classification [11].

7. Discussion

The proposed on-site relevance assessment methodology is used to increase the construction quality of ETICS but can also be used for other on-site construction activity assessments. The ranking exercise is planned to be carried out with experts from Germany and Estonia. By spanning different climate zones, the study will enable the combination of diverse experience while the results will be transferable to both climatic areas. The Köppen-Geiger Map shows that Germany lies in the climate zones CfB (warm temperate climate, fully humid, hot summer) and DfB (snow climate, fully humid, warm summer), while Estonia is in the DfB region. These two climatic regions are applicable to western, central and eastern Europe. It is expected that, in a colder climate, the freeze-thaw cycles accelerate the degradation of the façade. Despite this, the severity and importance of the DFs will still be comparable.

Based on the essential technical performance requirements a questionnaire is composed. The evaluation of the DFs by the experts is conducted in-person to provide clarification if needed. As the evaluation is on an ordinal scale, the results are influenced by the subjective views and experience of the participants. It is accepted that the experts do not have knowledge in all relevant fields, that there is greater awareness with respect to the most popular components and that the background of the participants can influence the outcomes. As cultural habits may affect the results experts from both Germany and Estonia are questioned. The experts need to be appropriately academically qualified to understand the technical influences under investigation, and they also need to have on-site experience to assess the occurrence and the detection possibilities of the factors.

8. Conclusions

ETICS has to meet specific technical performance criteria. Minor alterations in on-site activities during the construction process modify the technical performance. The consequences lead to deterioration of the system, reduce energy efficiency and to the decreased lifetime of the façade. To improve the situation a methodology is developed, which enables to rank the relevance of on-site activities. The framework relates specific technical requirements to on-site DFs, enabling to expose the severity and frequency of on-site activities. The influence of technical requirements is prioritized and defined as an element of a problem tree. Beside technical severity, the risk is affected by the occurrence rate and the possibility to detect the shortcoming during the construction phase.

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References

[1] V. Sulakatko, I. Lill, E. Soekov, R. Arhipova, E. Witt, and E. Liisma, "Towards Nearly Zero-energy Buildings through Analyzing Reasons for Degradation of Facades," *Procedia Econ. Financ.*, vol. 18, no. September, pp. 592–600, 2014.
[2] E. Community, "COUNCIL DIRECTIVE of 21 December 1988 on the approcimation of laws, regulations and administative provisions of the Member States relating to construction products.," *Off. J. Eur. Communities*, vol. 40, no. L, pp. 12–26, 1989.
[3] European Organisation for Technical Approvals, "External Thermal Insulation Composite Systems (Etics) With Rendering," no. March 2000, 2013.
[4] E. Cziesielski and F. U. Vogdt, *Schäden an Wärmedämm-Verbundsystemen*, 2nd ed. Stuttgrat: Fraunhofet IRB Verlag, 2007.
[5] T. Schrepfer, "Faserbewehrte Putze auf hochdämmenden Untergründen," *Bauphysik*, vol. 30, pp. 117–122, 2008.
[6] H. E. Aurnhammer, "Verfahren zur Bestimmung von Wertminderung bei (Bau-)Mängeln und (Bau-)Schäden," *Baurecht*, vol. 2, 1981.
[7] M. Wunderlich, "Schäden, Mängel, Wertminderungen," 2006.
[8] V. Sulakatko, I. Lill, and E. Liisma, "Analysis of On-site Construction Processes for Effective External Thermal Insulation Composite System (ETICS) Installation," *Procedia Econ. Financ.*, vol. 21, pp. 297–305, 2015.
[9] Italian Housing Federation, "Housing Statistics in the European Union 2010," 2010.
[10] H. Künzel, H. M. Künzel, and K. Sedlbauer, "Long-term performance of external thermal insulation systems (ETICS)," *ACTA Archit.*, vol. 5, no. 1, pp. 11–24, 2006.
[11] M. Kottek, J. Grieser, C. Beck, B. Rudolf, and F. Rubel, "World map of the Köppen-Geiger climate classification updated," *Meteorol. Zeitschrift*, vol. 15, no. 3, pp. 259–263, 2006.
[12] J. Layzell and S. Ledbetter, "FMEA applied to cladding systems - Reducing the risk of failure," *Build. Res. Inf.*, vol. 26, no. 6, pp. 351–357, 1998.
[13] M. Abdelgawad and A. Fayek, "Risk Management in the Construction Industry Using Combined Fuzzy FMEA and Fuzzy AHP," *Eng. Manag.*, vol. 136, no. September, pp. 1028–1037, 2010.
[14] S. Mecca and M. Masera, "Technical Risk Analysis in Construction By Means of Fmea Methodology," *15th Annu. ARCOM Conf.*, vol. 2, no. September, pp. 425–34, 1999.
[15] D. M. Levine, M. L. Berenson, T. C. Hrehbiel, and D. F. Stephan, "Friedman Rank Test: Nonparametric Analysis for the Randomized Block Design," *Stat. Manag. using MS Excel. 6/E*, pp. 1–5, 2011.
[16] E. McCrum-Gardner, "Which is the correct statistical test to use?," *Br. J. Oral Maxillofac. Surg.*, vol. 46, no. 1, pp. 38–41, 2008.