THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

A design–build contractor risk assessment framework for new technical solutions in the construction industry

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Abstract

Design–build contractors are often challenged to introduce new technical solutions into construction projects. However, they might not have methods and resources required to avoid serial failure, which is defined as multiple cases of failure when a technical solution fails to sustain the performance requirements. Here, the focus is on serial failures arising from the design or production that could have been predicted through calculations or assessment during the design phase.

This work aims to reduce the occurrence of serial failures related to new technical solutions by suggesting a systematic approach for risk assessment with a focus on moisture safety, seen from a design–build contractor perspective.

Earlier studies on methods and tools for evaluation and risk assessment of technical solutions were used to define a framework for the risk assessment approach. Current practices of implementing new technical solutions and the need for improvement were explored via semi-structured interviews. Two case studies of recent new technical solutions were used in the subsequent evaluation: cross-laminated timber in the construction phase and joint sealing tape in precast concrete sandwich facades.

Besides the technical findings of risk evaluations based on the framework used in each case study, the proposed risk assessment framework is shown to provide a structured evaluation method that can be applied as a pre-qualification for new technical solutions before their implementation in construction projects. The company-level perspective, tollgates to structure the process, expert involvement in workshops and structured documentation and communication of assessment and results are the framework's key elements. The framework facilitates the implementation of new technical solutions and helps the design–build contractor to prevent or reduce the occurrence of serial failures when introducing new technical solutions.

Keywords: Risk assessment, New technical solutions, Hygrothermal performance, Moisture safety, Design–build contractor, Serial failure

Sammanfattning

Nya tekniska lösningar presenteras kontinuerligt för byggbranschen, ofta direkt för enskilda byggprojekt. Entreprenörerna saknar ofta metoder och resurser att utvärdera dessa nya tekniska lösningar. Historiskt sett finns exempel på nya tekniska lösningar som resulterat i seriefel, dvs. där den nya tekniska lösningen i upprepade fall inte klarar att upprätthålla tillämpliga funktionskrav. I detta arbete fokuseras på seriefel som hade kunnat undvikas genom bedömning eller beräkning i projekteringsskedet.

Övergripande mål för arbetet har varit att minska förekomsten av seriefel vid införandet av nya tekniska lösningar genom att föreslå en systematik för riskbedömning med fokus på fuktsäkerhet anpassad till totalentreprenörens perspektiv. Med utgångspunkt i studier av metoder och verktyg för riskbedömning av tekniska lösningar har ett ramverk för riskbedömning anpassats till totalentreprenörens perspektiv för utvärdering av nya tekniska lösningar. För att utforska nuvarande praxis, och behov av förbättringar, vid implementering av nya tekniska lösningar genomfördes semistrukturerade intervjuer med branschaktörer. Det framtagna ramverket användes i två fallstudier där arbetssättet applicerades på två olika aktuella nya tekniska lösningar: korslimmat trä under produktionsskedet samt förkomprimerade fogband i fasader med betongsandwich element.

Fallstudierna visar att det föreslagna ramverket för riskbedömning innebär ett strukturerat arbetssätt för bedömning av nya tekniska lösningar innan de appliceras i byggprojekt. Nyckelfaktorer identifieras som företagsperspektivet, den stegvisa utvärderingen med ledningsbeslut (tollgates), expertinvolveringen samt den strukturerade dokumentationen och kommunikationen. Respektive fallstudie gav dessutom resultat i form av förkvalificering och rekommendationer till byggprojekt som vill använda de studerade nya tekniska lösningarna. Ramverket underlättar implementeringen av nya tekniska lösningar samtidigt som det hjälper totalentreprenören att förhindra att seriefel skapas när nya tekniska lösningar introduceras.

List of publications

This thesis is based on the work presented in the following papers, referred to by Roman numerals in the text:

I. Svensson Tengberg, C., & Hagentoft, C.-E. (2019). Introducing new technical solutions in the Swedish construction industry: Interviews with key actors. In *Proceedings Thermal Performance of the Exterior Envelopes of Whole Buildings XIV International Conference, December 9-12 2019*, (pp. 810–817). Clearwater, FL: ASHRAE

II. Svensson Tengberg, C., & Hagentoft, C.-E. (2020). Implementing a framework for qualitative assessment of new technical solutions: A case study on CLT. In C. Serrat, J. R. C. and V. G. (Eds). *DBMC 2020 Proceedings XV International Conference on Durability of Building Materials and Components, October 20-23 2020, (pp.* 247-254). Barcelona. https://doi.org/10.23967/dbmc.2020.078

III. Svensson Tengberg, C., & Hagentoft, C.-E. (2020). Relying on reference cases when evaluating new technical solutions? Evaluation of technical documentation in a case. *NSB 2020 12th Nordic Symposium on Building Physics / E3S Web Conf., 172,* 10007. https://doi.org/10.1051/e3sconf/202017210007

IV. Svensson Tengberg, C., & Hagentoft, C.-E. (2021). Risk assessment framework to avoid serial failure for new technical solutions applied to the construction of a CLT structure resilient to climate. *Buildings, 11(6)*, 247. https://doi.org/10.3390/buildings11060247

V. Svensson Tengberg, C., Olsson L., & Hagentoft, C.-E. (2021). Risk assessment of joint sealing tape in joints between precast concrete sandwich panels resilient to climate change. *Buildings, 11(8)*, 343. https://doi.org/10.3390/buildings11080343

VI. Svensson Tengberg, C., & Bolmsvik, Å. (2021). Impact on a CLT structure concerning moisture and mould growth using weather protection. *IBPC 2021, 8th International Building Physics Conference/ J. Phys.: Conf. Ser., 2069*, 012017. https://doi.org/10.1088/1742-6596/2069/1/012017

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Preface

At the turn of the millennium, I was working on a licentiate thesis around the effects of remedial measures used in outdoor air ventilated crawl spaces with mould and moisture problems. The aim was to define the effects of the remedial measures on hygrothermal conditions and predict the risk of mould growth. The studied material contained 102 crawl spaces remediated due to moisture problems. This was my first encounter with a serial failure: the studied outdoor air ventilated crawl spaces proved to come with a high probability of mould and moisture problems resulting in similar failure in many buildings. Although the licentiate thesis primarily addressed building physics, I found my interest in risk assessment and quantifying risks. The licentiate thesis was followed by working for a design–build contractor where I was repeatedly challenged with introductions of new technical solutions. It made me realise the advantages of establishing a more predictable process to introduce technical solutions than conventional ones.

In 2018, SBUF (The development fund of the Swedish construction industry) and Skanska Sweden gave me the opportunity to explore how risk assessment can be used by the design–build contractor to reduce the occurrence of serial failures when realising novel technical solutions. With the excellent guidance of my supervisor Carl-Eric Hagentoft and the two co-supervisors Jan Bröchner and Joakim Jeppsson, I tried to navigate through several exciting topics, such as risk management and innovations as well as building physics, to create a more predictable evaluation process, appropriate for the design–build contractor when introducing new technical solutions.

I would like to express my gratitude to you who helped, inspired, encouraged and challenged me along the way of this work. A warm thank you to my supervisor, co-supervisors, colleagues and family. I hope that this work contributes to a more predictable performance of new technical solutions applied in construction industry and thus to reducing the occurrence of serial failures.

Mölndal, February 2022

Table of contents

1 Introduction

This section contains the introduction to the thesis.

In 2019, the Swedish construction industry (contractors) employed 327,000 people in nearly 111,000 companies and had a total turnover of 549.5 billion SEK, equivalent to 10.8% of GDP (Byggföretagen, 2021), (SCB, 2021). Furthermore, greenhouse gas emissions from the Swedish construction industry (including imports) were estimated to be 8.4 megatons CO_2e for new buildings and additional 4 megatons CO_2e for refurbishment in 2018 (Boverket, 2021). Globally, the Intergovernmental Panel on Climate Change (IPCC) estimated the contribution of the construction industry as 6.4% of total emissions (IPCC, 2014). During the operation, the buildings also contribute to emissions, adding additional impact. Thus, it can be concluded that the construction sector is important from both economic and environmental perspectives. The industry mainly comprises small companies, with 87% of them having fewer than five employees. In contrast, only the largest 29 companies have more than 500 employees (Byggföretagen, 2021), (SCB, 2021). Furthermore, the construction industry is primarily project-based, focussing on individual construction projects in temporary organisations and involving many stakeholders. Apart from the contractors' organisation, stakeholders involved in the operations of the construction industry include clients, architects, design engineers, expert consultants, suppliers and authority representatives. Currently, design–build contracts are frequently used in the construction industry globally. In Sweden, for example, according to the general contract[1], the design–build contractor[2] is responsible to the employer (client) for design works and execution based on the client's description of intended use and characteristics, performance specifications and possible reference cases. The performance requirements[3] according to the Swedish building regulations and design–build contract specify the performance of the building. Thus, the design–build contractor can choose the technical solution and therefore owns this responsibility.

The construction industry has historically battled with a reputation of having low efficiency regarding costs of poor quality and slow productivity growth. In the last 20 years, the Swedish government has initiated investigations related to productivity and costs of poor quality every two to four years (Byggkostnadsdelegationen, 2000), (Byggkommissionen, 2002), (Byggkommittén, 2004), (Byggkostnadsforum, 2007), (Boverket, 2009), (Statskontoret, 2009), (Boverket, 2014), (Boverket, 2018). The reports conclude that high costs are associated with different types of waste, failure and defects in the construction industry. Several other reports show considerable quality-related costs in the Swedish construction industry (Josephson & Saukkoriipi, 2005), (Josephson & Lindström, 2010), (Odén & Täljsten, 2019). A report by the Swedish National Board of Housing, Building and Planning (Boverket, 2018)

[1] ABT06: 'General conditions of contract for design and construct contracts for building, civil engineering and installation works' (Byggandets kontraktskommitté BKK, 2006)

[2] Term definitions are collected in Appendix A1.

[3] Term definitions are collected in Appendix A1.

estimates the annual costs related to faults, defects and damages as 7%–11% of production cost. Inefficiency and indirect consequential costs constitute another 20% of the production cost. Studies in other countries also relate high costs with defects. For example, an Australian study on dwellings (Mills et al., 2009) shows that defect-related costs amount to 4% of the contract price. Meanwhile, a Norwegian study (Ingvaldsen, 2008) shows that 2%–6% of net production costs of a contractor and a USA based study (Hwang et al., 2009) shows that 5% of total construction costs are associated with defects.

In 2015, two verdicts[4] in the Swedish Supreme Court particularly drew attention to the design–build contractors' liability for (new) technical solutions. The case concerned whether the application of the technical solution external thermal insulation composite system (ETICS), in a development area with one-family houses, was a defect and whether the contractor was liable for the defect. The verdicts stated the contractor's liability due to negligence to appropriately evaluate the performance of the used technical solution before its implementation, even though the solution at the time was a common practice in the industry. However, in the verdicts, it was noted that the court did not define performance evaluation measures that should have been taken. The verdicts attracted attention within the industry, with 10–20 articles in trade journals and daily press, several of them expressing surprise of the outcome. Positive reactions anticipated an emphasised focus on quality in the industry, whereas negative reactions concerned anticipated higher costs and delayed introduction of innovations (Stenberg, 2016), (Badur, 2016), (Holm, 2015), (Schedin & Eriksson, 2016), (Rosen, 2015).

Based on a government initiative, the Swedish construction industry, including civil engineering and property sectors, has decided on a common roadmap for net-zero greenhouse gas emissions in 2045 (Fossilfritt Sverige, 2018). The roadmap indicates that current technology can achieve half of this change, whereas technological shifts and innovations are needed to reach the full goal. Recently, (Karlsson et al., 2020) created a roadmap for decarbonising the sector, analysing supply chains and confirming the possibility of reaching the goal 'by applying a combination of circularity and material efficiency measures, biofuel and biomaterial substitution, electrification (direct or indirect) with renewable electricity, and carbon capture and storage …'. The suggested new technical solutions relate to changes in cement, concrete and steel; increased use of wood-based and circular products as well as new solutions derived through optimization from a greenhouse gas perspective. However, some of these solutions as well as new technical solutions in general are mentioned in (Boverket, 2018) as potential quality issues in future.

Historically, some of the new technical solutions in the construction industry have failed to fulfil performance requirements, resulting in additional costs for failing solutions and remedial measures. As some of these unsuccessful solutions were introduced on a large scale before the problems were acknowledged, the costs related

[4] Högsta domstolen (the Swedish Supreme Court) Case T916-13: NJA 2015 s 110, and NJA 2015 s 1040

to one solution were not isolated to one or two construction projects but affected numerous projects causing a substantial impact on the industry. Serial failure[5] is multiple cases of failure[6], where a technical solution fails to sustain the requirements. Failure characteristics of the serial failures include both slow process of initiation of damage as well as low detectability. These characteristics are also typical for moisture problems. Three well-known and costly examples of historical serial failures from three different decades are outdoor air-ventilated crawl spaces (Svensson, 2001), ETICS (Samuelson & Jansson, 2009) and magnesium-oxide (MgO) boards (Hansen et al., 2016). The characteristics of these serial failures are given in Appendix A2.

To conclude, the driving forces for realizing an environmental change together with a quest for improved efficiency are expected to increase the push for innovations in materials, goods, designs and methods in the construction industry at the same time as the industry is battling with quality issues. An appropriate technical risk assessment will be crucial in handling the needed and anticipated transformation, and design–build contractors must navigate these issues wisely to avoid developing serial failures. This challenges the construction industry, the design–build contractors, to develop appropriate methods for risk assessment and evaluation of new technical solutions for an efficient implementation resulting in low costs for quality failures.

[5] Term definitions are collected in Appendix A1.

[6] Term definitions are collected in Appendix A1.

2 Aim, objectives and limitations

This section explains the aim, objectives, limitations and assumptions, as well as an overview of the content of this thesis.

2.1 Aim

This work aims to reduce the occurrence of serial failures related to new technical solutions by suggesting a systematic approach for risk assessment with a focus on moisture safety from a design–build contractor perspective.

2.2 Objectives

The three objectives of the work are formulated as follows:

- Objective 1: Investigate current practice on how new technical solutions are introduced and evaluated. To describe how new technical solutions are introduced and evaluated in the construction industry today.
- Objective 2: Establish a risk assessment framework. To provide an elaborated risk assessment framework according to a design–build contractor perspective.
- Objective 3: Evaluate two case studies using the risk assessment framework. To assess the potential of the risk assessment framework by evaluating two current case studies.

2.3 Limitations and assumptions

This thesis focuses on fulfilling the performance requirements of new buildings in the construction industry with a focus on moisture safety. Legal issues are not handled. Other issues, such as environmental aspects or other engineering fields, are not covered. This work is limited to new technical solutions. Other types of innovations (e.g. organisational and digitalization) in construction are not targeted. No other methods except for the proposed framework have been used for risk assessment in the two case studies. This study is performed in Sweden from the contractor perspective within a design–build context.

2.4 Content

The content of sections, papers and correspondence with objectives is shown in Figure 1.

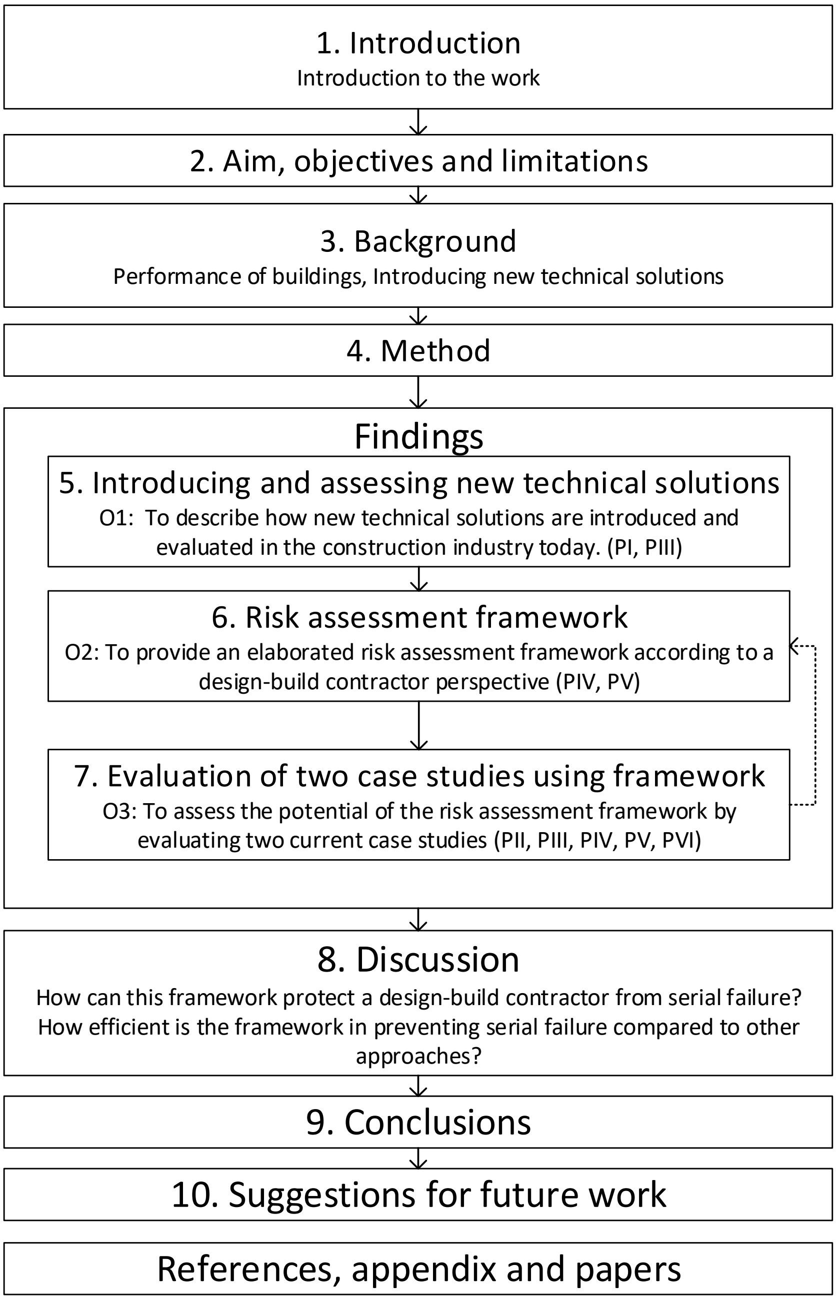

Figure 1. Content of thesis, papers and correspondence with objectives.

3 Background

This section contributes with background concerning performance of buildings and introduction of new technical solutions in the construction industry.

3.1 Performance of buildings

Anticipated performance of buildings is defined in requirements set mainly by the society and client, where the responsibility of different parties is distributed according to regulations and contracts. Moisture requirements and corresponding verification of these are described.

3.1.1 Design–build contracts

The design–build contract assigns the design and construction responsibility to the contractor, in contrast to a design–bid–build contract, in which the client takes the design responsibility, whereas the contractor takes the construction responsibility. In Sweden, design–build contracts are usually based on a general contract[7], which states the general responsibilities and liabilities of the parties involved. In a design–build contract, the client states their requirements in the contract documents. When the contract is signed, the chosen design–build contractor is responsible for delivery of the works, including design, planning, organisation, control and construction. Thus, the contractor is empowered to choose technical solutions for design and construction, consequently shifting the risk of the design from the client to the contractor. This emphasises the need for risk assessment from a design–build contractor perspective.

An argument for design–build contracts is that contractors can propose innovative solutions. The potential for the design–build contractor to choose innovative technical solutions depends on when, in the process, the contract is signed (generic phases shown in Figure 2) and how the requirements and corresponding required verification (e.g. level of detailing) are expressed in the contract. For a design–build contractor, the entry point in the process should, at the latest, be in the 'detail design' phase.

Figure 2. Generic phases in the project development process. The entry point of the design–build contractor can vary depending on when the procurement of the design–build contractor occurs but should, at the latest, be in the 'detail design' phase.

3.1.2 Requirements and fulfilling requirements

There are several sources of requirements in the construction industry, where society, clients, end-users and internal company guidelines can stipulate requirements for a building. Furthermore, these requirements can be expressed in different ways:

[7] ABT06: 'General conditions of contract for design and construct contracts for building, civil engineering and installation works' (Byggandets kontraktskommitté BKK, 2006)

performance requirements, product requirements or construction process requirements. Requirements from the society that concern buildings are expressed at different levels in Sweden: laws[8], regulations[9], mandatory provisions[10] and general recommendations. The mandatory provisions are expressed as performance requirements. Although the arrangement of requirement management throughout the process is not stipulated, the national building regulations give a general recommendation on verification in paragraph 2.32 (Boverket, 2019a):

> *To ensure that the finished building meets the requirements set out in the main statutes and in these mandatory provisions, the developer should ensure that this is verified at an early stage. Verification may be made either at the design and construction stage or in the finished building or any combination thereof. The way in which verification is to be made in the individual case is stipulated in the inspection plan. Unless otherwise specified, the limit values for the requirements given in this Statute must not be deviated from. The uncertainty of the method should be taken into account with regard to calculation, testing and measuring.*

In addition, construction products could be subject to CE marking[11] in compliance with the EU Construction Products Regulation, CPR (European Commission, 2011). For products covered by a harmonized standard[12], it is mandatory to have a declaration of performance and CE marking. For other products, CE marking can be issued using an ETA[13] based on an EAD[14]. CE-marked products should have a declaration of performance issued, accounting for performance parameters as given in the applicable harmonized standard or the applicable EAD. In Annex I of the CPR directive (European Commission, 2011), the basic requirements for construction works are given (main topics: mechanical resistance and stability, safety in case of fire, hygiene, health and environment, safety in accessibility in use, protection against noise and energy economy and heat retention), with a short explanation:

> *Construction works as a whole and in their separate parts must be fit for their intended use, taking into account in particular the health and safety of persons involved throughout the life cycle of the works. Subject to normal maintenance, construction works must satisfy these basic requirements for construction works for an economically reasonable working life.*

In addition to performance requirements formulated by society, the client can specify requirements regarding performance but also concerning the use of specific technical solutions, resulting in product or design requirements. The design–build contractor can have internal guidelines addressing for example the construction process. Several other national laws or regulations are applicable during the construction phase, such as work safety at the construction site.

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[8] PBL (2010:900) with amendments up to SFS 2021:788

[9] PBF (2011:338) with amendments up to 2021:786

[10] BBR: BFS 2011:6 with amendments up to BFS 2020:4 and EKS 11: BFS 2011:10 with amendments up to BFS 2019:1

[11] CE marking: a part of the EU's harmonisation legislation

[12] Harmonised standard: a European standard developed by a recognised European Standards Organisation on a request from the European Commission. The references of harmonised standards are published in the Official Journal of the European Union.

[13] ETA: European Technical Approval www.eota.eu

[14] EAD: European Assessment Document, www.eota.eu

3.1.3 Not fulfilling requirements

Not fulfilling the requirements can be regarded as a failure (to fulfil requirements). Failure, fault and defect are sometimes used interchangeably in the literature, and there are several interpretations of these terms. In (Watt, 2007), a defect is described as follows: 'a defect may be considered to be a failing or shortcoming in the function, performance, statutory or user requirements of a building, and might manifest itself within the structure, fabric, services or other facilities of the affected building'. The definition from the earlier Swedish quality standard SS-ISO 02 01 04, 'non-fulfilment of intended usage requirements', is used in (Josephson & Hammarlund, 1999). In the current quality standard ISO9000, a similar definition can be derived: 'non-fulfilment of a requirement related to an intended or specified use'. Within the general contract usually used in Sweden, a defect is defined as 'non-conformance which implies that a part of the total works has not been executed at all or has not been executed in accordance with the contract' (Byggandets kontraktskommitté BKK, 2006). Within a design–build contract, the contractor is liable for the design and construction works. The contractor is usually liable for damage to the works before handing them over and defects that appear during the guarantee period. For substantial defects that become apparent after the guarantee period, the contractor is liable if the defect is proved to be due to the contractor's negligence. The liability period is ten years.

There are several suggestions for categorising building defects. In (Georgiou et al., 1999), the defects were categorised according to building elements, defect types and trades, whereas other studies consider building elements, effect on building performance and primary source (Watt, 2007); defect type and severity (Macarulla et al., 2013) as well as defect origin, causes and root causes (Josephson & Hammarlund, 1999). In (Fayek et al., 2004), a fishbone-structured classification system is used to explore three levels of potential and actual causes of reworks (a consequence of the defect). By pairwise comparing the root causes, multiple root causes can be apportioned for a rework incident. Top level causes are human resources capability, leadership and communications, engineering and reviews, construction planning and scheduling and material and equipment supply.

A distinction between fault and defect is suggested in (Atkinson, 1987): 'a fault is a departure from good practice, which may or may not be corrected before the building is handed over. A defect, on the other hand, is a shortfall in performance which manifests itself once the building is operational'. In the ISO standard on general principles on the design of structures for durability (ISO 13823:2008, 2008), failure is defined as 'loss of the ability of a structure or component to perform a specified function'. In 'Guideline on Design for Durability of Building Envelopes' (Lacasse et al., 2018), failure is defined as 'the loss of performance coincident with the inability of a material, component, assembly or system to perform its required function'. From a design–build contractor perspective, failure is of interest independent of whether it occurs during the construction or operation phase. The term failure[15] (to fulfil set

[15] Term definitions are collected in Appendix A1.

targets, for example, performance requirements) is used in this work.

The consequences of failing to meet the requirements can go beyond a technical solution, affecting other components and parts of a building. Consequences can be related to direct costs for measures, such as work and material replacements, and to indirect costs for inefficiency and indirect consequences.

3.1.4 Moisture safety in focus

In this study, moisture safety is in focus. The basis of both moisture and structural reliability can be defined as follows: the applied effect (load) should not exceed the structure's resistance. However, significant differences exist between handling of structural and moisture-related reliability. There is also a fundamental difference between structural collapses and other failures in buildings. In the case of structural collapse, the potential range of environmental loads can be easier to identify and quantify. Moreover, the consequences of the collapse, the immediate loss of life and damage to property, can be easily recognised. Thus, the development of precise building regulations (codes) for structural design, nowadays often relying on a probabilistic quantitative approach to risk based on extensive research, has been possible. Other types of failures, such as moisture related failures, are more complicated to foresee and prevent. The complexity of context (environmental loads, combinations with other materials and components) and the complexity of predicting the consequences of failure must be acknowledged. Often, failure and thus consequences are slow to appear and imply gradual deterioration of a structure. Detection of the failure might be delayed. The health effects of such failures also hold large uncertainties. These effects may be aggravated for some individuals in combination with age and particular lifestyle issues, such as association with smoking. Because the origins and consequences of such failures are more complicated than the outright structural failures, building regulators have chosen other approaches to minimize risk.

For structural reliability, there is explicit guidance from the Swedish application of the Eurocodes (Boverket, 2019b) how to use quantifiable probability-based loads and load combinations, with quantifiable probability-based material properties to define the resistance of the structure. There are also well-defined limit state conditions to be fulfilled. Uncertainties[16] are considered using probabilities and safety margins aiming at the well-defined accepted probability of failure. In comparison, the top paragraph on moisture safety in the Swedish building regulations (Boverket, 2019a) is expressed as follows: 'Buildings shall be designed to ensure moisture does not cause damage, odours or microbial growth, which could affect hygiene or health.', followed by the general recommendation to use the industry standard ByggaF[17] as guidance throughout the design and construction phase. Here the moisture safety during the construction phase is included. For verification, three ways of working are defined in

[16] Term definitions are collected in Appendix A1.

[17] ByggaF is an Swedish method for including moisture safety in the building process (Mjörnell et al., 2012)

the building regulations concerning moisture safety: quantitative determination, proven solutions and qualitative assessment (Table 1). All verification should be performed systematically through the entire building process. Detailing including combination of materials, joint and connection details as well as the long timespan of the processes should be considered, and adverse conditions should be used to determine moisture levels.

Table 1. Options for verification of moisture safety requirements in moisture safety design as defined in Swedish building regulations, BBR (Boverket, 2019a). Text is translated and condensed. All verifications should be performed systematically throughout the entire building process.

Quantitative determination	Proven solution	Qualitative assessment
Check through calculations or tests. The plausibility of calculations should be assessed. Tests should be performed with measurements and controlled observations. Consideration should be taken to the measurement uncertainty.	Check against documented and verified experience from similar building components with comparable climate impact. These should be controlled and documented for a sufficient time (10 years) and function without problems.	Check against applicable instructions and design examples from industry guidelines, handbooks and test results. The reference material should be based on quantitative determination or a proven solution.

Comparing to structural safety, less guidance on loads and load combinations, material properties, modelling assumptions and limit states, as well as handling uncertainties and criteria for acceptance of probabilities of failure is provided. Regarding moisture safety, there is a strong tradition in the construction industry of claiming to use 'proven solutions', potentially due to the complexity involved in assessing the hygrothermal behaviour, where adverse load combinations are not obvious. Unfortunately, these claimed proven solutions, including parts of our traditional building technology (for example cold attics), come with a quite high probability of exceeding the critical moisture level as defined in the Swedish building regulations. When introducing new technical solutions, using 'proven solutions' by definition is not possible, implying other alternatives must be used according to Table 1. Furthermore, a change of loads, for example climate loads, can change the status of the proven solution to a non-proven solution.

3.2 Introducing new technical solutions

A technical solution includes materials, goods, design or process (construction method), which should be specified through a drawing, description or other means. A new technical solution is interpreted as a technical solution with a change to current practice by introducing a different material, product, design or process. It can also be a change in the application of a technical solution of current practice, for example, a known material or design introduced to new climate conditions. In this work, a new technical solution should be understood as an applied solution not covered by the concept 'proven solution' (Boverket, 2019a) but at the same time applicable in the construction industry, at least at the level of TRL7 'system prototype demonstration in operational environment', defined by the European Commission in Horizon 2020 (European Commission, 2014).

The new technical solutions can differ in impact, from incremental (modest changes, no or low impact on other solutions) to radical (significant new concept or approach). In the context of innovation (Slaughter, 2000), innovations can be differentiated into incremental, architectural, modular, systemic or radical, and the source of innovation can differ depending on the innovation type. For incremental innovation, the source can be any actor with knowledge or experience, whereas other innovations, modular or radical, might demand an actor with more advanced R&D departments, such as suppliers. The traditional way of product development is through a supplier or equivalent to develop a technical solution to sell to the user (the design–build contractor). The supplier's product development before placing a product on the market presumably follows a generic product management process shown in (Ulrich & Eppinger, 2011). The result of the development process is a new technical solution, which can be offered to a client. It is crucial for the suppliers to be aware of the changes in other components or processes required when implementing new technical solutions (Slaughter, 2000). When the design–build contractor uses a new technical solution, the contractor implements the solution into the building system to interact with all other components and becomes responsible for the applied new technical solution. The design–build contractor handles the risks of introducing the solution within their business. New technical solutions are introduced in the concept design, the detailed design or even the production stage. Depending on the entry point of the new technical solution in the building project, the liabilities and the assessment process of the design–build contractor are affected. New technical solutions are abundant, either recently introduced or on the verge of being introduced in the construction industry. They are promoted by different actors. The design–build contractor must assess the new technical solutions in the actual application within the building.

3.2.1 Risk management in the construction industry

The concept of risk[18] can have several interpretations. There are standards on risk management[19] (ISO 31000:2018, 2018), (Project Management Institute, 2017) and other vocabularies on risk analysis from ISO (ISO Guide 73:2009, 2009) and the Society of Risk Analysis (Aven et al., 2018) elaborating the relevant concepts. There are differences in definitions and descriptions of the process. However, the general risk process, based on a defined scope, usually are risk assessment[20], including risk identification[21], risk analysis and risk evaluation[22], followed by risk treatment[23] (ISO 31000:2018, 2018). Risk treatment is defined as a process that modifies risk, described as risk avoidance, risk optimization, risk transfer or risk retention in (Aven, 2012).

Risk management in the construction industry typically focuses on risks in a particular

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[18] Term definitions are collected in Appendix A1.

[19] Term definitions are collected in Appendix A1.

[20] Term definitions are collected in Appendix A1.

[21] Term definitions are collected in Appendix A1.

[22] Term definitions are collected in Appendix A1.

[23] Term definitions are collected in Appendix A1.

construction project. A design–build contractor is probably familiar with the concept of risk used frequently to assess a wide array of risks mainly related to the business and safety aspects of the construction. Often, matrixes of likelihood and consequences are used to assess different activities in the construction process. The concept of risk in this context is then perceived as a 'subjective measurement of uncertainty', whereas in traditional engineering disciplines, it is more of a quantitative property (Aven, 2012). Furthermore, although risk management in the construction industry complies with relevant standards, there is an identified lack of guidelines and systematic approaches for selecting appropriate risk identification techniques and risk classification (Siraj & Robinson Fayek, 2019).

3.2.2 Available models for assessment

There are different approaches for assessment of new technical solutions depending on if an innovation or durability perspective is adapted.

Models for implementing innovations can be found in the innovation literature. In (Murphy et al., 2015), a flowchart is presented for the combined implementation activities of four stakeholders, client, project manager, designer and supplier, throughout the process. There are seven stages: intention to innovate, formulation of the design concept, resolution of detailed design, preparation of production information, preparation of implementation, implementation of the innovation and post-project evaluation. However, these do not usually hold any specific guidance on technical risks or particularly building physics risks.

In structural engineering, the basic principles of reliability of structures are given in an international standard (ISO 2394:2015, 2015). An approach for durability is given in an ISO standard 'General Principles on the Design of Structures for Durability (ISO 13823:2008, 2008) (Figure 3). This standard for durability builds on how the reliability of structures is handled, including the limit states method. By using the structure environment, the transfer mechanisms and the environmental action, the action effects are determined. By comparing with the resistance and serviceability limits, the durability of the technical solution is assessed. In compliance with structural safety, the approach is probabilistic.

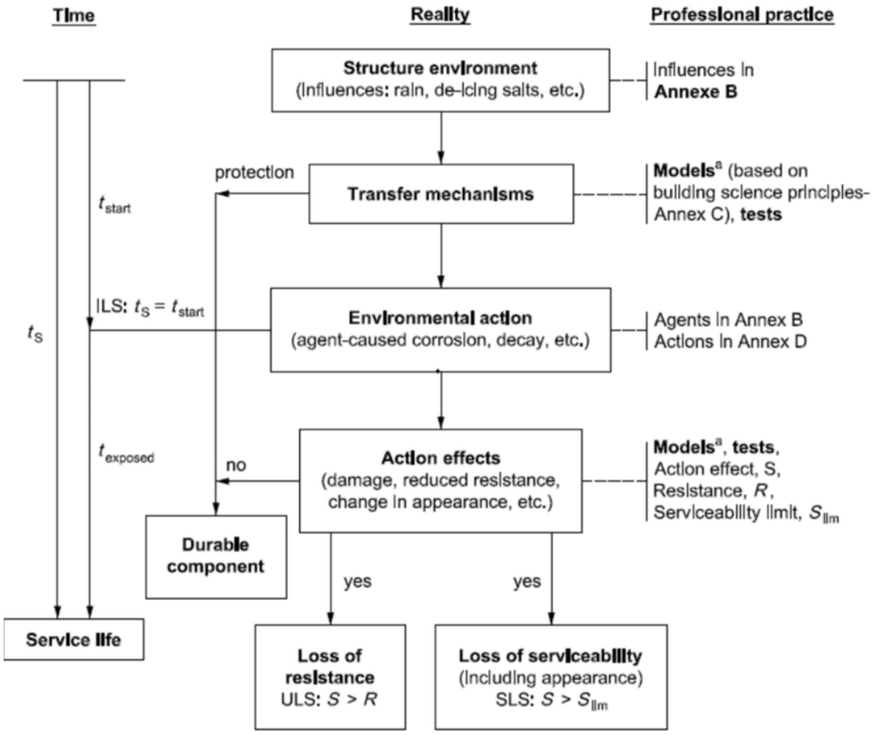


Figure 3. Limit state method for durability according to ISO 13823 (ISO 13823:2008, 2008).

In addition, a guideline for durability evaluation is suggested in (Lacasse et al., 2018), with the purpose of providing information on evaluating the durability of building elements based on the results derived from a hygrothermal simulation tool when the envelope is subjected to anticipated loads. The procedure is pictured in Figure 4. The guideline gives special guidance on selected building elements in wall assemblies where performance evaluation attribute, criteria and evaluation process are suggested. At the same time, no particular methods for identifying risks and risk scenarios are provided. The given methods concentrate on quantifying performance and comparing performance to limit state.

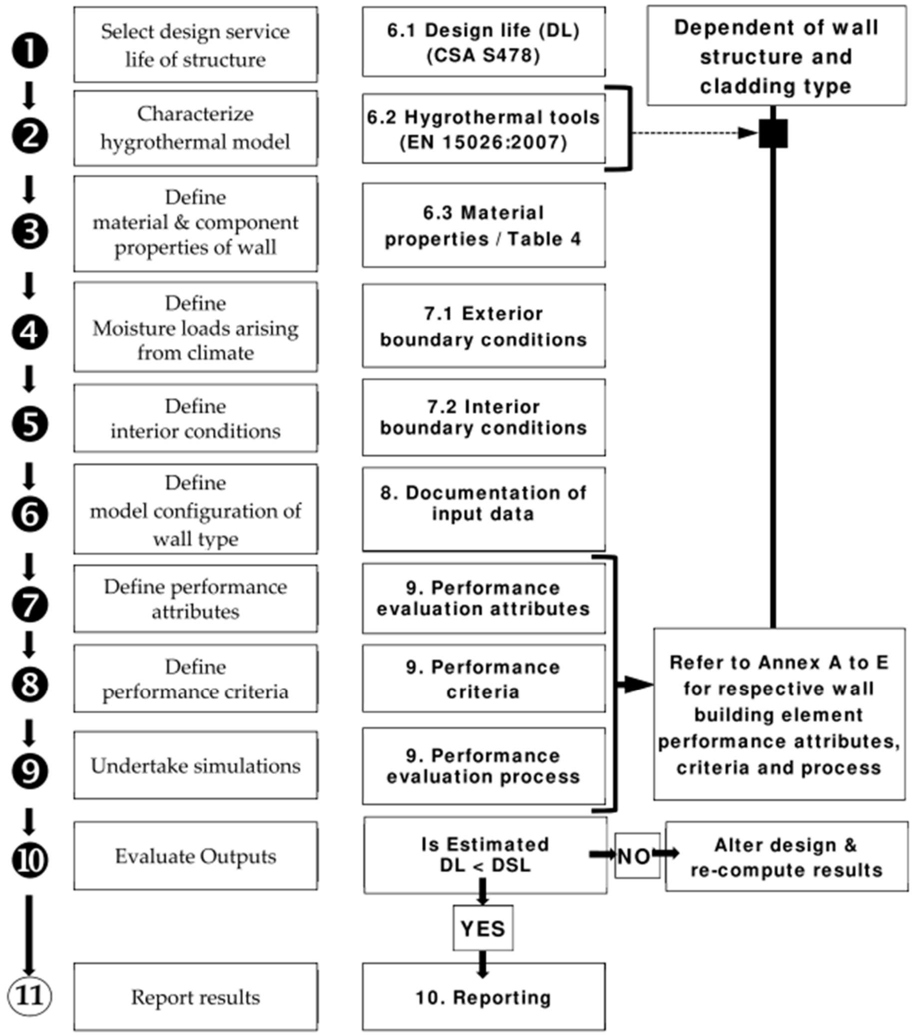


Figure 4. Procedure for completing a durability evaluation according to (Lacasse et al., 2018).

Beyond the probabilistic methods, there have been several efforts to compile the research results based on advanced simulation tools and probabilistic methods into easy-to-use tools, such as RIBuild—addressing interior insulation of brick walls (di Giuseppe et al., 2017)—and BSA—addressing exterior walls (Boudreaux et al., 2018). Within the predefined boundaries and with pre-set assumptions, the user can benefit from probabilistic assessment of a building component based on large sets of simulations when evaluating the moisture safety performance. However, this approach is not generally suitable for new technical solutions because it relies on predefined parameters with limited flexibility. Tallfacades (Tietze et al., 2017) presented a risk assessment approach particularly for timber facades, involving a method based on a probabilistic approach for developing components (timber walls) and a qualitative approach using event trees for details.

ByggaF, method for moisture safe building process (Mjörnell et al., 2012) is referred to by the Swedish building regulations (Boverket, 2019a) as a general recommendation for managing moisture safety throughout the building process. ByggaF assigns tasks to different actors within a construction project and suggests a common risk identification in the design stage, where all actors in the design group should conduct moisture risk analysis based on a checklist using each building part as a starting point. The checklist starts by applying relevant moisture sources to the design and assessing the (unwanted) effects on the design. The conceptual outline of ByggaF is shown in Figure 5. This model provides good support within a particular construction project using the known technical solutions. However, the 'dry building design' requires a lot of knowledge, time and resources within the construction project when a new technical solution is applied, as the lack of documented data and experiences necessitates a comprehensive study.

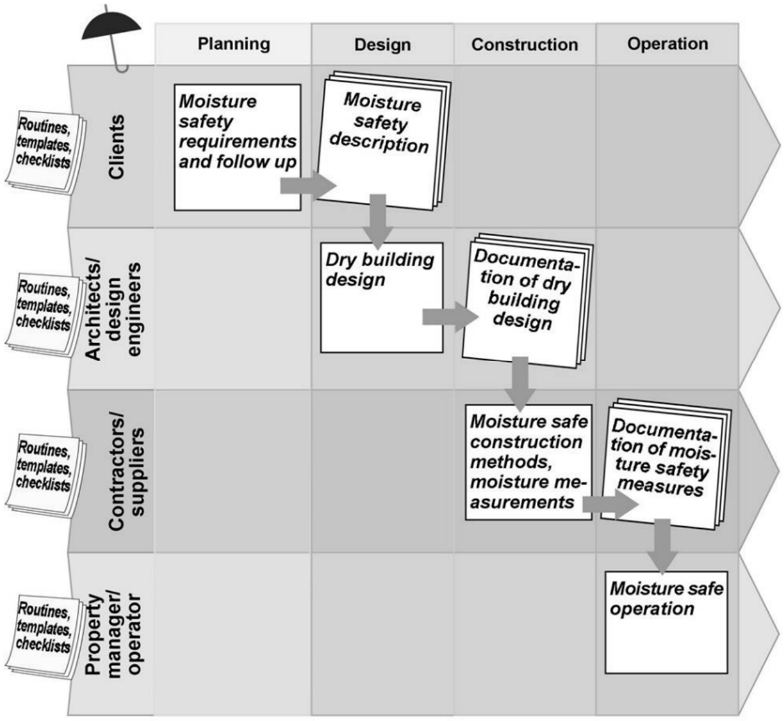


Figure 5. Conceptual outline of ByggaF (Mjörnell et al., 2012).

For retrofitting projects, a more elaborate framework for testing, evaluating and documenting variations in the performance of building envelopes was suggested in a research project focussing on reliability through probability assessment of performance and cost (Bednar & Hagentoft, 2015), (Sasic Kalagasidis & Rode, 2015). The framework, based on risk assessment, is divided into three main steps as pictured in Figure 6. The assessment process starts with Scope, where the scope of the analysis is defined. This is followed by Benefits and hazards, which includes a qualitative performance analysis based on the scope. Influential parameters and uncertainties are identified based on existing knowledge and possibly by simplified calculations, and the first evaluation of the result is presented. The final step is the Quantitative probabilistic assessment, where the performance is calculated by selecting the method of analysis including a numerical method and a sampling technique. Within this step, the influential parameters are statistically processed to probabilities and used for calculating the performance. The second evaluation of the results is performed, where the results are compared with targets. In retrofitting projects, well-proven solutions might not be applicable, and uncertainties are often manifold, creating a need for a structured risk management process to assess the retrofitting strategies and probabilistic methods are of interest. Similar to retrofitting projects, uncertainties is of great importance when implementing new technical solutions. Thus, this framework for retrofitting was used as a starting point to elaborate a framework for a systematic risk assessment approach focussing on moisture safety for new technical solutions from a design–build contractor perspective.

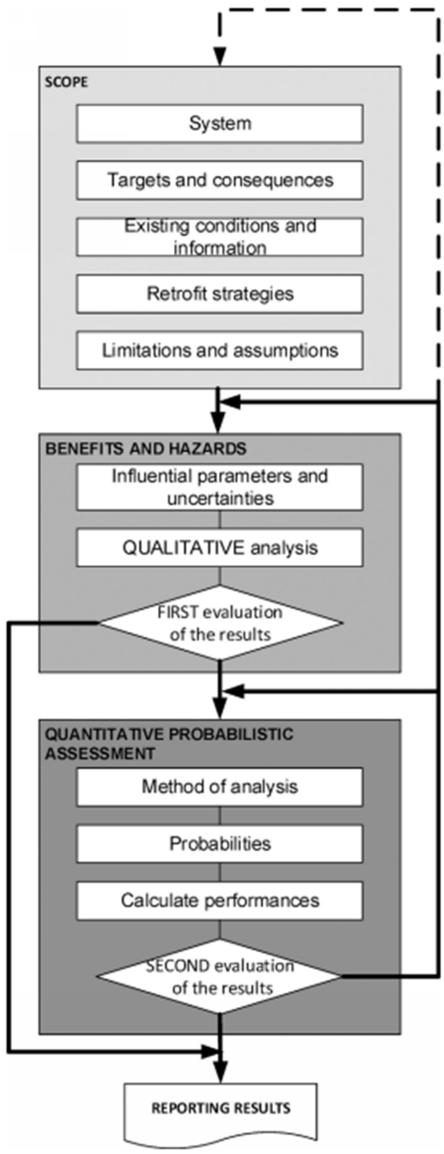


Figure 6. Framework for risk management according to (Hagentoft, 2017).

4 Method

This section describes the method of work.

Through literature review, relevant methods for evaluation and risk assessment were selected. Moreover, an interview study was performed to investigate practice in the Swedish construction sector today. Semi-structured interviews with selected key actors in the industry were used to explore how new technical solutions are introduced and evaluated, as well as to identify possible improvements to practice.

A risk assessment framework for retrofitting was selected and adapted to the design–build contractor perspective and to the evaluation of new technical solutions. Suitable tools available for the design–build contractor—risk assessment tools and building physics simulation tools—were identified from the literature.

The elaborated framework was assessed and further developed by applying the framework on two case studies of new technical solutions currently introduced in the Swedish construction industry. Within these two case studies, literature studies and risk identification, as well as relevant simulations of hygrothermal conditions and corresponding anticipated mould growth were performed. The suggested workshop format was tested. For the hygrothermal simulations, commonly used modelling tools were applied, such as WUFI (Fraunhofer IBP, 2021) as well as a simplified model for mass balance. For mould growth simulations, the VTT model (Hukka & Viitanen, 1999), (Viitanen & Ojanen, 2007) and the m-model (Togerö et al., 2011) were applied to hygrothermal conditions. The Monte Carlo method was used to assess probabilities.

Based on the experiences of the two case studies, the possibilities and need for future research on the elaborated risk assessment framework were explored.

5 Introducing and assessing new technical solutions: Current practice

This section summarises the findings and conclusions of Papers I and III, focussing on Objective 1: Investigate current practice on how new technical solutions are introduced and evaluated to describe how new technical solutions are introduced and evaluated in the construction industry today.

A steady stream of new technical solutions is entering the construction industry. Because of the problematic record of accomplishment showing both too slow adaption and too fast adaption, a set of semi-structured interviews, as described in Paper I, was conducted. The aim was to explore how new technical solutions are currently introduced and evaluated regarding performance requirements, focussing on building physics, from the design–build contractor perspective. Serial failure was defined as multiple cases of failure, where a technical solution fails to sustain the performance requirements. Here, the focus was on serial failures arising from problems in the design and production that could have been predicted through calculation or assessment in the design phase.

Nineteen interviewees selected for semi-structured interviews answered questions on six topics concerning how new technical solutions are identified, introduced and evaluated, as well as who makes the decisions and holds the responsibility. All interviewees were experienced and active in the Swedish construction industry. The answers concerning the process of identification and evaluation were clustered in possible steps in an evaluation process (see Figure 7).

Figure 7. Possible steps in identification and evaluation of new technical solutions. (Paper I)

It was found that main drivers for introducing new technical solutions were related to cost and productivity followed by environmental benefits, with the overall picture that the construction industry, the design–build contractors, are mainly applying the solutions provided to them by suppliers. New technical solutions are usually introduced by the design–build contractor directly in construction projects, where the evaluation is restricted to the ordinary design process (with its constraints regarding time and resources). Qualitative assessment based on documentation from suppliers was perceived to be used, while quantitative assessment was perceived as uncommon. The interviewees had a positive perception of both mock-ups and reference cases, however the evaluation of these were described as limited to a single issue, for example buildability or aesthetics, restricted to the project (mock-ups) or without documented evaluation (reference cases).

The conducted interviews also helped identify potential for improvements to prevent serial failure when introducing new technical solutions. The interviews identified a lack of methodology for verifying performance requirements, such as building physics when introducing new technical solutions in the Swedish construction industry. Three main issues of concern and a corresponding need for improvement were identified:

- Weak evaluation process: there is a need to define and strengthen different steps in the evaluation process, namely, qualitative and quantitative assessment, mock-ups, pilot project and feedback loop, as they are not commonly defined. The evaluation of building physics is often weak in all steps.
- Insufficient documentation: there is a need to clarify any requirements related to documentation, samples and references to be fulfilled by the supplier. Documentation and reference cases given by the supplier are often the main source of evaluation.
- Reference cases without references: there is a need to define the requirements for reference cases used for verification. There are signs of the use of reference cases for a new technical solution, although the reference case lacks relevant technical documentation and evaluation, which might be a key issue for development of serial failures.

In Paper III the potential of available documentation to evaluate new technical solutions was further explored in the case study (see Chapter 7). A request for data was sent out to four suppliers of a selected new technical solution—cross-laminated timber (CLT[24])—to address questions on what kind of documentation concerning building physics is provided by suppliers and how well the suppliers' documentation meets the need for evaluation and verification according to a design–build contractor (Table 2).

Table 2: Requested suppliers' data. Left column: Requested product properties related to building physics. Right column: Requested handling instructions, design solutions and reference cases related to building physics.

Product properties	**Handling instructions**
Density	Material, handling instructions (transport)
Porosity	Material, handling instructions (storage)
Water vapour diffusion resistance	Material, handling instructions (construction)
Moisture storage functions	References, construction
Liquid transport coefficient	Suggested building components
Air tightness	Suggested details
Critical moisture level	Maintenance instructions
Change in shape / moisture content	References, buildings
Moisture content at delivery	
Thermal conductivity	
Specific heat capacity	

The findings show that the typically provided documentation corresponded to product data defined in the EAD[25]. All data provided were deterministic, using generic properties (pure wood). For handling instructions, only qualitative data were provided, and the given reference cases did not carry any documented verification. The provided data were assessed as not meeting the need for appropriate evaluation to verify

[24] Term definitions are collected in Appendix A1.

[25] Applicable EAD (EOTA, 2015).

performance because data on the critical moisture level of the material were not provided. Furthermore, neither any handling instructions nor performance concerning moisture during construction were given. The given reference cases were given without any documented verification of performance. The study indicates that the documentation provided by suppliers in the studied case does not allow evaluation to verify performance of the applied technical solution. To conclude, gaps are identified in the suppliers' provided product data and documentation of reference cases, indicating that the construction industry (the design–build contractors) might have too high confidence in the product suppliers providing data for appropriate evaluation to verify the applied new technical solution. For construction and operation of a CLT structure with respect to moisture safety, further details on documentation provided by the suppliers are found in Paper III.

6 Risk assessment framework

This section summarises the findings and conclusions of Papers IV and V, focussing on Objective 2: Establish a risk assessment framework, to provide an elaborated risk assessment framework according to the design–build contractor perspective.

A risk assessment framework is suggested based on the identified need to define and strengthen the evaluation process when a design–build contractor introduces new technical solutions. The suggested framework is an elaboration of a framework developed in the International Energy Agency (IEA) Annex 55 (Bednar & Hagentoft, 2015), (Sasic Kalagasidis & Rode, 2015). The elaborated framework is adapted to the introduction of new technical solutions (Paper I) and the design–build contractors perspective using elements of product development (Ulrich & Eppinger, 2011). The main elaborations concern the following:

- Organisation: the organisation of assessment and evaluation is highlighted; the framework is preferably used in a stand-alone project at company level, initiated by management, run by a designated project manager responsible for the assessment and answering to a steering group appointed by management.
- Tollgates: tollgates for steering group decisions and communication were added to further structure the process, reflect the design–build contractor's interests and contribute to an efficient process. In each tollgate, the steering group can decide to proceed, revise an earlier step or cancel the assessment.
- Pre-processing: before initiating the framework, the new technical solution should be selected by company management based on market potential and anticipated benefits to ensure the effective use of evaluation resources.
- Results and post-processing: the output from the evaluation should be managed within the company. This is achieved using results as pre-qualification on a central level, with possibility to add conditions to be fulfilled within construction projects. Assessment and rationale for decision are documented. The pre-qualification on a central level lowers the threshold for implementation of new technical solutions in subsequent building projects.

6.1 Elaborated framework

The elaborated framework presented in Paper IV is shown in Figure 8. The suggested organisation is given in Section 6.1.1. The assessment steps and tollgates are further described in Section 6.1.2. The suggested application of tools is given in Section 6.1.3.

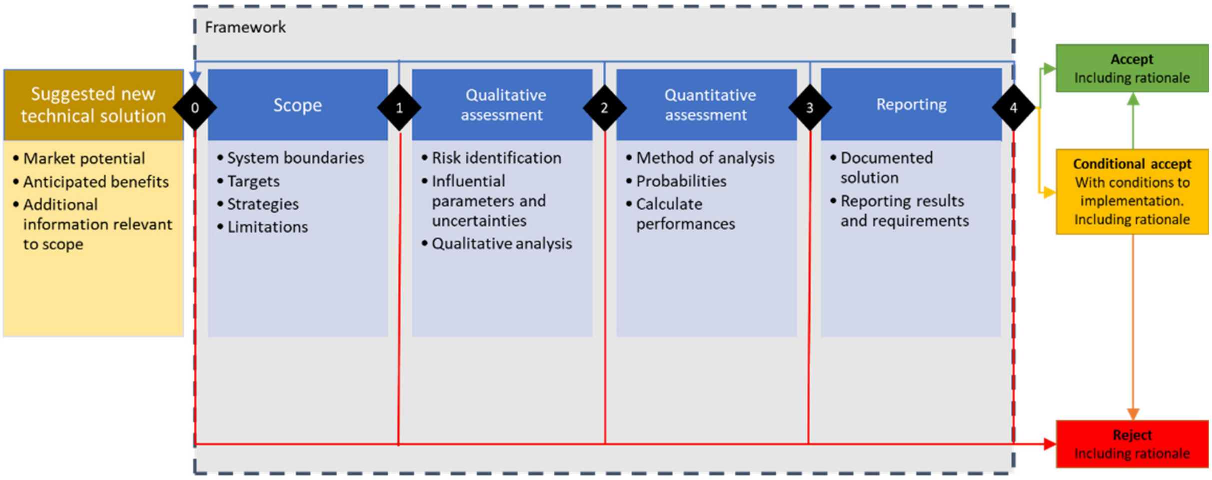


Figure 8. Elaborated risk assessment framework with tollgates for steering group decisions. Tollgates are marked 0 (decision to initiate framework) to 4 (decision to implement). Cf. Paper IV.

6.1.1 Suggested organisation

The assessment is suggested to be run as a standalone project at the central level within a company, initiated, defined and financed by company management and led by a designated project manager for the assessment reporting to a steering group representing management. The project manager leads the assessment between tollgates and the steering group takes decisions based on the assessment in each tollgate.

The assessment should provide basis for decision of the potential of new technical solutions and define requirements as a pre-qualification before evaluation and possible implementation in building projects. By predefining requirements, the threshold for a construction project to implement new technical solutions is lowered as time and resources for the assessment are redirected to a company level. At the same time, the assessment is given adequate time and resources, and standards of evaluation are uniformed.

6.1.2 Assessment steps and tollgates

The components of the process include assessment steps and tollgates (Figure 8). Different assessment steps use adequate common available tools and can be iterated if the scope is changed or new information is added. Each step in the process is followed by a tollgate (black diamond in Figure 8). In each tollgate, the decision to proceed/accept the assessment, revise an earlier step (blue arrow) or reject/cancel the assessment (red arrow) is taken. For all decisions, the rationale should be documented.

- ♦ **Tollgate 0:** prior to the actual framework process, in Tollgate 0, the decision to initiate the process should be taken based on market potential and anticipated benefits of the new technical solution. A project manager, a budget and an organisation should be assigned and documented with directives of the assessment.
- ○ **Scope:** the scope is established by defining system boundaries, targets, strategies and limitations to the new technical solution to specify what is being assessed. Relevant stakeholders should also be identified. This step is essential

to define and create a mutual understanding of the assessment. The scope is followed by Tollgate 1.

- ♦ **Tollgate 1:** in the first tollgate, the scope is assessed. If accepted, the steering group agree on the scope as described, and the process proceeds to a qualitative assessment. The scope can also be rejected or revised. If the scope is incomplete or does not meet the expectations of the steering group, it is revised (blue arrow). If the scope is considered not viable, it is rejected (red arrow).
- ○ **Qualitative assessment**: the qualitative assessment includes the identification of risks, influential factors and their corresponding uncertainties. Adequate tools can constitute risk workshop, literature review and risk identification/assessment techniques. The suggested application of tools is given in Section 6.1.3.
- ♦ **Tollgate 2**: the decision of the process pathway is made based on the qualitative assessment. The decision could either be to proceed with reporting or quantitative assessment. If the qualitative assessment is incomplete or not meeting the expectations of the steering group, the qualitative assessment or scope is revised (blue arrow). If the solution is considered unviable, it is rejected (red arrow).
- ○ **Quantitative assessment:** the quantitative assessment is based on the results of the qualitative assessment and includes the analysis method identification, as well as identifying probabilities and performing simulations. Although appropriate tools depend on the analysis method, they include simulations. The tools for determining probabilities might include the Monte Carlo method and different climate scenarios. Laboratory/field testing can be performed. Suggested tools are given in Section 6.1.3.
- ♦ **Tollgate 3:** based on the quantitative assessment results, the decision could be to accept and proceed with reporting. If the quantitative assessment is either incomplete or not meeting the expectation of the steering group, the quantitative assessment or earlier steps are revised (blue arrow). If the solution is considered unviable, it is rejected (red arrow).
- ○ **Reporting:** all input and results of the assessment are compiled, and the recommendations and specification of requirements to be fulfilled are established to serve as the basis of decision. The recommendations should also contain the suggested verification and risk mitigation steps for the applied solution.
- ♦ **Tollgate 4:** in the last tollgate, the full results are presented to the steering group. The case could be accepted (green arrow) or conditionally accepted (yellow arrow). The conditions could concern evaluation during construction and operation or limitations to the application. If the results are not meeting the expectation of the steering group, the earlier steps can be revised (blue arrow). If the solution is considered not viable, it is rejected (red arrow).

6.1.3 Suggested application of tools in framework

There are several tools that are applicable to the risk assessment process. In the presented framework, the following available and known tools are suggested to be applied.

Risk workshop

Because the issue of new technical solutions comes with a lack of experience and knowledge, where expert judgement is identified as an essential element of risk identification and risk assessment. Although objectivity is the goal, expert judgement potentially holds subjective elements. The selection of stakeholders and structure of the risk workshop can mitigate subjectivity. The elements of risk workshops are described both in the literature, e.g. (Oakley & O'Hagan, 2016) and by many management consultants, and usually contain elements of identification of experts, preparation of workshop, preparation of the experts, structure of workshop, workshop and post-processing. The setup used in this work includes the following:

- Identification of experts: a stakeholder analysis should be performed, suggested tools are a power/interest grid or a participation planning matrix (Bryson, 2004) to identify experts to involve.
- Preparation of workshop: essential elements include preparation of the background material based on literature and other relevant sources, clarification of the scope to be scrutinized based on the scope agreed on in Tollgate 1 and formulation of the explicit expectation on workshop participants.
- Preparation of the experts: a key issue is to prepare experts by providing and communicating the background material. This includes asking the participants to submit their identified risks as preparation of the experts and workshop.
- Structure of workshop: the agenda includes an introduction, presentation of submitted material, including suggested risk classification pre-populated by this material, assessing risks, identifying relevant unknowns and uncertainties and finally reflections and conclusions.
- Workshop: the workshop is conducted according to the agenda, using visual elements (for example the fishbone structure) and documented in a spreadsheet template.
- Post-processing: using the spreadsheet template, risk identification and corresponding uncertainties are coupled for further analysis.

During the expert workshop, other values were identified, mainly new insights to participants. The possibilities of iterating workshop format at an increasingly detailed level and quantification of purposes were also identified.

Risk assessment techniques

To illustrate and structure the qualitative assessment, a fishbone diagram is suggested in the qualitative analysis to visualise the influencing factors for an unwanted event to occur (see Figure 9). The fishbone diagram is used to cluster the factors in four main categories: Organisation, Design and material, Loads and Production methods.

For the quantitative analysis, even though a fault tree might not fully suitable for the probabilistic risk analysis because of the interdependencies of hygrothermal conditions, the tree structure is suggested to visualise the elements contributing to a failure in preparation of the modelling of the analysis. The fault tree can also be used to qualitatively compare the new technical solution with current practice.

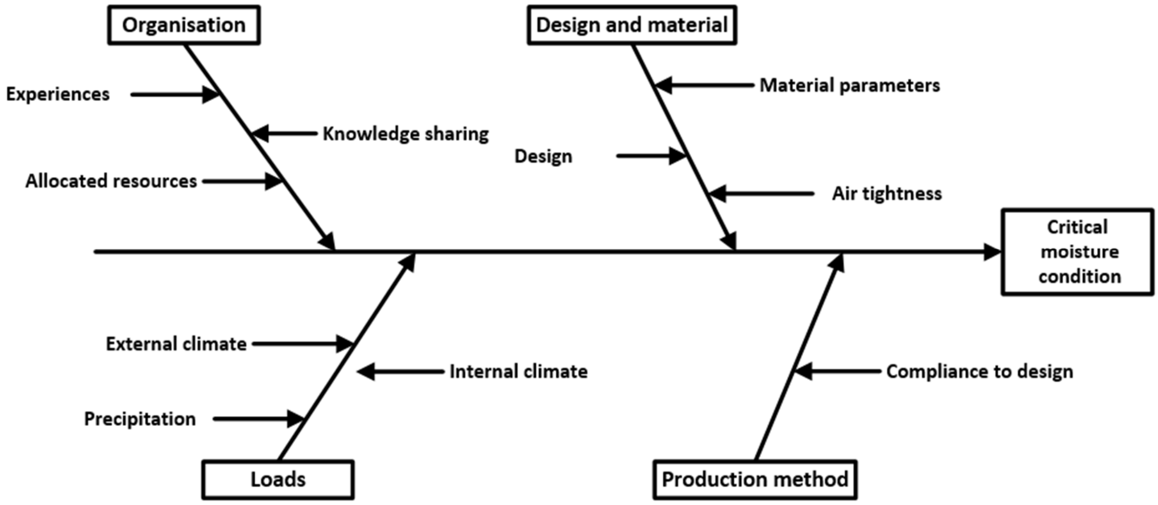


Figure 9. A two-level generic fishbone diagram used for visualising influencing factors for "exceeding critical moisture condition".

Quantitative methods

Established tools are used for the simulations, for example commercially available hygrothermal simulation tools or basic mass balance models suitable for the analysis. The Monte Carlo-based methods are suggested for probabilities in the quantitative analysis, suitable for the time-dependent, non-linear nature of the hygrothermal performance of the building envelope (Janssen et al., 2015). The Monte Carlo methods use a large number of simulations with randomized input parameters creating a probability function for the performance. Thus, the uncertainties and sensitivity of the results can be analysed. The accuracy of simulations can be increased by increasing the number of randomized simulations. By setting up a mathematical model to simulate the performance, using identified influencing parameters, defining probability density functions for influencing parameters, the performance can be simulated using random sampling of input values. The simulations are used to set up probability functions and sensitivity analysis.

Field or laboratory testing

As new technical solutions are studied, these can come with large uncertainties requiring additional knowledge. Depending on the case, field testing or laboratory testing might be needed to explore unknowns. Mock-ups or full-scale testing can be used for quantifying leakage of water into the construction dependent on precipitation or for exploring uncertainties in relevant material parameters. Testing should preferably follow available applicable standards and so forth.

7 Evaluation of two case studies using the risk assessment framework

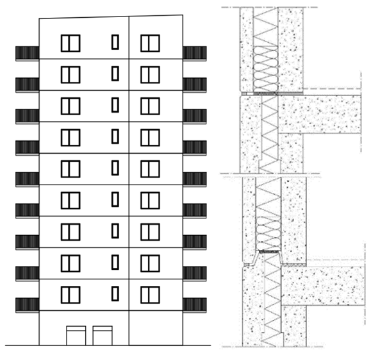
This section summarises the findings and conclusions of Papers II, III, IV, V and VI, focussing on Objective 3: Evaluate two case studies using the risk assessment framework, to assess the potential of the risk assessment framework by evaluating two current case studies.

The suggested risk assessment framework (Chapter 6) was used in two case studies: CLT in the construction phase (Paper IV) and joint sealing tape[26] in precast concrete sandwich facades (Paper V). Cases were independently identified at the company level as new technical solutions of interest having a market potential and potentially benefiting the design–build contractor. The framework was applied to each case, and insights from the case studies were used to suggest modifications to the framework. The scopes of the two cases are briefly pictured in Table 3. The definition of the scope was identified as important to establish a mutual understanding of the assessment (Papers IV and V) because several possible applications of the new technical solutions exist in both cases. In Paper II, it was noted that the level of details of the scope definition defines the level of detail required for the workshop. This also affects the applicability of the results. A clear definition of the scope is perceived crucial for an efficient assessment (Paper V).

Table 3. Brief overview of the two case studies: cross-laminated timber in the construction phase and joint sealing tape in precast concrete sandwich facades. Detailed descriptions are given in Paper IV and V.

Scope	Cross-laminated timber (CLT) in the construction phase (Paper IV)	Joint sealing tape in precast concrete sandwich facades (Paper V)
System boundaries	System comprises CLT structure, including structural elements and interconnections, limited to moisture safety in the construction phase.	System comprises pre-compressed joint sealing tape applied in joints between precast concrete sandwich panels contributing to performance requirements applicable to the facade.
Targets	Two targets were established based on moisture safety during construction, derived from the Swedish building regulations. The critical moisture conditions defined in (Boverket, 2019a) and the moisture content limit defined in (Svensk Byggtjänst, 2018) should not be exceeded.	Targets were based on the joint's contribution to the fulfilment of performance requirements, starting from basic requirements as in the Construction Products Regulation, Annex I (European Commission, 2011). The focus is on keeping a weather tight facade during its life span while handling the dimensional changes.

[26] Term definitions are collected in Appendix A1.

Strategies	Six-story multi-dwelling building in southern Sweden, where five-layer panels of CLT are chosen in floors, balconies and exterior and interior walls. Construction on site, where walls are externally insulated and the windows and the facade are installed. Typical time schedules for exposure of CLT are used. 	Horizontal and vertical joints between precast concrete sandwich panels, where joint sealing tape with an air gap between tape and insulation is chosen. In contrast to traditional solution*, air gap has no intentional connection to exterior. Width of joint is dependent on size of concrete sandwich elements. 
Limitations	The assessment is limited to defined scope and targets.	The assessment is limited to defined scope and targets.

*Joints traditionally have an outer rain protecting sealant on backing rod and a small air gap connected to outdoors by small openings (tubes) for depressurisation, drainage and ventilation.

Experiences of new technical solutions are scarce for obvious reasons, and suppliers' information constituted an important source of data in the two cases. A common finding was that suppliers provided the available documentation of product properties. In both cases, the product data from suppliers only comprised product properties specified in the corresponding EAD (EOTA, 2015), (EOTA, 2018). It was also found in Papers III and V that suppliers provide reference cases or refer to reference cases. However, these typically only provide descriptive information and not documented evaluated performance. In Paper III, it was found that the design–build contractor might have disproportionately high confidence in the product suppliers providing data for full verification of construction and operation of the CLT solution as the available data did not reflect all the needs of the design–build contractor. In Paper V, similar findings were obtained for the joint sealing tape case where for example water penetration properties were not given and reference cases did not have documented performance evaluation.

Stakeholder analysis using a power/interest grid was made in each case study to ensure an assessment covering relevant aspects and knowledge. At the workshops, risks and influencing factors were identified and categorised. In the CLT case, the conducted workshop was perceived as fruitful for risk identification but not for expert elicitation of likelihoods of failure. Tools, namely, fishbone diagrams and fault trees (see section 6.1.3), were used to illustrate identified main risks. The fishbone diagram was used to visualise and organise the influencing factors and illustrate the character of connected uncertainties. A fishbone diagram showing the unwanted event of exceeding critical moisture conditions during the construction of a CLT structure was created from workshop data (see Figure 10). By sorting identified influencing factors by organisation, design and material, loads and production method, and by assigning type of uncertainty to the factors, the loads, and design and material were identified to have considerable variations in data (aleatory uncertainties[27]) while organisation and production methods were dominated by unknowns (epistemic uncertainties[28]).

The fishbone diagram and corresponding data from the qualitative assessment was further developed into a fault tree to prepare for the quantitative assessment, as shown for the case of unwanted event of failing moisture requirements in the joint sealing tape case study in Figure 11. The corresponding figure for the CLT case study is presented in Paper IV. The fault tree was used when setting up the method for the quantitative assessment.

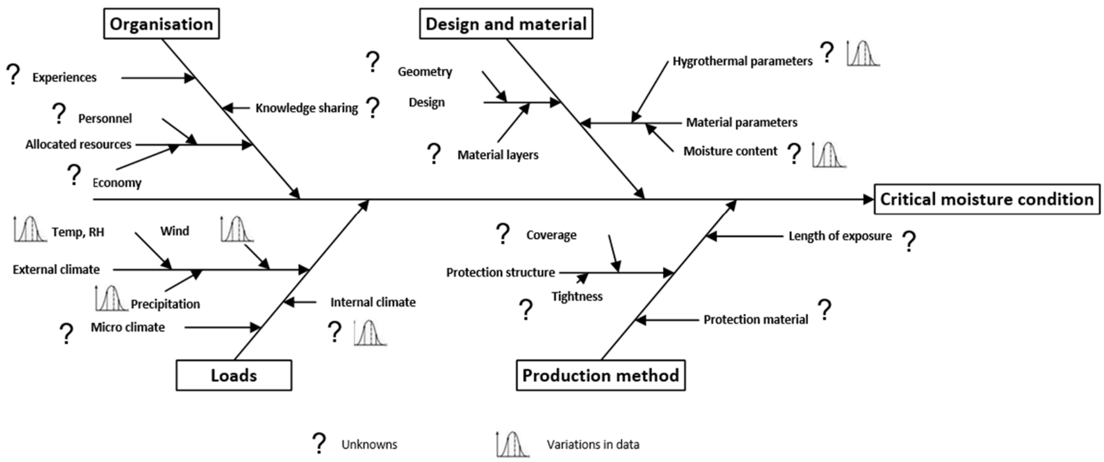


Figure 10. Overview of qualitative analysis using the fishbone diagram. The influencing factors for the case of not exceeding the critical moisture conditions during construction are shown for the CLT case study. The type of uncertainty is given for all factors of perceived influence. Cf. Paper IV.

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[27] Term definitions are collected in Appendix A1.

[28] Term definitions are collected in Appendix A1.

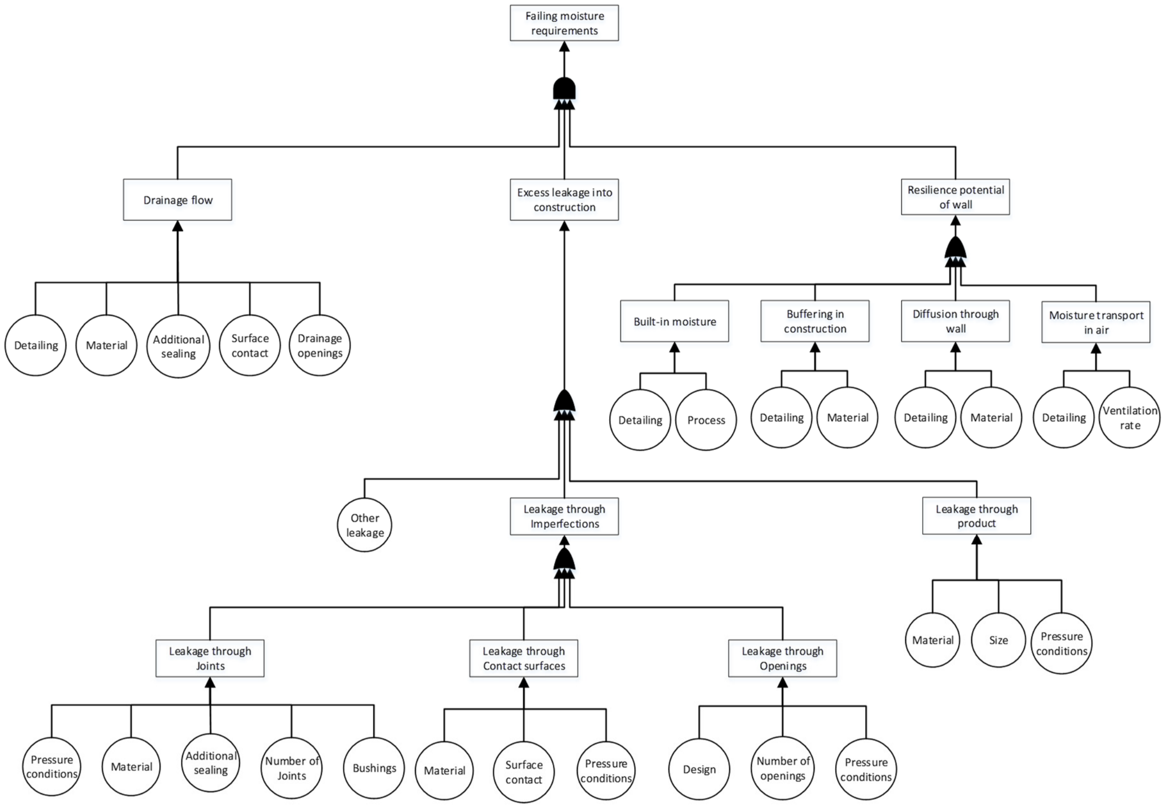

Figure 11. Overview of the qualitative analysis using the structure of a fault tree. The influencing factors for the case of failing moisture requirements are shown for the joint sealing tape. (Paper V)

In both cases, a quantitative analysis was recommended based on the qualitative analysis (tollgate 2). Furthermore, in both cases the qualitative analysis indicated assessment of the loads constituted a significant part of the analyses. In both cases, the climate conditions were visualised in relation to relevant exposure (see Figure 12). The figures were used for qualitative analyses as well as for communicating data to the design–build contractor on the importance of climate conditions.

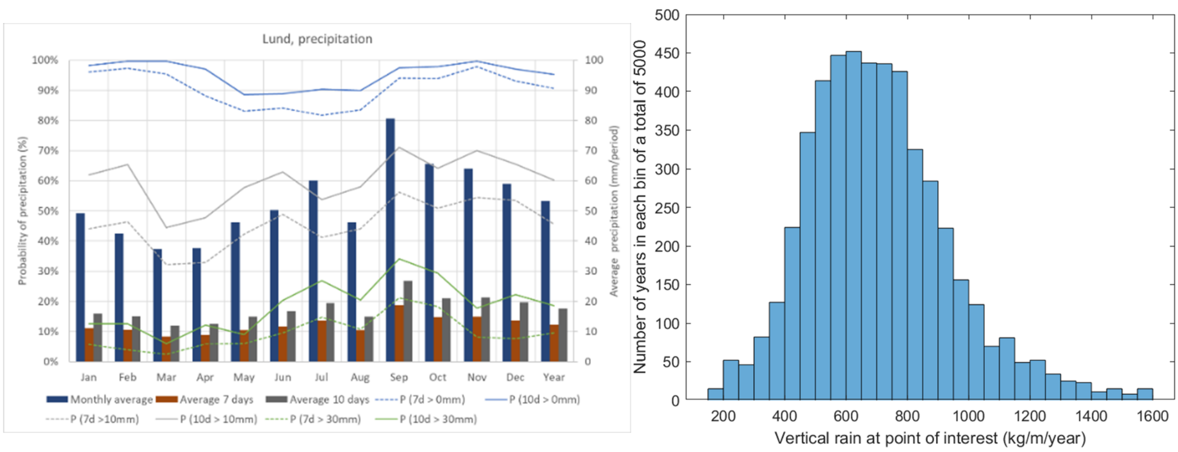

Figure 12. Visualisation of climate loads. Left: Case study on cross-laminated timber during construction. Expected precipitation during construction period. Probabilities of precipitation (<0 mm, 10 mm, 30 mm) for 7 and 10 days. Average horizontal precipitation for 7 days, 10 days and monthly. (Paper IV) Right: Case study on joint sealing tape in precast concrete sandwich facades. Rain load at the catch area of the joint in the studied façade (kg/m/year). Driving rain when the pulsating pressure over the building envelope is estimated to exceed 60 Pa (based on hourly precipitation and wind conditions). (Paper V)

The selected method of analysis differed between the two cases. For the CLT case, WUFI was used to assess hygrothermal conditions and the VTT model for the following mould growth assessment. In addition, field measurements were used to study the unknown influence of a full weather protection on hygrothermal conditions. Field measurements and corresponding findings are described in Paper VI, indicating a positive effect on hygrothermal conditions within the weather protection for the studied case, where the average temperature was slightly increased during the studied period resulting in a lower relative humidity. Based on the results of the simulations, probabilities of exceeding the two targets were presented.

For the joint sealing tape case, a simplified mass balance model was set up for the horizontal joint, and using the Monte Carlo method, the probabilities of resulting water drainage in the joints were simulated (see Figure 13). The leakage potential was determined using laboratory measurements and the results were used as input to the simulations (Paper V).

The need for probabilistic simulations using sequences of years was emphasised as the 'normal' year in WUFI resulted in the lowest mould risk potential of all years for almost all the scenarios used in the CLT case. Correspondingly, in the joint sealing tape case the rain load at the facade differed eight times when comparing the lowest and highest yearly load.

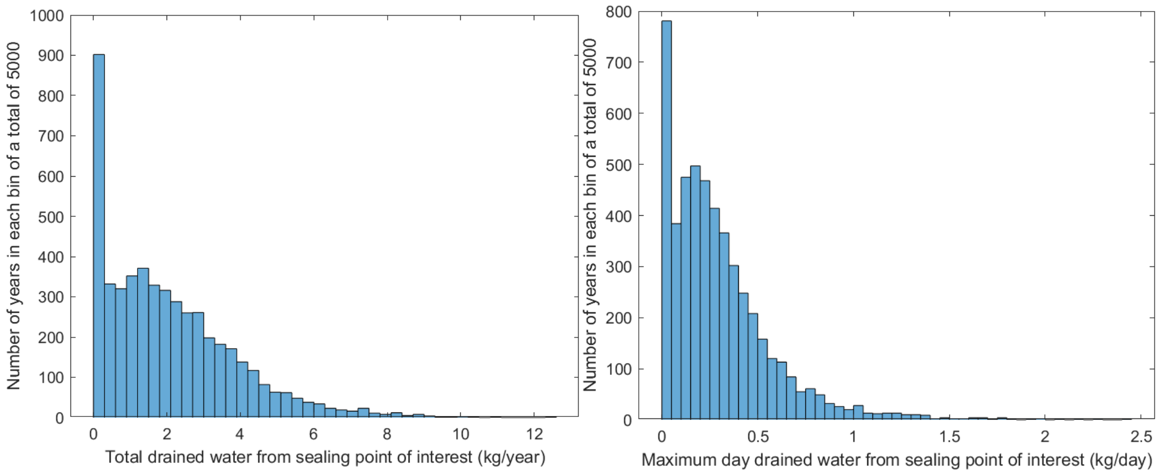

Figure 13. Joint sealing tape in precast concrete sandwich facades. Resulting draining water using assumptions based on (Olsson, 2021). Left: total annual drained water from joint (kg/year). Right: yearly day maximum drained water from joint (kg/day). (Paper V)

In the presentation of results to a design–build contractor, the probabilities are preferably interpreted. The results obtained for the CLT case study are given in Table 4 and Table 5. The criterion for colours in the tables refers to the acceptable levels of failure.

Table 4. Summary of assessment concerning moisture target for CLT during construction. Results for exposed and protected CLT structure. Colour assessment of risk related to moisture targets in scope (green = low, yellow = medium, orange = high, and red = very high). Cf. Paper IV (corrected).

Moisture content	Normal construction period				Short construction period			
Start of construction	**January**	**April**	**July**	**October**	**January**	**April**	**July**	**October**
Exposed case summary	red	red	red	red	red	red	red	red
Exterior wall	green	yellow	red	red	red	green	yellow	red
Intermediate floor	green	yellow	red	red	red	green	yellow	red
Shafts/ leakages	green	yellow	red	red	red	green	yellow	red
Water trapping	red	red	red	red	red	red	red	red
Protected case summary	green	green	orange	yellow	green	green	green	orange
Exterior wall	green	green	orange	yellow	green	green	green	orange
Intermediate floor	green	green	orange	yellow	green	green	green	orange

Table 5. Summary of assessment concerning mould target for CLT during construction. Results for exposed and protected CLT structure. Colour assessment of risk related to mould targets in scope (green = low, yellow = medium, orange = high, and red = very high). Cf. Paper IV (corrected).

Mould growth	Normal construction period				Short construction period			
Start of construction	**January**	**April**	**July**	**October**	**January**	**April**	**July**	**October**
Exposed case summary	red	red	red	red	red	red	red	red
Exterior wall*	yellow	red	red	red	yellow	yellow	red	red
Intermediate floor	green	yellow	yellow	yellow	green	green	yellow	yellow
Shafts/ leakages	yellow	red	red	red	yellow	red	red	red
Water trapping	red	red	red	red	red	red	red	red
Protected case summary	green	yellow	yellow	yellow	green	green	yellow	yellow
Exterior wall	green	yellow	yellow	yellow	green	green	yellow	yellow
Intermediate floor	green	yellow	yellow	yellow	green	green	yellow	yellow

In the case of joint sealing tape in precast concrete sandwich panels in Paper V, the evaluation reporting is given as recommendations with a brief description of the available documentation. It is concluded that the new technical solution might be possible if the draining potential is ensured in all detailed designs. Additional measures should be considered for highly exposed facades, such as the south-facing facade, in the study. This should be further explored and might include joints with a separated rain tight layer and a tight wind barrier using a ventilated and drained air space combined with meticulous measures to ensure the wall's drainage in every detail, with a particular focus on the base of the building. The impact of driving rain is significantly lower for less exposed facades and locations. The recommendations include full-scale testing in a building, before implementing in additional buildings.

To summarise the findings on framework evaluation, an analysis of strengths, weaknesses, opportunities, and threats (SWOT) of the framework using the design–build contractor perspective was performed in Paper IV. Three success factors were identified: documentation and communication, expert involvement and a structure using tollgates. In Paper V, an additional emphasis was laid on the period of the evaluation process, where several months were needed in both cases mainly to collect data from different stakeholders and allocate time for the expert group besides the actual analysis.

8 Discussion

This section discusses the findings in Papers I–VI, whether this framework can be expected to help protect a design–build contractor from serial failure and how efficient the framework can be compared to other approaches.

A new technical solution holds uncertainties regarding its performance in buildings. The initial interviews described in Paper I indicated that new technical solutions are often introduced directly in a specific building project. The interviews identified a lack of methodology for verifying the fulfilment of requirements, such as moisture safety, when introducing new technical solutions in the Swedish construction industry. Instead, the implementation was perceived to rely on the normal design process, where steps in evaluation and requirements of documentation were perceived as unclear. Even though there are methods for risk assessment, the interview study indicated that they are not commonly used to assess the performance of new technical solutions when implemented in the construction industry. Other studies imply similar observations for simulation tools. For example, in (Burke, 2009), it is found that building physics tools are not used in industry because of high costs or usability issues, including inadequate information. Furthermore, Boverket[29] expresses a need for learning to handle new technical solutions because these are expected in the future (suggesting an improvement in handling compared to the current practice level is needed) (Boverket, 2018). The issue of non-existent or insufficient feedback in the construction industry is also confirmed in both articles studying defects, which indicate that feedback from inspections is valued by contractors but lack process to support feedback (Lundkvist, 2011), and articles on innovation in the construction industry, which identify the need for more efficient re-use of innovations in future construction projects (Slaughter, 2000).

As a substitute for other evaluations, there are indications of using reference cases to verify new technical solutions (Paper I). At the same time, there is an identified lack of structured documented evaluation of performance in reference projects (Papers III and V). Furthermore, to use a reference case for verifying two sets of evaluation concerning reference cases needs to be in place: the first evaluation involves the performance of the reference case itself, whereas the second evaluation addresses the applicability of the reference case to the current application. The use of insufficiently evaluated reference cases constitutes a potential key issue for developing a serial failure. When the design–build contractor introduces a new technical solution in a single construction project, it exposes that specific construction project to the risk of using a potentially inferior solution. In the risk assessment, the consequences of failure in a single project must be handled. However, by using reference cases without appropriate evaluation, solutions can be copied without control of the consequences. If the solution is inferior, serial failures develop. In contrast to a failure in a single project, serial failures can impact not only the specific construction projects but also the construction industry and society, as indicated in the historical examples.

[29] The Swedish National Board of Housing, Building and Planning

Furthermore, even though a reference case does not hold sufficient evaluation, it might give a false sense of confidence in the new technical solution, and the risk awareness might be lower in the sequent construction projects. Reference cases are also problematic to use as proven solutions[30] in this context because the hygrothermal processes are slow and the detectability of a failure is low. Detection of a failure can be delayed.

As the design–build contractor can be involved in applying new technical solutions, it is essential to raise awareness of the phenomena of serial failures within the companies and the potential negative impact of using reference cases without appropriate documentation and/or without appropriate applicability to the current application. Furthermore, by providing a framework particularly addressing the design–build contractor perspective, the ambition is to lower the threshold to evaluate new technical solutions and, at the same time, provide an appropriate evaluation for the design–build contractor. Although the framework aims to prevent serial failure, a framework might also be beneficial by providing confidence to design–build contractors in implementing new technical solutions.

8.1 How can this framework protect a design–build contractor from serial failure?

The overall aim of the work was to reduce the occurrence of serial failures related to new technical solutions. As described in Chapter 6 (Papers IV and V), the framework was elaborated from an existing framework and practices to provide a systematic risk assessment approach focussing on moisture safety for new technical solutions from a design–build contractor perspective. The earlier indicated lack of resources and time to allocate to evaluation within an individual construction project and the identified lack of methodology and complexity in finding an appropriate level of evaluation are mitigated by performing a pre-qualification on a central level. A separate organisation is used answering to a steering group appointed by management throughout the evaluation process. The framework does not intend to cover the actual innovation of new technical solutions, only the evaluation of a new technical solution applied by a design–build contractor. Thus, unlike an innovation process, the suggested framework is pictured as a linear process. However, if the decision is taken to change the scope during evaluation, then steps in the framework could be iterated.

The management decides, based on a business perspective, which new technical solutions should be evaluated using the framework before applying the risk assessment framework. The use of the suggested framework should be assessed as favourable from a design–build contractor perspective. In other words, the time and resources of the evaluation should be assessed in relation to the anticipated benefits of the evaluation of the new technical solution. Furthermore, the importance of defining a clear scope was noted in Papers IV and V. The scope should align with the anticipated application of the technical solution to enable adopting results into future

[30] Boverket's building regulations, BBR

construction projects. It was noted that the level of detail of the scope also affects the general applicability of the results. In Paper IV, the scope was limited to the construction phase of a typical multi-dwelling building because it was identified as critical. At the same time, the possibility of iterating the process with an expanded scope was identified. In Paper V, several different applications were identified in practice, and by delimiting the scope to the one solution recommended by the supplier, the work was concentrated, thereby increasing the effectiveness of the evaluation.

A methodology that can structure the evaluation process of the application of different kinds of new technical solutions was established. The focus within the assessment and the tools used might be different depending on the nature of the new technical solution. This should be suggested by the project manager and decided by the steering group. The case of CLT during construction is an example of a more radical new technical solution affecting the whole building, while the case of joint sealing tape in precast concrete sandwich panels is more incremental but still impacts the surrounding elements. In the first case, the probabilistic methods were highly relevant for assessing moisture content and mould growth potential because these were not qualitatively accessible. In the second case, the probabilistic methods are relevant, but several uncertainties are highly dependent on the design of details. By complementing with results from laboratory testing, these uncertainties could be further explored, increasing the value of the quantitative assessment.

By using the framework, new technical solutions assessed as high risk in the documented pre-qualification could be avoided in construction projects, mitigating the risk for serial failure without affecting the costs and time in the individual construction projects. In Paper IV, the pre-qualification was visualised in a matrix (using different colours) together with recommendations. Several combinations of solutions were assessed as high risk. In Paper V, the pre-qualification identified an anticipated substantial leakage for an exposed facade indicating high water intrusion risks. The risk assessment also resulted in recommendations to be followed, including full-scale testing.

In Paper II, the workshop's participants indicated increased insights. In both case studies, the expert workshops were perceived as powerful for risk identification, including influencing factors, while the impact of factors, consequences and corresponding probabilities were perceived to have remarkable uncertainties and were thus complex to assess. This could have been mitigated using expert elicitation of probabilities based on one of the suggested protocols (Delphi (Rowe & Wright, 1999), SHELF (Oakley & O'Hagan, 2016) or Cooke (Cooke, 1991)). However, these methods involve quite large resources, and in the two case studies, quantitative simulations and data from with laboratory (Paper V) and field measurements (Paper VI) were chosen.

To conclude and shortly answer the question 'How can this framework protect a design–build contractor from serial failure?', a design–build contractor should be able to avoid or reduce serial failure occurrence when introducing new technical solutions by using the suggested framework. The engagement of management representatives in the evaluation steering group is expected to facilitate understanding and implementing results in the company's construction projects. Using predefined steps and tollgates, encouraging documentation and engaging the management, the formalised framework is also expected to increase knowledge in the organisation and thus prevent ad hoc assessment, excessive use of checklists or relying on undocumented reference projects. Each company has its internal processes and specific set of capabilities. Certain companies can rely heavily on internal capabilities, while others need external collaborations to use the proposed risk framework. The proposed framework and related processes need to be aligned with the related processes in the company implementing them.

Finally, would the suggested framework have identified and prevented earlier mentioned costly serial failures (ETICS, MgO-boards or crawl spaces) if used before implementation? The question is not easy to answer in retrospect, as hindsight bias affect the ability to assess historical events. All three technical solutions came with remarkable anticipated benefits. However, in the case of outdoor air-ventilated crawl spaces, the potential serial failure should have been discovered in a quantitative assessment (using today's simulation methods), where the probabilities of critical moisture levels of wooden materials should have been identified as too high. In the case of MgO-boards, the potential serial failure might have been discovered in the qualitative assessment where material properties for relevant conditions as identified in a risk identification workshop would have been inaccessible. In the case of ETICS, the potential serial failure might have been revealed during the risk identification workshop, if the new technical solution had been lifted to a central level with a wide range of experts not invested in the solution able to identify the strong reliance on meticulous workmanship or when international problems were identified in a literature search. But it should be humbly noticed. It is easier to say 'what did I say' with all cards on hand, and the risks have proved to surpass the anticipated benefits.

8.2 How efficient is the framework in preventing serial failure compared to other approaches?

To assess the framework's efficiency the definition an appropriate evaluation method needs to be addressed. From a legal perspective, the Swedish Supreme Court stated[31] the contractor should not rely on common practice but perform an appropriate evaluation of the technical solutions used. Even though the concept of the appropriate evaluation was not defined, it was also stated that if performed, it would not necessarily have identified the problems. One way to interpret appropriate evaluation could be to relate efforts of evaluation to potential negative consequences avoided. The framework's efficiency in preventing serial failure can then be interpreted as a cost-benefit question, where the evaluation costs should be assessed in relation to the possible negative outcomes of a serial failure for the contractor. Another

[31] Högsta domstolen (the Swedish Supreme Court) Case T916-13: NJA 2015 s 110, and NJA 2015 s 1040

interpretation can relate to the efficiency of the framework in identifying potential serial failures.

In this work, no alternative frameworks or methods have been used to evaluate the same two new technical solutions studied within the two case studies. Several available methods are strongly focused on assessing project-level risks, with or without focussing on building physics (Mjörnell et al., 2012), (Bednar & Hagentoft, 2015) or even the ad hoc evaluation within projects indicated in Paper I. In Paper V, the evaluation took months depending on planning, information retrieval, organising expert group and data analysis. Independent of the alternative method, allocating time for evaluation and information retrieval should be obstacles to a construction project where this time interval is usually not available. From the efficiency perspective, evaluating with a focus on individual construction projects could lead to multiple evaluations and/or lack of implementation in other construction projects. For cases relying on reference cases without documentation, the time and resource aspects should not be a problem. However, relying on reference cases without documentation is not expected to be efficient in preventing serial failure.

Finally, within the case study on joint sealing tape in precast concrete sandwich facades, the traditional solution seemed to have several deficiencies in documentation and a troublesome track record regarding moisture safety (Paper V). Even if the industry perceives the solution as a proven solution, continuous incremental changes have been made in materials, detailing, processes and possibly climate loads, and the performance has not been documented. Apart from confirming the need for improvement of evaluation, it emphasises on the problem of using proven solutions or qualitative assessment. Design–build contractors may use many other current technical solutions that are not evaluated in a structured way, neither when implemented nor later. An increased evaluation of new technical solutions is expected to highlight deficiencies in current solutions in practice as well.

9 Conclusions

This section includes the conclusions.

This work resulted in an elaborate framework for risk assessment, addressing new technical solutions. The framework was perceived as essential for a design–build contractor to avoid developing serial failures. This was in line with the overall aim: to reduce the occurrence of serial failures related to new technical solutions by suggesting a systematic approach for risk assessment with focus on moisture safety, seen from a design–build contractor perspective. The work had three objectives: (1) investigate current practices on how new technical solutions are introduced and evaluated, (2) establish a risk assessment framework and (3) evaluate two case studies using the risk assessment framework.

Based on early studies of methods and semi-structured interviews with selected key actors in the construction industry, even though there were methods for different aspects of risk assessment and tools for simulation and analysis of building physics, these were not used in a structured way in the construction industry. In addition, an unfortunate use of reference cases without documented verification in the industry was identified. The suppliers' verification of the application of the new technical solution was identified with a disproportional trust. In the semi-structured interviews, a need for improving the current practice of implementing new technical solutions was identified, where interviewees identified a need to define and strengthen steps in evaluation and define requirements on reference cases.

Based on literature findings and semi-structured interviews and workshops, the framework was elaborated, adding a company perspective to the evaluation using tollgates and a management steering group to a framework developed for retrofitting. The framework was evaluated using two real-life case studies addressing different current new technical solutions: CLT in the construction phase and joint sealing tape in precast concrete sandwich facades. In conclusion, key elements of the suggested framework are as follows:

- Company-level perspective: the new technical solution for evaluation should be selected from a company perspective before initiating the framework to ensure effective use of the company's evaluation resources. During post-processing, the output from the evaluation should be managed from a company perspective to ensure acceptable risk exposure at the company level. The central perspective also enables the appropriate allocation of time and resources to the evaluation. A steering group assigned by company management should ensure the company-level perspective.
- Tollgates: tollgates for steering group decisions and communication were added to further structure the process, reflect the design–build contractor's interests throughout the process and contribute to efficiency in evaluation. In each tollgate, the evaluation must deliver the documented basis used for decision-making, while the steering group assigned by company management makes the decisions.

- Expert workshops: expert workshops for risk identification and possibly for risk analysis involving stakeholders selected using a power/interest matrix to ensure different relevant perspectives were represented was perceived as a success factor. For new technical solutions, experience is by definition sparse; thus, experts are crucial.
- Documentation and communication: the framework facilitates structured evaluation documentation using the tollgates to file the evaluation to facilitate future use; thus, contributing to mitigating serial failures. The communication of evaluation is facilitated using tollgates.

Apart from the evaluation of the framework, the two case studies resulted in pre-qualification and recommendations on CLT in the construction phase and joint sealing tape in precast concrete sandwich facades, respectively:

- CLT in the construction phase: the set targets are found to be achievable with the defined prerequisites. A large variation in outcomes where the season and the duration of the construction period have substantial impact on results is identified. Avoiding exposing the material to precipitation is crucial, and the selected new technical solution, as described in the scope of the evaluation, is recommended to be allowed for use if complete weather protection is used during construction. In a field study of complete weather protection, the hygrothermal conditions were significantly improved by redirecting precipitation and slightly increasing temperature. Identified details are preferably qualitatively assessed. It is also recommended to document the solution in construction projects, including monitoring onsite experiences and mould sampling.
- Joint sealing tape in precast concrete sandwich facades: the set targets might be possible to meet if draining potential is ensured in all detailed design, but additional measures should be considered for highly exposed facades. The quantitative assessment shows a substantial leakage for the studied exposed facade. However, the leakage is potentially mitigated using the water draining property and materials with high critical moisture levels. Thus, full-scale testing in a building is recommended combined with comprehensive documentation and monitoring of moisture conditions to create a documented and evaluated reference case before implementing on a large scale.

In the coming years, the construction industry needs to play an essential role in reducing CO_2 emissions to mitigate climate change. This will require new technical solutions, but the industry has long battled with high costs related to quality issues and serial failures, implying the need for new ways of work. In design–build projects, the contractor plays an important role in being liable for the design and construction when implementing new technical solutions. The suggested systematic approach to evaluating new technical solutions facilitates the needed global change of the construction industry by instilling confidence in the design–build contractor to use new technical solutions and reducing the occurrence of serial failures when new technical solutions are used.

10 Suggestions for future work

This section includes suggestions for future work.

Based on the results and conclusions of this work, three suggestions for future work on the framework are pictured.

1. A strong suggestion is to develop an assessment method for reference cases based on the proposed framework, where new technical solutions of interest are implemented and evaluated by monitoring and other means. The documentation of the reference case can then serve as a documented reference case for other construction projects. The assessment method should comprise guidance for assessment of both the reference case and the applicability of the reference case to the current application.
2. Also, the two case studies can be followed to evaluate the applicability of the pre-qualification and recommendations in one or several real-life construction projects. Possibly, these real-life projects can then serve as documented and evaluated references for each solution, respectively.
3. In the future, the framework could also be implemented as a standardized method in the design–build contractor companies as well as in the construction industry, potentially reducing the occurrence of serial failures in the construction industry.

In addition to these suggestions, the two case studies gave rise to several studies on technical properties and performance where documented information holds large uncertainties as given in Paper IV and V. Suggestions for future work:

- CLT in construction phase (Paper IV): Full-scale testing with monitoring onsite experiences regarding targets is suggested to increase knowledge.
- Joint sealing tape in precast concreate facades (Paper V): Exploring impact of different climate scenarios (scenarios and locations), laboratory testing of draining properties of joints using joint sealing tape and full-scale testing including measurements and documentation onsite are suggested to increase knowledge.

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A1: Definitions of key concepts used

CLT: cross-laminated timber, a wooden product consisting of orthogonal layers of wood glued together. Typically, three, five or seven layers of spruce or pine are used in structural components in buildings.

Design–build contractor: contractor responsible to the client for design works and execution based on the client's description of intended use and characteristics, performance specifications and possibly reference cases.

Failure: failure to fulfil set targets, for example, performance requirements.

Joint sealing tape: pre-compressed impregnated sealing tapes made of cellular plastics (polyurethane foam) for sealing of outside wall joints.

Performance requirement: criteria on how the building (or part of) should perform

Risk: effect of uncertainty on objectives (ISO Guide 73:2009, 2009), which can be positive or negative. Risk is often expressed in terms of a combination of the consequences (in relation to targets) and probability of these consequences to occur.

Risk management: coordinated activities to direct and control an organization with regard to risk (ISO Guide 73:2009, 2009). Activities to handle risks, such as prevention, mitigation, adaption or sharing, are considered. It often includes trade-offs between costs and benefits of risk reduction and choice of a level of tolerable risk (Aven et al., 2018).

Risk assessment: systematic process to comprehend the nature of risk and express and evaluate risk with the available knowledge (Aven et al., 2018).

Risk identification: process of finding, recognizing and describing risks, including sources, events and potential consequences (ISO Guide 73:2009, 2009).

Risk evaluation: process of comparing the result of risk analysis against risk criteria to determine the significance and acceptability of the risk (Aven et al., 2018).

Risk treatment: process to modify risk, described as risk avoidance, risk optimization, risk transfer or risk retention.

Serial failure: multiple cases of failure where a technical solution fails to sustain the requirements. Here, the focus is on serial failures arising from reasons in the design or production that could have been predicted by calculations or assessment in the design phase (Svensson Tengberg & Hagentoft, 2019).

Uncertainties: imperfect or incomplete information/knowledge about a hypothesis, a quantity or the occurrence of an event (Aven et al., 2018). Uncertainties can be divided into aleatory and epistemic uncertainties.

Uncertainties, aleatory (stochastic): variation of quantities in a population, its natural variability. Aleatory uncertainties cannot be reduced but can be handled by probabilistic methods.

Uncertainties, epistemic: comprises model uncertainties, parameter uncertainties and scenario uncertainties. Epistemic uncertainties can be reduced by increased knowledge.

A2: Three historical serial failures

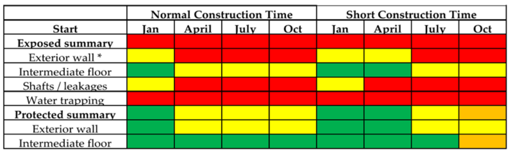
Table A2.1. Summary of three historical serial failures using a structure to describe characteristics.

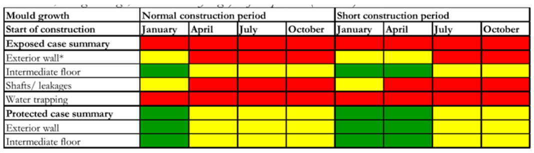
	Outdoor ventilated crawl spaces	**MgO-boards**	**ETICS**
Type of solution	Design	Product	Design
Short description	Crawl spaces were designed with a wooden intermediate floor over an outdoor air-ventilated space.	MgO-boards were used as a wind barrier in wooden walls and as boards in wet room walls.	ETICS with plaster on insulation board (cellular plastic or mineral wool) were applied to wooden stud walls.
Innovation	A traditional design solution was modified.	A new material was introduced.	A known solution was modernized and applied to wooden stud walls.
Anticipated benefits	Effective solution enabling prefabricated wooden constructions.	A cheap alternative to paper gypsum boards prone to mould growth.	An efficient way to achieve aesthetic walls with good energy performance.
Basis of introduction	References from abroad. Common practice.	Documentation of some product parameters.	References from abroad. Common practice.
Performance requirement not fulfilled	Moisture safety	Moisture safety	Moisture safety
Description of overseen risk scenario	The effect of the modifications with respect to hygrothermal conditions was not sufficiently investigated.	The critical moisture condition of the material was not sufficiently investigated, as mould growth was in focus. Differences in material properties between similar products overseen.	The impact of water intrusion on moisture conditions was underestimated. The impact of details and performance on water intrusion was underestimated.
Risk characteristic	Major consequences, high probabilities	Major consequences, high probabilities	Major consequences, high probabilities
Description of failure	Critical moisture conditions were exceeded for materials resulting in odour, mould growth and, in some cases, decay of wooden materials.	Critical moisture conditions were exceeded for the material causing corrosion on adjacent material and loss of strength and shape of the product.	Critical moisture conditions were exceeded for wall construction resulting in mould growth and, in some cases, decay of wooden materials.
Failure characteristic	Slow process with low visibility	Slow process with low visibility	Slow process with low visibility

Papers I to VI

Errata

<table>
<tr><th>In paper</th><th>Should be</th></tr>
<tr><td>Paper I</td><td></td></tr>
<tr><td>Introduction: Reference (Samuelson, 2011)</td><td>(Boverket, 2018)</td></tr>
<tr><td>Introduction: Reference (Boverket, 2018)</td><td>(Samuelson, 2011)</td></tr>
<tr><td>Paper III</td><td></td></tr>
<tr><td>Section 2.3: Reference [4]</td><td>[11]</td></tr>
<tr><td>Paper IV</td><td></td></tr>
<tr><td>Section 3.2.3</td><td>Section 3.3.2</td></tr>
<tr><td>Table 2: Reference missing for 3 “Normal year” WUFI/LTH</td><td></td></tr>
<tr><td>Table 4: Protected case, normal construction time, October: Summary, exterior wall and intermediate floor are marked green.</td><td>Table 4: Protected case, normal construction time, October: Summary, exterior wall and intermediate floor should be marked yellow.</td></tr>
<tr><td>Table 5: Protected case, Intermediate floor is not correct. This also impacts the Protected summary.


<table>
<tr><th></th><th colspan="4">Normal Construction Time</th><th colspan="4">Short Construction Time</th></tr>
<tr><th>Start</th><th>Jan</th><th>April</th><th>July</th><th>Oct</th><th>Jan</th><th>April</th><th>July</th><th>Oct</th></tr>
<tr><td>Exposed summary</td><td>red</td><td>red</td><td>red</td><td>red</td><td>red</td><td>red</td><td>red</td><td>red</td></tr>
<tr><td>Exterior wall *</td><td>yellow</td><td>red</td><td>red</td><td>red</td><td>yellow</td><td>yellow</td><td>red</td><td>red</td></tr>
<tr><td>Intermediate floor</td><td>green</td><td>yellow</td><td>yellow</td><td>yellow</td><td>green</td><td>green</td><td>yellow</td><td>yellow</td></tr>
<tr><td>Shafts / leakages</td><td>yellow</td><td>red</td><td>red</td><td>red</td><td>yellow</td><td>red</td><td>red</td><td>red</td></tr>
<tr><td>Water trapping</td><td>red</td><td>red</td><td>red</td><td>red</td><td>red</td><td>red</td><td>red</td><td>red</td></tr>
<tr><td>Protected summary</td><td>green</td><td>yellow</td><td>yellow</td><td>yellow</td><td>green</td><td>green</td><td>yellow</td><td>orange</td></tr>
<tr><td>Exterior wall</td><td>green</td><td>yellow</td><td>yellow</td><td>yellow</td><td>green</td><td>green</td><td>yellow</td><td>yellow</td></tr>
<tr><td>Intermediate floor</td><td>green</td><td>green</td><td>green</td><td>green</td><td>green</td><td>green</td><td>green</td><td>orange</td></tr>
</table></td><td>Table 5: Protected case, Intermediate floor, as well as Summary should have the same colors as Protected case, exterior wall.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<tr><td>Exposed case summary</td><td>red</td><td>red</td><td>red</td><td>red</td><td>red</td><td>red</td><td>red</td><td>red</td></tr>
<tr><td>Exterior wall*</td><td>yellow</td><td>red</td><td>red</td><td>red</td><td>yellow</td><td>yellow</td><td>red</td><td>red</td></tr>
<tr><td>Intermediate floor</td><td>green</td><td>yellow</td><td>yellow</td><td>yellow</td><td>green</td><td>green</td><td>yellow</td><td>yellow</td></tr>
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</table></td></tr>
<tr><td>Paper VI</td><td></td></tr>
<tr><td>Figure 4. Legend for the right figure

“Temperature within the weather protection …”</td><td>“Temperature within the weather protection and external temperature …”</td></tr>
</table>