# Exploring Safe and Sustainable by Design (SSbD) Framework for Responsible Facade Design: A Case Study with Leafy

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# Exploring Safe and Sustainable by Design (SSbD) Framework for Responsible Facade Design: A Case Study with Leafy

by


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Cover: Visual representation of Leafy Façade Panel.
Source: Generated by Leafy design team (2025)

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# Acknowledgement

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Anuj Goyal
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# Executive Summary

This thesis, titled "Exploring Safe and Sustainable by Design (SSbD) Framework for Responsible Facade Design: A Case Study with Leafy," addresses the critical need for integrating safety and sustainability in the built environment amidst challenges like rapid urbanization and climate change. The building sector significantly contributes to global greenhouse gas emissions and material consumption, necessitating transformative approaches beyond mere efficiency gains. While biobased materials offer compelling benefits, their widespread adoption is hindered by concerns regarding fire safety, material durability and long-term performance. The European Union's (EU) SSbD framework aims to embed safety and sustainability from the earliest stages of product development, but its application to the construction sector, particularly for novel biobased façade systems, remains underdeveloped.

The primary objective of this study was to explore how the SSbD framework can be practically applied to the development of biobased green façade panels, using Leafy, a startup specializing in bamboo-based façade panels, as a case study. The research focused on identifying critical design characteristics, uncovering operational challenges within the current framework and generating actionable recommendations for startups, designers and policymakers.

The methodology employed a qualitative case study with quantitative aspects, drawing on abductive reasoning. Data collection involved document analysis (including material data sheets and regulatory frameworks) and semi-structured interviews with key stakeholders such as architects, façade engineers, raw material suppliers and the Leafy team. The research applied the EU's five-step SSbD framework to evaluate Leafy's panel design, providing detailed scores for each material's safety and sustainability performance.

Key findings and insights from the study include:

- **SSbD Applicability and Contribution:** This thesis academically examines the application of the SSbD framework within construction materials and façade systems, an area previously underrepresented in literature. The exploratory case study demonstrates how theoretical SSbD principles can be practically applied in the construction industry, informing theoretical discourse and providing practical insights for scaling responsible innovation.

- **Material Performance in SSbD Evaluation:** The evaluation revealed clear distinctions between recyclable materials (e.g., bamboo fibre, bio-based resin, jute cloth, stainless steel (SS) and conventional synthetic materials (e.g., epoxy resin, low-density polyethylene (LDPE), polypropylene (PP), ethylene propylene diene monomer (EPDM) in terms of their hazard profiles and environmental impacts.
    - In Step 1 (Hazard Assessment), the evaluation found that none of the materials reached Level 3 overall, which suggests a stringent threshold within the SSbD framework for materials considered free of concern.
    - In Step 3, several materials achieved 'Level 3' for that specific phase's safety performance and in the comparative LCA (Step 4), biobased materials showed the highest scores (Level 4, equivalent to SSbD Score 3). However, when aggregated across all steps using the non-compensatory approach, no material reached the overall SSbD Level 3.
    - Epoxy resin was the only material evaluated to receive a Level 0 score, an outcome consistent with observations about its volatility, user exposure risks and emissions.

  - In the comparative LCA (Step 4), biobased materials such as bamboo fibers and jute cloth showed the highest scores (Level 4), which appeared to be influenced by their carbon uptake during growth and renewability.
  - The findings suggest that the assumption that biobased materials are automatically benign may need further consideration, as the evaluation emphasizes the importance of exposure routes, degradation mechanisms and data gaps, even for natural materials.

- **Identified Challenges and Limitations:** Incomplete and non-transparent material data for biobased façade systems limited the ability to fully identify and assess potential risks. Conducting accurate Life Cycle Assessments (LCA) at early stages of product development proved particularly challenging, especially when working with pilot-scale materials. Within the SSbD framework, Step 1 focuses on assessing intrinsic hazards without accounting for actual use conditions or potential risk mitigation measures during the initial evaluation. Similarly, Step 5, the Socio-economic Assessment, remains underdeveloped, lacking clear standardized guidelines and user-friendly tools, posing significant operational challenges for startups. In addition, outdated certification pathways and regulatory conservatism continue to hinder the adoption of novel biobased materials. These issues are compounded by the resource constraints typical of startups, which limit their capacity to conduct comprehensive SSbD evaluations.

- **Stakeholder Perspectives:** Stakeholders affirmed the framework's relevance, perceiving it as a helpful guide for structured and holistic product development. They found it useful for balancing diverse demands such as safety, sustainability, usability and business cases. Stakeholders emphasized the importance of system-level evaluation, maintenance, end-of-life planning and addressing market viability, suggesting flexibility in the SSbD steps for biobased contexts. Safety was consistently a non-negotiable priority, followed by performance and durability, with sustainability as an essential but secondary consideration.

In conclusion, this thesis demonstrates how to operationalize the SSbD framework for green façade panels using a tiered, multi-criteria assessment that integrates hazard analysis, life cycle thinking and practical risk mitigation. The SSbD assessment results indicate that Leafy's material strategy aligns well with SSbD principles, with bio-based materials performing strongly across safety and environmental dimensions. Based on these findings, Leafy should consider restricting epoxy resin to non-visible, structural applications and actively explore alternative resin systems. The study highlights that a responsible design employs a hybrid material strategy, implying neither perfection nor a one-size-fits-all approach, but instead meets minimum thresholds across safety and sustainability dimensions, guided by principles of precaution and transparency. It also points to the need for the SSbD framework to evolve, accommodating the unique characteristics of biobased materials and the dynamic needs of the construction industry.

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# Acronyms

| | |
|---|---|
| SSbD | Safe and Sustainable by Design |
| EU | European Union |
| GHG | Greenhouse Gas |
| UNEP | United Nations Environment Programme |
| EbA | Ecosystem-based adaptation |
| EN | European Standard |
| ISO | International Organization for Standardization |
| CSS | Chemicals Strategy for Sustainability |
| JRC | Joint Research Center |
| SbD | Safe by Design |
| REACH | Registration, Evaluation, Authorisation and Restriction of Chemicals |
| ECHA | European Chemicals Agency |
| R&D | Research & Development |
| LCA | Life-Cycle Assessment |
| PCR | Product Category Rules |
| EPD | Environmental Product Declaration |
| IBU | Institut Bauen und Umwelt e.V. (Institute for Construction and Environment) |
| CE | Conformité Européenne (European Conformity) |
| LEED | Leadership in Energy and Environmental Design |
| BREEAM | Building Research Establishment Environmental Assessment Method |
| FSC | Forest Stewardship Council |
| VOC | Volatile Organic Compound |
| LSA | Lifecycle Sustainability Assessment |
| CLP | Classification, Labelling and Packaging |
| PPE | Personal Protective Equipment |
| SME | Small and Medium Enterprise |
| HREC | Human Research Ethics Committee |
| MoSCoW | Must-have, Should-have, Could-have and Won't-have |
| SVHC | Substance of Very High Concern |
| Arbo | Arbeidsomstandigheden (working conditions) |
| RI&E | Risk Inventory & Evaluation |
| LDPE | Light Density Polyethylene |
| EPDM | Ethylene Propylene Diene Monomer |
| PP | Polypropene |
| TRL | Technology Readiness Level |
| MDF | Medium Density Fibreboard |
| PBT | Persistent Bioaccumulative and Toxic |
| PMT | Persistent Mobile and Toxic |
| STOT-RE | Specific Target Organ Toxicity - Repeat Exposure |
| STOT-SE | Specific Target Organ Toxicity - Single Exposure |
| GHS | Globally Harmonized System of Classification and Labelling of Chemicals |
| MSDS | Material Safety Data Sheet |
| OSH | Occupational Safety and health |
| RMM | Risk Management Measure |
| EF | Environmental Footprint |
| RCR | Risk Characterization Ratio |

| | |
|---|---|
| VSD | Value-Sensitive Design |
| MCDA | Multi-Criteria Decision Analysis |
| LCC | Life-Cycle Costing |
| WRB | Weather-Resistive Barrier |
| ACP | Aluminium Composite Panel |
| GWP | Global Warming Potential |
| ESG | Environmental, Social and Governance |

# Use of AI Tools

During the process of writing this thesis, I used OpenAI's ChatGPT as a supportive tool to aid with several academic writing-related tasks. Specifically, ChatGPT was used to:

- Enhance the structure and flow of written sections.
- Suggest grammar and phrasing improvements.
- Offer feedback on the coherence of ideas and arguments in development.
- Provide a second perspective on parts of the thesis I have already drafted.
- Assist in explaining complex concepts when I encounter difficulties in articulating them clearly.

All research, analysis and final decisions regarding content and phrasing were entirely my own. ChatGPT acted purely as a supportive tool, offering feedback rather than contributing original content. This note is included to ensure full transparency and responsible use of AI tools in the context of academic writing.

# 1 Introduction

## 1.1 Background and Context

Urbanization and climate challenges have placed sustainability and safety in the built environment at the forefront of architectural innovation. The building sector contributes over 30% of the European Union’s (EU) Greenhouse Gas (GHG) emissions related to energy consumption, a major driver of climate change (European Environment Agency, 2022). At the same time, cities face mounting environmental degradation and infrastructure-related safety concerns, often caused by aging buildings and inadequate maintenance (Sudheshwar et al., 2023). As urban populations continue to grow and construction activity persists, these challenges are expected to intensify (European Commission JRC, 2023).

In response, the United Nations Environment Programme (UNEP) has promoted Ecosystem-based Adaptation (EbA) strategies integrating biodiversity and ecosystem services into urban planning to enhance resilience. EbA solutions blend green (vegetation), blue (water) and grey (engineering) infrastructure to provide a holistic, adaptive response to climate risks (Depietri & McPhearson, 2017). While the European Green Deal strategically endorses green infrastructure, including biobased building materials, as a “no-regret” solution due to its co-benefits and low risks even under uncertain climate projections, the practical implementation of these innovations in the built environment faces acknowledged trade-off (European Commission, n.d.).

These trade-offs include higher upfront costs, maintenance burdens and variability in performance under extreme conditions. Perceptions of these risks vary widely among stakeholders, from regulators to real estate investors, highlighting a difference between high-level policy goals and operational realities. For instance, concerns regarding fire safety, material durability and uncertain long-term performance significantly limit the widespread adoption of biobased façade panels. This apparent contrast is not a contradiction but rather illustrates different levels of analysis: the strategic desirability from a macro-policy perspective versus the tangible challenges and perceived barriers encountered by specific stakeholders during implementation.

Façade panels are exterior cladding elements that provide weather protection, insulation and aesthetic value to buildings while significantly influencing their environmental footprint. Among these, biobased façade solutions are particularly relevant for retrofitting existing buildings, where there is significant potential to improve energy efficiency and reduce environmental impact without major structural overhauls. Despite trade-offs, these panels offer compelling benefits, including reduced embodied carbon, improved insulation and support for biodiversity. They are gaining attention in sustainable construction (Leso et al., 2024; Sudheshwar et al., 2023b). However, widespread adoption remains limited due to concerns around fire safety, material durability and uncertain long-term performance (Apel et al., 2023; Leso et al., 2024).

As a result, the construction industry is witnessing a shift toward bio-architecture, a design approach that integrates natural materials and systems into buildings façades, once passive barriers, are evolving into multifunctional building skins that regulate temperature, improve air quality and offer aesthetic and ecological value. This evolution creates both opportunities and challenges for validation, particularly when it comes to retrofitting Europe’s aging building stock, which accounts for 35% of buildings that are over 50 years old (Menna et al., 2021). In this changing landscape, a critical question arises: How can we ensure that innovative façade systems are not only sustainable but also safe throughout their lifecycle?

The EU's SSbD framework can help us answer this question. SSbD is a policy-driven approach that aims to embed both safety and sustainability considerations into the earliest stages of product development. Initially developed for the chemical and materials industry, the framework is now gaining recognition in construction and architecture. It emphasizes a stepwise assessment of hazards, human health risks, environmental sustainability and socio-economic impacts to ensure a transparent evaluation of trade-offs and the prioritization of safer, more sustainable alternatives (Fuentes et al., 2019). However, applying SSbD principles to novel biobased construction products, such as green façades, is not straightforward. Technical knowledge gaps, a lack of standardized testing and unfamiliarity among designers and engineers hinder widespread implementation which is particularly evident in façade applications, where design and function must align with both performance and regulatory expectations.

In this context, Leafy, a startup specializing in bamboo-based façade panels, represents a promising case study. The company's self-sustaining panels integrate lightweight structures, plant systems and resource-efficient manufacturing. Their goal is to enhance biodiversity, air quality and insulation in dense urban settings while offering scalable, modular solutions for sustainable retrofitting (van der Hoeven, 2023). Applying an SSbD approach can benefit the development of these panels by systematically addressing stakeholder concerns around fire safety, long-term durability and uncertain material performance, while ensuring that environmental gains are not achieved at the expense of user safety or regulatory compliance. By integrating SSbD early, Leafy can increase stakeholder confidence and market acceptance while minimising unforeseen risks during scaling.

This thesis aims to operationalize the SSbD framework within the realm of biobased façade systems by collaborating with Leafy. It will evaluate the safety and sustainability performance of their products across the four SSbD steps, explore practical implementation strategies and generate actionable insights for startups, designers and policymakers seeking to advance climate-smart, resilient building solutions.

## 1.2 Problem Statement

A key challenge in implementing biobased façade systems is ensuring that these innovative materials meet comprehensive safety and sustainability requirements across diverse urban contexts, particularly on existing buildings. Existing technical protocols such as EN 13501 (fire safety) and EN ISO 14040/44 (LCA) provide partial guidance but are not fully suited to assess the integrated performance of emerging materials like biocomposites or biobased facades (Wakili et al., 2024). Current assessment approaches are often fragmented, treating structural integrity, environmental impact, human health and maintenance as isolated metrics. (Fuentes & Smyth, 2016). This results in incomplete assessments, performance uncertainties and limited trust in the long-term viability of biobased façades, ultimately hindering their market adoption. The SSbD framework which aims to address this complexity, is, however, underdeveloped in the context of the built environment. Its compatibility with building-sector practices is not clearly defined and its stepwise structure has rarely been tested on hybrid products such as biobased façades.

## 1.3 Research Objective and Scope

This study examines the practical application of the SSbD framework in developing biobased green façade panels, using Leafy as a case study. The study focuses on identifying critical design characteristics that ensure safety, sustainability and regulatory compliance while also uncovering operational challenges within the current framework. By integrating stakeholder perspectives and real-world constraints, the study aims to generate actionable recommendations that enhance the framework's usability for startups like Leafy.

The research focuses on façade materials made from bamboo composites integrated with rainwater irrigation, excluding conventional materials like metal or glass. It is grounded in the European regulatory context, particularly in the Netherlands and evaluates compliance with relevant standards. Rather than proposing a new framework, the research operationalizes and critically examines the SSbD methodology within the biobased construction sector. The research incorporates insights from key stakeholders, including an architect, a façade engineer, a raw material supplier and a startup through exploratory semi-structured interviews. The study's focus on short- to medium-term implementation potential and decision-making needs is a practical approach to operationalize the SSbD framework. This is because the SSbD framework itself is fundamentally designed for long-term impact, aiming to embed both safety and sustainability considerations from the earliest stages of product development and throughout the entire lifecycle of materials and products.

The SSbD framework supports a shift towards more responsible and future-proof material systems by guiding innovation through a stepwise process from ideation to commercial deployment. By concentrating on short- to medium-term implementation, this study helps to rationalize and facilitate the immediate application of SSbD principles, moving beyond speculative design scenarios towards generating actionable recommendations for startups, designers and policymakers. This ensures that the long-term vision of SSbD is grounded in practical realities and decision-making processes

## 1.4 Research Question and Sub-Question

The main research question guiding this study is:
*How can the Safe and Sustainable by Design (SSbD) framework be applied to arrive at a responsible green facade panel design?*

To address this overarching question, the study will explore the following sub-questions:

1. **What are the design characteristics that define safety and sustainability in green facade panels?**
   This question aims to identify the key material, structural and environmental criteria that ensure both safety (e.g., fire resistance, durability) and sustainability (e.g., recyclability, carbon footprint reduction) in green facade panel design.

2. **How can qualitative and quantitative tools be integrated within the SSbD framework to assess when biobased facade panels are safe and sustainable enough to be considered responsible?**
   The question explores the opportunity for using different qualitative and quantitative tools within the SSbD framework and how they can complement each other. It also explores the context of responsibility in specific contexts related to safety and sustainability, including how to measure and assess them and what it means when it is safe enough. It generally provides the values of safety and sustainability.

3. **What are the limitations in the SSbD framework implementation, as identified through the case study with Leafy?**
   This question examines practical challenges encountered when applying SSbD to green façade panel design. Through case studies, stakeholder feedback and real-world constraints, the study will identify gaps in the existing framework. These findings will provide insights into the challenges associated with implementing SSbD in general and contribute to recommendations for enhancing SSbD implementation in practice.

## 1.5 Significance of Study

Academically, this thesis tries to fill an important gap in the literature by extending the application of the SSbD framework, primarily explored in chemicals and manufacturing sectors, into the underrepresented domain of construction materials and façade systems (Fuentes & Smyth, 2016; Reins & Wijns, 2024). Through its exploratory case study, the research demonstrates how theoretical SSbD principles can be translated into practice within the construction industry. Moreover, by exploring ways to integrate safety validation (e.g., fire performance) with environmental sustainability assessments (e.g., life cycle assessment), this research makes the existing SSbD framework into a more holistic one, which provides practical insights for its implementation in future research on sustainable innovation in the built environmentIt also offers conceptual advancements by identifying gaps in the current SSbD framework and proposing refinements for its application to construction materials. Finally, the research lays a foundation for further academic inquiry, encouraging the testing and refinement of SSbD and related frameworks across diverse materials and products.

Building on this conceptual foundation, the study also delivers practical insights for startups, innovators and professionals involved in the development of biobased façade products. Through collaboration with Leafy, the research demonstrates how SSbD can inform responsible product development by striking a balance between safety, sustainability and regulatory compliance. Key design features and decision points are identified, enabling more informed material selection and risk mitigation strategies. Finally, the findings provide policymakers with timely feedback by revealing limitations in the current SSbD implementation when applied to construction contexts, thereby providing a basis for refining future regulatory guidance.

# 2 Literature Review

## 2.1 Safe and Sustainable by Design Framework

The European Green Deal sets the overarching goal of transitioning the EU towards a more sustainable, low-pollution and climate-neutral economy (EC, 2019a). As part of this agenda, the Chemicals Strategy for Sustainability (CSS) introduces targeted actions to reduce harmful impacts of chemicals and materials on human health and the environment (EC, 2020a). A key ambition is to phase out the most hazardous substances unless proven essential and to substitute or minimise the use of all substances of concern, as defined under the Sustainable Products Initiative (EC, 2021b; EC, 2022a).

To support this transition, the European Commission is actively working on the development and refinement of the SSbD framework, even if its foundational concepts have been established. It is not a fully "built" or completed system in its application across all sectors and regulatory contexts. The SSbD concept builds upon earlier approaches such as "Safe-by-Design" (SbD) and "Benign-by-Design," which focus on minimizing risks and environmental impacts from the early stages of product development (Sudheshwar et al., 2023). It goes beyond compliance by integrating safety, functionality, circularity and sustainability considerations from the earliest design stages. The framework also addresses potential trade-offs and aims to avoid burden shifting between different environmental or health impacts (Gottardo et al., 2021). By embedding lifecycle thinking into the innovation process, SSbD supports a shift towards more responsible and future-proof material systems aligned with the Green Deal and zero pollution.

The SSbD strategy is built on three core pillars (JRC, 2022). The first focuses on designing safe and sustainable products from the outset by using responsible materials and minimizing hazards during the R&D. The second ensures safe and sustainable production processes by reducing emissions, energy and water use and improving waste management. The third addresses product safety during use and end-of-life, aiming to minimize exposure to harmful substances and promote safe recycling and disposal.

Efforts to operationalize the framework are currently underway across European policy, academic and industrial domains (Sudheshwar et al., 2024). The framework has demonstrated broad applicability across sectors from assessing occupational exposure risks associated with nanomaterials (Jiménez et al., 2024) to identifying environmental hotspots in rubber gaskets (Tsalidis et al., 2022). Case studies using organic wool (Tawfiq, 2023) and lignin-based polymers (Margarita et al., 2024) further demonstrate the relevance for sustainable product development, utilizing natural and renewable materials.

This section lays the foundational understanding of the SSbD framework, which is the central theoretical concept explored and operationalized throughout the thesis for biobased façade design. It highlights how SSbD integrates safety and sustainability from early product development stages, directly addressing the thesis's primary objective to apply this framework to Leafy's panels.

### 2.1.1 Challenges and Barriers in Implementation

The implementation of the SSbD framework faces several systemic challenges across industries, spanning technical, regulatory, economic and organizational dimensions. A key difficulty lies in its integration into existing innovation processes which requires a tiered, expertise-aligned approach often lacking due to insufficient scoping and support (Abbate et al., 2025). Sectors like construction face additional obstacles, as sustainability criteria are not yet fully integrated into decision-making, mainly due to gaps in legislation and limited financial resources (Poderytė & Banaitis, 2024).

From a technical perspective, SSbD is hindered by data gaps and limited methods for assessing safety and sustainability across material life cycles (JRC, 2022). Tools for predictive toxicology are underdeveloped for novel materials such as bio-composites, while Life Cycle Assessment (LCA) often overlooks the trade-offs between material performance and environmental impact. Additionally, balancing multiple criteria such as cost, functionality and circularity remains difficult due to a lack of consensus on how to prioritize them (European Commission, 2021).

Regulatory and standardization gaps also slow SSbD implementation. Existing frameworks such as REACH emphasize risk management over preventive design, creating compliance ambiguities for SSbD alternatives (ECHA, 2020). In construction, building codes often favour conventional materials, delaying approval for sustainable options despite meeting safety standards. This may be due to outdated fire safety classifications that were developed for traditional materials, which do not apply to modern materials. The lack of harmonized SSbD standards or certifications further adds to market confusion and inconsistent adoption (JRC, 2023).

Organizationally, industries face challenges in aligning safety and sustainability goals. Methodological inconsistency, internal resistance and cost concerns often hinder adoption particularly in manufacturing and supply chains (Abbate et al., 2025; Reynolds, 2024). A lack of skilled personnel in areas such as green chemistry and SSbD-specific tools is a critical gap, especially for SMEs with limited resources (EU Skills Agenda, 2022). However, larger companies may have in-house expertise. SMEs need clearer implementation pathways, support mechanisms and incentives (Apel et al., 2023). Engaging transdisciplinary experts early and aligning SSbD practices with strategic business and regulatory goals are key to overcoming these barriers (Soeteman-Hernández et al., 2024).

Economically, the higher upfront costs of SSbD-compliant materials combined with the absence of subsidies or tax incentives make adoption less attractive, particularly in high-risk or cost-sensitive industries (Akano et al., 2024). Practical challenges also arise when assessing recyclability due to limited end-of-life infrastructure, often forcing reliance on speculative assumptions or expensive pilot testing. In sectors such as construction, legislative backing and financial incentives are crucial for the scaling of the SSbD adoption (Poderytė & Banaitis, 2024).

The discussion addresses Sub-question 3, which examines the practical limitations of applying the SSbD framework to biobased façade systems, as observed in the Leafy case study. It offers essential context for understanding the technical, regulatory, economic and organizational challenges that can impede SSbD adoption in the construction sector.

### 2.1.2 Assessment Tools & Methodologies

A range of qualitative and quantitative methods can be used as tools to operationalize the SSbD framework in practice. While not officially part of SSbD, frameworks such as Value-Sensitive Design (VSD) can support the qualitative and empirical dimensions of SSbD by embedding ethical and societal values into technological development from the outset. Similarly, stakeholder interviews are valuable for capturing diverse user needs and contextual constraints, requiring empathy, flexibility and deep inquiry to effectively translate findings into design decisions (Dias et al., 2023). Safe-by-Design (SbD) checklists further complement early-stage innovation by aligning qualitative insights with safety and sustainability targets (Baas et al., 2022; IRISS, 2023).

On the quantitative side, LCA is a core SSbD tool that quantifies environmental impacts across a material's lifecycle (JRC, 2022). Combined with Risk Characterization Ratios (RCRs) for toxicological hazards, LCA forms the basis for Life Cycle Risk Assessment (LCRA), allowing for robust evaluation of novel materials. Additionally, Multi-Criteria Decision Analysis (MCDA) can assist in complex decision-making by integrating diverse indicators, such as cost, toxicity and carbon footprint, into a unified, transparent framework (Dias et al., 2023).

The SSbD Toolbox (PARC, 2024) is a structured collection of tools designed to support stakeholders in implementing SSbD, offering practical guidance to align material and product innovations with safety, sustainability and regulatory requirements. It integrates Risk Assessment (RA), LCA and stakeholder inputs to enable holistic evaluations throughout the design process. While frameworks such as VSD, stakeholder interviews and MCDA are not official components of the SSbD Toolbox, they can complement its application by addressing the qualitative and empirical dimensions of SSbD. For example, VSD can help align technical assessments with societal values, while MCDA can assist in balancing multiple criteria such as cost, carbon footprint and toxicity (Soeteman-Hernández et al., 2024). Using these additional approaches alongside the SSbD Toolbox can improve the acceptability, practicality and effectiveness of SSbD implementation in practice, providing a comprehensive pathway for systematically designing safer and more sustainable material systems.

This section informs the methodology in Chapter 3 and directly addresses Sub-question 2, which investigates how qualitative and quantitative tools can be effectively integrated within the SSbD framework to assess biobased façade panels. It establishes the theoretical foundation for the study's diverse data collection and analysis methods, including LCA, MCDA and stakeholder interviews.

## 2.2 Sustainability in the Built Environment

The built environment represents one of the most critical sectors for implementing the SSbD framework, accounting for approximately 40% of global $CO_2$ emissions and 50% of material consumption (Stevenson, 2020). This substantial environmental impact has prompted a shift toward transformative approaches that go beyond incremental efficiency gains to focus on rethinking materials and systems. The EU is advancing this agenda through initiatives such as the Green Deal's Renovation Wave and recent revisions to the Construction Products Regulation which now integrate SSbD principles via requirements for Digital Product Passports and Whole-Life Carbon Assessments (Mêda et al., 2024). However, the path to widespread implementation remains challenging due to technical, economic and regulatory barriers that reveal tensions between sustainability ambitions and practical constraints.

Material innovation is central to SSbD in construction, with emphasis on bio-based and circular alternatives. Examples include hempcrete insulation and mycelium composites, which offer promising environmental benefits but face hurdles related to durability and fire performance standards (Collet & Prétot, 2014; Volk et al., 2024). Biobased materials illustrate these tensions: while they deliver carbon-negative outcomes through biogenic carbon storage, the chemical treatments required for performance may compromise biodegradability at the end of life (Islam et al., 2024). Similarly, geopolymer concrete can reduce $CO_2$ emissions by up to 80% compared to Portland cement but raises concerns about alkali leaching and the availability of recycling infrastructure (Zhao et al., 2021). These examples underscore the SSbD challenge of managing trade-offs where gains in one impact category may introduce drawbacks in another.

To address such complexities, assessment methodologies are evolving. JRC's SSbD framework incorporates chemical foot printing and social impact metrics into lifecycle analysis while dynamic LCA models are being developed to better account for temporal variations in biogenic carbon flows (Wang et al., 2024). Nonetheless, significant gaps persist, particularly a lack of standardized testing protocols and long-term data for novel materials, which may exhibit unpredictable behavior over decades of use.

As mentioned earlier, SSbD-compliant materials often carry a 15–40% cost premium (RICS, 2023) and face skepticism from insurers and contractors wary of unproven systems. In the fragmented and conservative construction sector, outdated procurement practices compound these challenges. As a result, only 12% of EU construction waste is currently subject to high-quality recycling (Eurostat, 2023).

Amid this shift, there is growing emphasis on circular design strategies, especially in façade systems. Research has highlighted the benefits of designing façades for disassembly and reuse, which enhances long-term sustainability by reducing waste and supporting modular upgrades (Htet et al., 2025). Evolving certification systems and regulations also influence sustainable façade innovation. Accurate environmental comparison of building materials depends on LCA data and adherence to Product Category Rules (PCRs). In Europe, Environmental Product Declarations (EPDs) for wood and bio-based materials often follow the PCRs established by the German Institute for Construction and Environment, which assess key impacts including global warming potential, acidification, eutrophication, smog formation and ozone depletion (IBU, 2009).

These standards enable the comprehensive evaluation of biobased materials within a rigorous environmental assessment framework, ensuring their impacts are measured consistently and transparently throughout their lifecycle. These certifications drive demand for verified sustainable materials in façade systems and broader construction projects. *Table 1* gives an overview of environmental standards for façade materials and buildings.

*Table 1: Overview of Environmental Standards for Façade Materials and Buildings*

| **Certification** | **Type** | **Scope** | **Key Focus Areas** |
|---|---|---|---|
| ISO 14025 (2006) | Type III EPD (Product Level) | Framework for developing Environmental Product Declarations (EPD) | Based on LCA and PCR for transparent product comparison |
| EN 15804 (2012) | Core PCR for Building Products | Standard for EPD of construction products in Europe | Modular lifecycle stages A1–D, allows after-life (Stage D) analysis |
| ISO 14024 (2018) | Type I Ecolabel | Multi-criteria environmental labeling standard | Considers full lifecycle environmental aspects and resource usage |
| Forest Stewardship Council (FSC) | Material Certification | Certifies sustainable sourcing of wood and forest products | Verifies responsible forestry and supply chain transparency |
| PEFC | Material Certification | Endorses sustainable forest management practices | Focuses on ecological, social and ethical forestry standards |
| CE Marking (EU) | Product Conformity Mark | Ensures compliance with EU regulations for safety, health and environment | Indicates conformity with EU directives for building materials |
| Cradle to Cradle | Product certification | Evaluates the environmental and social impact | Renewable Energy & Carbon Management |

| | | | |
|---|---|---|---|
| LEED | Building Certification | Whole-building sustainability assessment | Materials, energy, water, indoor quality, innovation |
| BREEAM (UK) | Building Certification | Environmental assessment methodology for buildings | Incorporates EPDs, energy, waste, health and well-being |

Policy initiatives are beginning to support SSbD adoption, with programs like Horizon Europe's Built4People funding large-scale pilot projects (CORDIS, 2023). However, progress is slowed by non-harmonized standards and the voluntary nature of tools like Level(s). Leafy's façade panels highlight both the potential and challenges of SSbD achieving carbon savings while facing trade-offs in performance, safety and circularity. Moving forward, successful implementation will require coordinated action to close technical gaps, align financial incentives and establish consistent assessment methods across the building lifecycle.

This section establishes the critical context for the "sustainability" dimension of the main research question, focusing on the significant environmental impact of the built environment and the shift towards bio-based and circular materials, like those used by Leafy. It elaborates on the compelling benefits and inherent challenges, such as fire safety and durability, associated with these sustainable materials, which are central to Leafy's product and the SSbD evaluation.

## 2.3 Safety in the built environment

Façade panels are essential to building envelopes, contributing both functionally and aesthetically. However, their safety is a complex, multidimensional issue that spans structural integrity, fire resistance, environmental performance and geographic adaptation. Despite their classification as non-structural elements, façade failures can result in significant hazards, including fatalities and regulatory repercussions (Beasley, 2016).

Environmental loads, including wind, precipitation and seismic events, are key factors in façade performance. Studies highlight that façade systems in seismic zones must strike a balance between structural resilience and occupant comfort ("Façade Design - Challenges and Future Perspective," 2023). Furthermore, marine environments and harsh climates accelerate material degradation, reinforcing the importance of selecting durable materials and planning for regular inspections and refurbishment (Durmisevic, E., 2006).
One of the most concerning risks associated with façade panels is structural detachment. Urban environments, characterized by dense populations and exposure to environmental stressors, amplify the consequences of façade failures. Notably, in Montreal, a 320 kg concrete façade element fell, causing a fatality and underscoring the catastrophic potential of design flaws, poor installation, or neglected maintenance (Beasley, 2016). Environmental degradation driven by pollutants such as acid rain and atmospheric $CO_2$ can accelerate the deterioration of façade materials, including marble, limestone and concrete, further increasing failure risks (Charola & Ware, 2002).

Safety in the built environment has traditionally been conceptualized through compartmentalized lenses of structural integrity, fire protection and occupational hazards, governed primarily by prescriptive building codes and reactive regulatory frameworks (Maiworm et al., 2023). However, contemporary paradigms, such as Safe-by-Design (SbD) and SSbD, are reshaping this approach by advocating for the proactive and systemic integration of safety considerations throughout a building's lifecycle, from material selection to demolition (JRC, 2023). SSbD exemplifies this shift by explicitly linking material safety with sustainability objectives, requiring buildings to be not only structurally sound but also non-toxic, durable and circular. This holistic conceptualization encompasses five critical dimensions:

material safety (avoiding hazardous substances such as PFAS and formaldehyde), structural safety (resisting seismic and wind loads), fire safety (particularly challenging for bio-based materials), occupational safety (protecting construction workers) and end-of-life safety (ensuring safe deconstruction and material recovery).

*Table 2* compares safety-related factors across existing and new buildings, highlighting key differences in structural safety, fire risk, energy retrofitting and construction techniques. Safety in the built environment varies significantly between different types of buildings.

*Table 2: Safety factors in existing vs new buildings*

| **Aspect** | **Existing Buildings** | **New Buildings** | **References** |
|---|---|---|---|
| Structural Safety | Require inspections and diagnostics due to unknowns post-construction | Benefit from modern materials and standards that reduce uncertainty | Couto et al., 2015 |
| Fire Safety - Reliability | Higher risk due to outdated regulations and maintenance gaps | Improved reliability; however, high-rise fire systems can be affected by human/organizational errors reducing effectiveness by up to 33% | Meacham, 2023; Tan et al., 2020 |
| Fire Safety - Retrofitting | Façade insulation retrofits in high-rises can increase fire risk if materials are uncertified | Incorporates certified materials by design; fire performance of new lightweight techniques (e.g., sandwich panels) still under evaluation | Dote, 2023; Rusinová & Šlanhof, 2016 |
| Energy Retrofitting | Homes can save 24–46% energy without full system replacements through targeted interventions | Often optimized for energy performance from the start | Liaukus, 2014 |
| Apartment Blocks | Require integrated urban and sustainability upgrades | Can integrate new technologies and designs more easily | Raslanas et al., 2011 |
| Construction Techniques | Often constrained by legacy design; retrofitting is complex | Use of advanced systems like glued sandwich panels allows for reduced weight and better thermal performance, though safety validation is ongoing | Rusinová & Šlanhof, 2016 |

*Table 3: Comparative Overview: Biobased vs. Traditional Façades*

| Criteria | Biobased Façades | Traditional Façades |
|---|---|---|
| Environmental Impact | 1. Lower embodied carbon and global warming potential (Keena et al., 2022; "Bio-based Building Material Solutions", 2022)<br>2. Carbon sequestration capacity (Fernandes et al., 2024)<br>3. Reuse of agricultural waste (Jenkins, 2023)<br>4. Biodegradable and renewable cladding (Nazrun et al., 2023) | 1. High embodied energy and $CO_2$ emissions during production (Shen et al., 2015)<br>2. Based on non-renewable materials; limited recyclability |
| Performance Metrics | 1. Meets modern thermal and acoustic standards (Pracucci et al., 2024)<br>2. Improves thermal regulation via bio-façades (Almandrawy, 2014)<br>3. Lower weight, contributing to energy savings (Pracucci et al., 2024) | 1. Proven durability and structural integrity (Shen et al., 2015)<br>2. Effective under high mechanical stress and varied climates |
| Aesthetic Contributions | 1. Unique textures and visual variability (Sandak et al., 2019)<br>2. Enables nature-integrated and adaptive designs (Sandak et al., 2019) | 1. Clean, uniform appearance (Friedrich & Friedrich, 2021)<br>2. Preferred for traditional architectural styles |
| Adoption Challenges | 1. Requires technical certifications and eco-labels (Pracucci et al., 2024)<br>2. Higher upfront costs and uncertain longevity perception (Friedrich & Friedrich, 2021) | 1. Well-established regulatory compliance (Shen et al., 2015)<br>2. Supported by mature markets, known material behavior |

This section defines the "safety" dimension of the main research question and Sub-question 1, outlining the critical, multi-dimensional safety characteristics essential for façade panels, including structural integrity, fire resistance and occupational safety. It underscores the imperative for Leafy's design to proactively address these concerns throughout the product's lifecycle, linking directly to the comprehensive safety evaluations performed in the SSbD assessment.

## 2.4 Responsibility in Material and Design Choices

The concepts of "safe enough" and "responsible design" are central to engineering ethics, guiding engineers in striking a balance between innovation, safety and societal impact. "Safe enough" refers to the acceptable threshold of risk in engineering decisions, which involves evaluating and mitigating hazards using tools such as risk models and safety checklists (Hansson, n.d.; Ny et al., 2024). Failures such as the Challenger disaster underscore the importance of this standard (Ny et al., 2024).

"Responsible design" extends beyond technical functionality to address long-term societal and environmental impacts. It incorporates macro ethical thinking, urging engineers to anticipate unintended consequences and promote public welfare (Vallero, 2008; Hansson, n.d.). Education also plays a critical role by embedding ethical frameworks into engineering curricula, fostering a culture of responsibility (Bairaktarova et al., 2024). Within this broader concept, VSD frameworks are instrumental as they embed ethical and societal values into product development from the outset. VSD can further help align technical metrics with societal values, thereby improving both the acceptability and effectiveness of SSbD implementations.

Ethical decision-making models, such as ethical risk assessment, support engineers in systematically integrating ethics into their work (Ny et al., 2024). The Safe-by-Design (SbD) approach extends this by emphasizing shared responsibility across stakeholders and continuous engagement with safety throughout a product's lifecycle (Baas et al., 2022).

Balancing safety, sustainability and innovation requires navigating complex trade-offs that influence sectors from engineering to food systems and corporate strategy. These elements, while often aligned in purpose, can come into tension depending on context and prioritization. Table 4 outlines the trade-offs between safety, sustainability and innovation.

*Table 4: Trade-offs between safety, sustainability and innovation*

| **Trade-off** | **Description** | **Example** | **Source(s)** |
|---|---|---|---|
| Safety vs. Sustainability | Integrating safety and sustainability may conflict when innovations favor one over the other. | Use of antimicrobials in food improves safety but may lead to antimicrobial resistance. | Vågsholm et al., 2020; Hauschild et al., 2022; Cassee et al., 2024 |
| Innovation vs. Sustainability | Early-stage innovation may initially increase environmental impact before achieving benefits. | Corporate innovation may raise emissions before reaching a sustainability threshold. | Lee & Kim, 2017; Sahani, 2025 |
| Economic vs. Environmental Goals | Balancing short-term profits with long-term sustainability objectives is often difficult. | Lifecycle tools help assess trade-offs between cost savings and environmental impact. | Hauschild et al., 2022 |
| Institutional & Behavioral Trade-offs | Leadership and governance are key to managing policy-level tensions in sustainability transitions. | Climate policy success often depends more on institutional change than technical solutions. | Munns, 2019 |
| Trade-offs as Innovation Drivers | Properly managed trade-offs can catalyze strategic innovation and systemic change. | Sustainability performance frontiers and circular business models foster both innovation and environmental gains. | Leseure, 2023; Stoycheva et al., 2024 |

Despite their value, these concepts pose challenges due to the subjectivity of "safe enough" thresholds and the potential tension between ethical commitments and commercial pressures. This highlights the need for adaptable ethical frameworks that evolve in response to technological and societal changes.

This section provides the ethical and philosophical underpinning for the "responsible" aspect of the main research question, connecting it to the broader societal and environmental implications of material and design decisions. It frames the decision-making process within SSbD as an ethical endeavor, informing how crucial trade-offs are navigated and how the concept of "safe enough" is defined for biobased façade panels.

## 2.5 Identified Research Gaps

Based on the literature review, several key research gaps emerge that directly inform the relevance and necessity of this thesis. First, while the SSbD has been conceptually established through EU policy instruments and applied in sectors such as chemicals, textiles and nanomaterials, its application to the construction sector, particularly biobased façade systems remains underdeveloped. There is a lack of empirical studies demonstrating how the SSbD principles can be operationalized in the context of multifunctional building materials that must simultaneously meet structural, aesthetic, safety and environmental performance requirements. Specifically, façade components made from novel biobased materials like bamboo face unresolved trade-offs between fire resistance, recyclability and long-term durability, which are not adequately addressed by current SSbD tools or building regulations.

Second, the literature highlights that existing LCA tools and hazard screening methodologies often fail to capture the multidimensional trade-offs that arise when integrating safety and sustainability in complex systems. For instance, bamboo's carbon sequestration potential may be offset by flame retardant treatments that introduce toxic byproducts or hinder biodegradability. These methodological limitations highlight the need for case-specific, integrated assessment models that combine both qualitative insights and quantitative performance data, particularly in design domains where real-world application data are scarce or fragmented.

Third, the lack of harmonized SSbD standards and alignment with existing regulatory systems (such as REACH and building codes) creates uncertainty for startups and SMEs. These smaller players, such as Leafy, often face barriers in validating novel materials due to high costs, unclear testing protocols and regulatory conservatism. Despite the policy push for circular and climate-resilient materials, the absence of standardized SSbD implementation pathways in the built environment slows innovation and limits market uptake.

Furthermore, there is limited research into how stakeholders interpret, implement, or adapt SSbD principles in practice. Most existing literature approaches SSbD from a top-down regulatory or conceptual perspective, with insufficient attention to the lived experiences, constraints and strategies of designers, developers and material suppliers working within constrained budgets and fragmented value chains.

Lastly, the integration of safety and sustainability is still largely siloed in both industry and academia. Although SSbD proposes a lifecycle-oriented and interdisciplinary framework, operational tools and case-tested procedures that integrate both dimensions remain lacking, especially in the context of biobased materials under real climatic and construction conditions. As such, this thesis addresses a pressing research gap by developing and applying an operational SSbD assessment for Leafy's bamboo façade panels while also proposing an implementation procedure grounded in empirical case data and stakeholder feedback. This approach not only advances the theoretical discourse on SSbD but also contributes practical value to startups and policymakers seeking to scale responsible innovation in the built environment.

This section explicitly states why this research is necessary and how it contributes to filling existing knowledge gaps in the application of SSbD to the construction sector, particularly for novel biobased façade systems. It justifies the entire study by demonstrating that the thesis, through the Leafy case study, directly addresses these identified shortcomings in the literature.

## 2.6 Evaluation Framework

*Figure 1* presents the integration of the SSbD assessment into the product development process, following the progression from early-stage ideation to commercial-scale deployment (JRC, 2023). This model aligns with increasing Technology Readiness Levels (TRLs) and is structured around a stage-gate approach, a method widely used in innovation management (Cooper, 2010; Cooper & Sommer, 2018). At each "Gate," critical decisions are made to assess whether the innovation meets predefined safety, sustainability and technical criteria before proceeding to the next phase. As the process advances, uncertainty decreases through the iterative application of assessments and the continuous refinement of innovation.

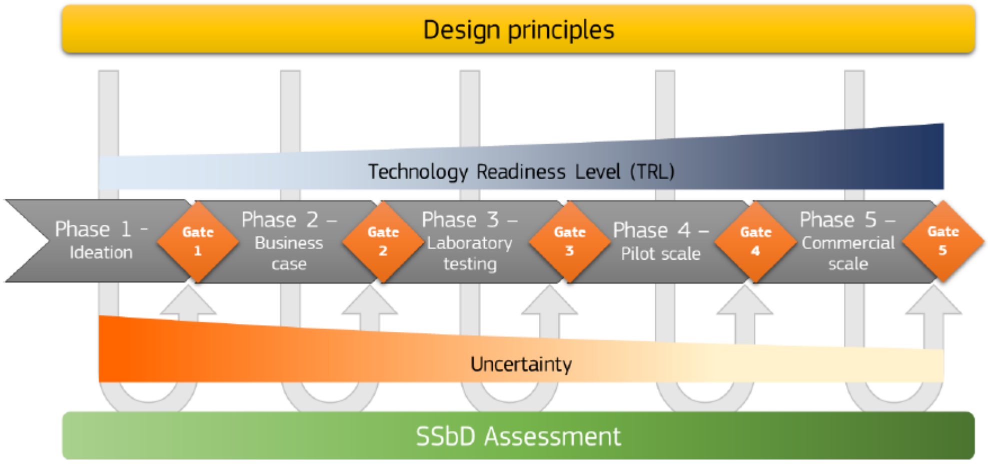


*Figure 1: Link between the innovation process, the design principles and SSbD*

The SSbD framework consists of two interrelated components: a design/redesign phase focused on embedding SSbD principles into the innovation, as shown in Table 5 and a parallel assessment phase that evaluates safety and sustainability impacts. They remain consistent throughout the development timeline and are translated into concrete design targets, such as maximizing biobased content, using non-toxic substances and ensuring modularity and recyclability in construction. To monitor progress and ensure alignment, each principle is linked with specific indicators that can be tracked over time.

*Table 5: SSbD design principles*

| SSbD Principle | Definition | Key Indicators |
|---|---|---|
| SSbD1: Material efficiency | Pursue full incorporation of chemicals and materials into the final product or ensure recovery, minimizing resource use and waste. | Raw material used (kg/m²), waste recovered, waste generation (kg/unit), modular reuse potential |
| SSbD2: Avoid hazardous chemicals | Preserve product functionality while eliminating or minimizing hazardous substances. | SVHC presence, REACH compliance, biodegradability of components, toxicity |
| SSbD3: Design for energy efficiency | Minimize the energy used in material production and processing. | Process energy (kWh/m²), transport $CO_2$ footprint |
| SSbD4: Use renewable sources | Conserve resources by selecting renewable or secondary feedstocks and minimizing fossil-based inputs. | % biobased, renewable feedstock |
| SSbD5: Prevent hazardous emissions | Avoid emissions or pollutant generation throughout material sourcing, processing and use phases. | VOCs, emissions profile, LCA data |
| SSbD6: Reduce exposure | Minimize direct and indirect human and environmental exposure to hazardous substances. | Exposure level, toxicity potential |
| SSbD7: Design for end-of-life | Ensuring materials can be separated, recycled, reused, or biodegraded without environmental risk. | Recyclable, biodegradable, repairable |
| SSbD8 – Whole lifecycle approach | Apply all SSbD principles across the full value chain from raw materials to disposal. | Cradle-to-cradle potential, modularity |

The SSbD framework evaluates the safety and sustainability of chemicals and materials through a five-step process:

1. **Hazard Assessment:** This initial step examines the intrinsic hazardous properties of a chemical or material, using criteria drawn from existing EU regulations.
2. **Occupational Health and Safety:** Focuses on the risks posed during production, processing and end-of-life handling, emphasizing worker safety and potential exposure during these stages.
3. **Use-Phase Impact:** Evaluates the impact on human health and the environment during the material's final application, including consumer exposure and potential environmental releases.
4. **Environmental Sustainability:** Applies LCA using the EU's Environmental Footprint method to evaluate impacts across 16 categories, grouped under toxicity, climate change, pollution and resource use.
5. **Socioeconomic Assessment (optional):** Evaluates broader social and economic implications throughout the material's life cycle, typically using Social LCA and Life Cycle Costing (LCC) methods.

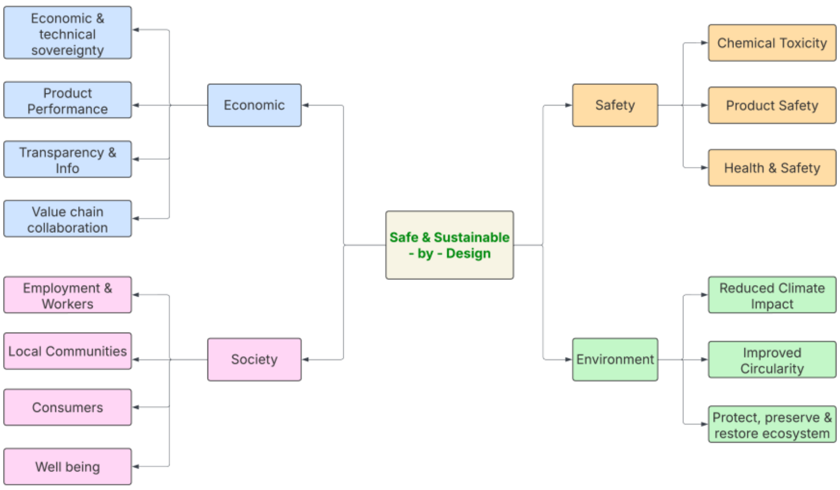


*Figure 2: A comprehensive list of Safety and Sustainability dimensions*

SSbD is applied as an ongoing process across all development phases, supported by an MCDA approach. A minimum threshold rule ensures that no single high score can offset a critical failure. This enforces the core SSbD principle: a product cannot be deemed safe and sustainable if it poses a critical hazard or exposure risk, regardless of its strengths in other areas.

In summary, this section provides the detailed operational blueprint for the SSbD assessment applied to Leafy's case study, outlining the precise five-step process and design principles used to evaluate safety and sustainability in Chapters 3 and 4. It directly links to the research objectives by explaining the multi-criteria assessment methodology and its non-compensatory approach, ensuring a comprehensive and stringent evaluation.

# 3 Methodology

## 3.1 Research Design

To explore how the SSbD framework can be operationalized in the development of biobased green façade panels, this thesis adopts a qualitative case study approach, incorporating quantitative aspects into the framework design, informed by abductive reasoning (Dubois & Gadde, 2002). This approach is particularly suited to contexts where existing theoretical frameworks (such as SSbD) are underdeveloped or untested in practical settings, especially within the fields of architecture and biobased construction.

The research follows an iterative abductive logic, moving between empirical findings and conceptual frameworks to identify gaps, reinterpret constructs and refine implementation pathways. This approach is well-suited for assessing the complex, multidimensional challenges faced by startups, such as Leafy, which navigate trade-offs between material safety, environmental performance and socioeconomic feasibility in real-world construction contexts.

The study utilizes two complementary data sources, including document analysis, which encompasses material data sheets, safety assessments and regulatory frameworks (e.g., EN 13501, REACH, ISO 14040/44). Another approach is to conduct semi-structured interviews with key stakeholders involved in sustainable façade design, regulation and product innovation.

The document analysis applies the five-step SSbD framework to evaluate Leafy's panel design through a structured audit of safety and sustainability. This assessment provides an exploratory lens on design performance, highlighting framework limitations within the context of building materials.

The interview study complements this assessment by eliciting stakeholder insights into the feasibility, challenges and perceived value of implementing SSbD principles in façade innovation. This dual-track method ensures that the analysis remains grounded in both theory and practice, yielding insights that apply to both academia and industry.

*Figure 3* illustrates the research methodology employed in this thesis as follows. The literature review and stakeholder interviews inform and shape the case study with Leafy by defining the conceptual framework, SSbD selection criteria and the focus of data collection. Rather than functioning as isolated, parallel tracks, the literature review and interviews are complementary, building on and refining each other while directly feeding into the case study and subsequent quantitative and qualitative analyses. This means the research process is interconnected, with these components collectively guiding and informing the assessment.

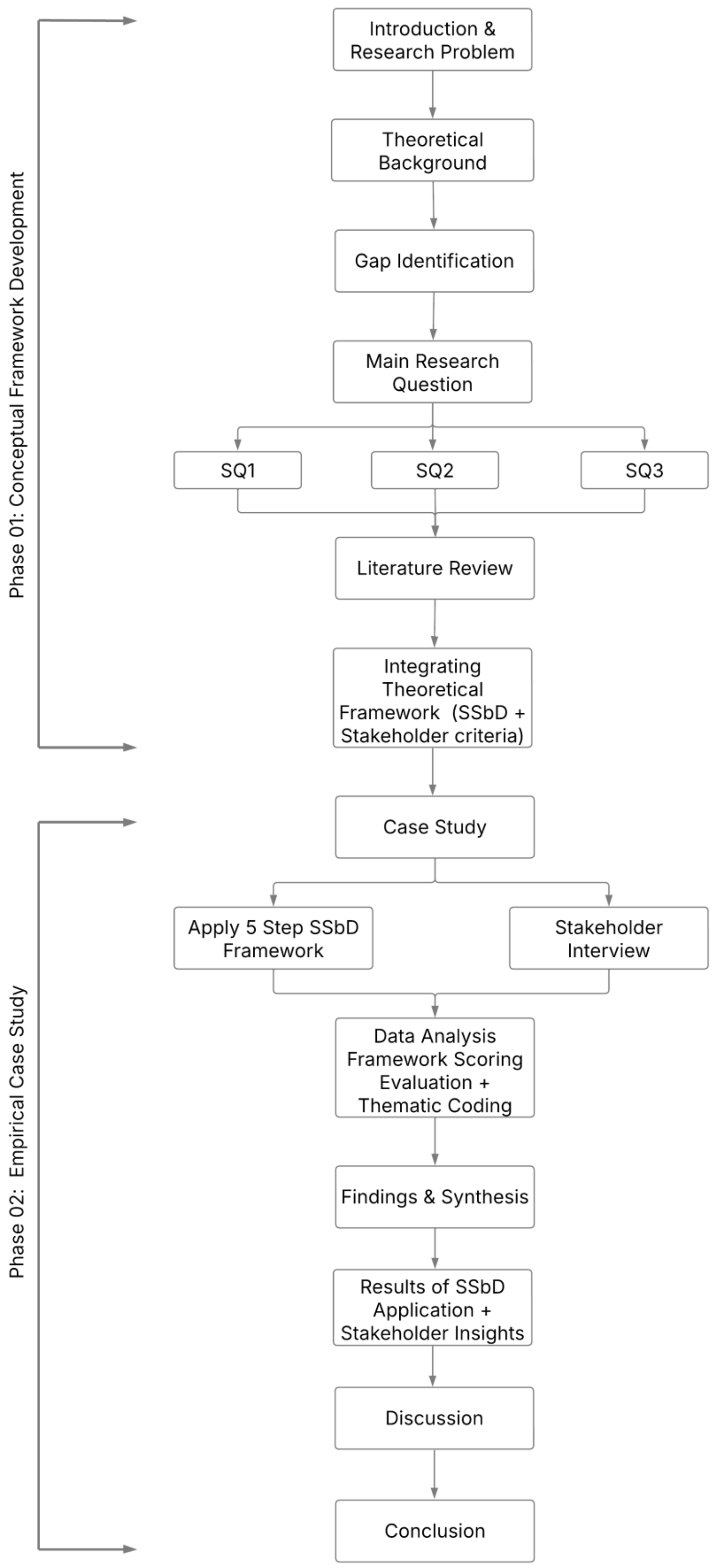


*Figure 3: Research Methodology*

## 3.2 Case and Participant Selection

This thesis employs a single embedded case study design, focusing on Leafy, a startup that develops bamboo-based façade panels for urban buildings. The focus of this thesis is existing buildings. Additionally, there has been consideration of installation risks associated with different external walls, including those made of concrete, bricks and asbestos. Rather than seeking generalizability through multiple cases, this design enables the exploration of SSbD application within a theoretically relevant and innovation-intensive context (Yin, 2014).

The case of Leafy, a startup developing bamboo-based façade systems, is used as a practical lens through which the SSbD framework is assessed. Rather than selecting the case, this study builds upon the opportunity to analyze Leafy's product as a real-world application scenario for testing and refining SSbD implementation.

To supplement the technical evaluation, semi-structured interviews were conducted with six purposefully selected participants, including Leafy's founder, Leafy's suppliers, an independent façade expert, an academic researcher and an architect/town planner.

Participants were selected based on their practical involvement in biobased material innovation and/or their expertise in one or more SSbD assessment domains. This purposive sampling strategy (Patton, 2002) ensured that data was drawn from individuals with both technical and strategic insight into façade safety, material validation and policy implementation. Where possible, interview insights were triangulated with internal documents and public regulatory data to enhance validity and reliability.

## 3.3 Data Collection

*Table 6* highlights different data sources and tools used to collect data for this thesis:

*Table 6: Research objectives mapped to methods and sources*

| Objective | Methodology | Data Source |
|---|---|---|
| Identify key design characteristics of safe and sustainable façades | Literature review + benchmarking + Interviews | Academic papers, EU standards, green building certifications |
| Apply and test the 5-step SSbD framework to Leafy's façade | Document analysis + SSbD audit | Material datasheets, internal product specs, regulatory checklists |
| Evaluate tool integration (e.g., hazard screening) within SSbD | Comparative tool mapping | hazard checklists, stakeholder-recommended tools |
| Gather stakeholder perspectives on risks, benefits, limitations | Semi-structured interviews | Architects, façade engineers, regulators, Leafy team |
| Identify SSbD limitations and develop SME-specific recommendations | Thematic analysis + Synthesis | Framework performance observations + interview data |

Recruitment for the semi-structured interview was conducted via academic networks, LinkedIn outreach and recommendations from Leafy. A total of six participants were interviewed. Each session lasted around 45 minutes and was conducted online via Microsoft Teams. Before each interview, participants received an information sheet and an informed consent form explaining the study's purpose, data use, confidentiality measures and their right to withdraw at any time. Verbal and written consent was obtained in line with TU Delft's Human Research Ethics Committee (HREC) guidelines.

A semi-structured interview guide was developed to maintain consistency across conversations while allowing flexibility to explore relevant issues raised by participants, as seen in Appendix D. The guide included open-ended questions grouped into four core themes:

- Design and material considerations related to safety and sustainability
- Regulations and compliance
- Practical challenges & trade-offs
- Perceptions of the SSbD framework, its clarity, usefulness and gaps

Interviews were audio-recorded (with consent), transcribed verbatim and anonymized during data processing. A summary of each interview's key insights was shared with participants after the interview to ensure validation and clarify their interpretations. All recordings and transcripts were stored securely in accordance with the approved data management plan (TU Delft HREC, approval date: 22 April 2025). The data will be permanently deleted after the project concludes to ensure full GDPR compliance and participant confidentiality.

The interviews serve a dual purpose: to triangulate the findings of the SSbD framework from the case study of Leafy's façade panels and to inform the refinement of SSbD implementation guidance for startups and SMEs in the sustainable construction space (*Appendix D*).

## 3.4 Data Analysis

The data analysis for this thesis combines qualitative and structured analytical techniques to evaluate the SSbD framework for biobased façade panels, using Leafy's bamboo-based system as a case study. The approach aligns with the exploratory case study design and is structured around the five SSbD steps and the corresponding research subquestions.

### 3.4.1 Framework Mapping and Scoring

The core of the analysis centers on applying the five-step SSbD framework as defined by the European Commission (JRC, 2023). Each step of the framework was operationalized into a set of assessment criteria, collectively forming an audit matrix to evaluate dimensions such as hazard presence, occupational safety, use-phase safety and environmental exposure, lifecycle environmental impacts and optionally, socio-economic and market readiness. A standardized scoring scale from 0 to 3 was used for each criterion, where 0 indicated no alignment and 3 represented high alignment with SSbD principles. All scores were substantiated using evidence drawn from product data sheets, safety assessments and relevant regulatory references. In cases where data was unavailable or uncertain, the criteria were marked as a "MISS" and systematically documented. This scoring approach enabled the creation of stepwise compliance charts, comparative graphs to assess material performance and gap matrices to visualize areas lacking sufficient validation for SSbD conformity.

### 3.4.2 Thematic Analysis of Stakeholder Interviews

To understand the practical challenges and stakeholder perceptions surrounding the implementation of the SSbD framework, semi-structured interviews were conducted and analyzed using thematic coding. The analysis began with a familiarization phase which involved reviewing transcripts and writing reflective memos. Initial codes were developed around key themes, including “safety validation,” “SSbD limitations,” and “cost trade-offs,” among others. These codes were then grouped using axial coding into broader categories, including “Safety” and “Sustainability,” among others. Patterns were identified across different stakeholder groups to highlight both divergent and convergent perspectives. The emerging themes were subsequently mapped back to the research sub-questions to provide a richer, real-world dimension to the evaluation of the SSbD framework.

### 3.4.3 Triangulation of Data Sources

To enhance the validity of the analysis, findings from multiple data sources were triangulated. This included the framework scoring results derived from audit tools, as well as qualitative insights obtained from interview data and secondary literature, which served as standard benchmarks and references for product specifications, such as Leafy’s resin type, fire rating and material lifecycle attributes. This cross-validation approach allowed for the confirmation of recurring patterns while also helping to identify inconsistencies and gaps between the theoretical structure of the SSbD framework and its practical application.

### 3.4.4 Synthesis and Interpretation

The final output of this thesis is a proposed implementation procedure for the SSbD framework, tailored explicitly for biobased façade systems to address the main research question: How can the SSbD framework be applied to develop a responsible, green façade panel design?

This synthesis was structured as follows:
1. A mapping of design stages to SSbD steps.
2. Identification of key integration points for qualitative and quantitative assessment tools (e.g., hazard screening).
3. A list of practical barriers and enablers for small enterprises like Leafy.
4. Recommendations for policy and regulatory alignment.

Where appropriate, the results were visualized to support clarity and interpretation. This included the use of color-coded heatmaps to display material scoring across SSbD criteria, radar diagrams to compare materials or illustrate alignment with the SSbD framework and structured tables outlining recommended improvements to the framework or its regulatory interpretation. These visual tools complemented the analytical findings, making complex evaluations more accessible. The overall procedure combining framework-based auditing with stakeholder insights offers a grounded and transferable model that can inform future applications of the SSbD approach in building product innovation and design.

## 3.5 Research Quality and Ethics

To ensure the credibility and rigor of this thesis, attention was paid to both research quality criteria and ethical safeguards throughout the study design, data collection and analysis. In qualitative research, the trustworthiness of findings relies not on statistical generalizability but on transparency, consistency and depth of interpretation (Lincoln & Guba, 1985; Shenton, 2004). This is particularly important for research situated at the intersection of sustainable construction, material safety and innovation frameworks such as SSbD.

The credibility of the research was strengthened through triangulation across two complementary data sources. First, a literature-based analysis was conducted to examine the SSbD framework in conjunction with relevant regulatory standards, providing a theoretical and normative foundation. Second, semi-structured interviews were held with key stakeholders, including architects, product developers, façade engineers and regulators who are actively engaged in sustainable building design. This combination of theoretical and practice-based perspectives ensured a more robust and well-rounded understanding of how SSbD principles are interpreted and applied in real-world contexts.

The interviews offer rich, experience-based insights into the practical feasibility and limitations of implementing SSbD for biobased façades. A semi-structured format allowed participants to reflect openly, enabling cross-case comparison. To increase internal validity, member checking was employed. Key interview insights were summarized and shared with participants to validate the accuracy of interpretations and to reduce the risk of researcher bias (Birt et al., 2016).

Methodological transparency was ensured through the documentation of each step: case selection, interview protocol, coding process and application of the SSbD framework. The conceptual framework developed and used in the study mapped how the five SSbD steps were assessed and linked to the research subquestions.
This study adhered to the ethical research standards of TU Delft's Human Research Ethics Committee (HREC). Prior to data collection, participants received a digital informed consent form that outlined the research purpose, voluntary participation, anonymity, data use and withdrawal rights. Participants were encouraged to ask questions and interviews proceeded only after explicit consent was granted. All interviews were conducted via Microsoft Teams for the convenience and security of the participants. Recordings and transcripts were securely stored in the researcher's TU Delft OneDrive account, accessible only to the researcher. In compliance with GDPR and university protocols, all data will be permanently deleted upon completion of this thesis.

To protect participant identities, all names and organizational affiliations were anonymized. While Leafy is presented as a named case study (with prior consent), all other interviewees are referenced in aggregate terms. Interview summaries were shared post-interview to ensure response validation, reinforcing ethical integrity and representational accuracy.

This ethical approach ensures that the insights informing the evaluation of SSbD's real-world application are not only methodologically grounded but also ethically sound and stakeholder validated.

# 4 Leafy Case Study and Analysis

## 4.1 Introduction to the Leafy Case Study

This case study examines the application of the SSbD framework in the development of a novel green façade solution by Leafy, a Dutch startup focused on sustainable urban innovation.

### 4.1.1 Background: Leafy's Vision and Product Design

Leafy develops modular, bio-based façade panels designed to enhance urban biodiversity while reducing the environmental impact of buildings. Its mission is to create climate-resilient cities by integrating lightweight, plant-based systems into building envelopes, providing insulation, air quality improvement and green infrastructure benefits. By focusing on scalable and circular design, Leafy aims to make sustainable retrofitting accessible for existing urban buildings while aligning with the EU Green Deal and the transition toward a low-carbon built environment.

The façade panel features a gravity-based rainwater irrigation system and a biobased substrate composed of bamboo, allowing plants to grow without the need for soil. This not only makes the system significantly lighter than traditional green walls but also ensures optimal water use. The panel supports a range of installation contexts, accommodating various heights and building typologies and offers "direct greening," which creates immediate environmental benefits such as heat stress reduction, improved air quality and flood mitigation.

This case is particularly suited to testing the SSbD framework due to the panel's emphasis on:

- Renewable and recyclable materials (biobased core, SS elements)
- Modularity and disassembly potential
- Safety concerns relating to structural anchoring, wind loads, fire resistance.
- Alignment with EU sustainability and circular economy goals

### 4.1.2 Façade Panel Design

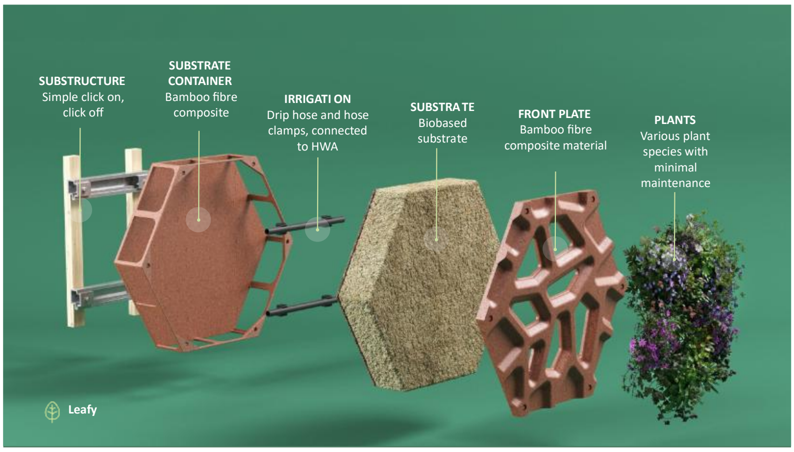


*Figure 4: Leafy's Modular Green Façade Panel System*

Note: A picture of the actual product and setup of the Leafy Façade Panel can be seen in Appendix A.

The design and component architecture of Leafy's bamboo-based façade panel provide critical insight into how safety and sustainability principles are embedded at the product level. *Figure 4* illustrates an expanded view of the Leafy façade panel, offering functionality for both vertical greening and passive environmental performance. The panel system comprises six distinct yet integrated components. The substructure features a click-on/click-off mounting interface that facilitates easy installation and replacement. Typically constructed from conventional framing timber or metal supports, this element allows for rapid assembly without the need for adhesives. Its design enables reversibility and supports circularity, aligning with the objectives of SSbD Step 4 concerning end-of-life considerations.

The substrate container, made from a bamboo fibre composite, serves as the rigid outer shell of the panel. It is engineered to house the planting substrate while maintaining a lightweight form. Another purpose of this is to prevent plants from growing inside. This component plays a key role in the panel's structural integrity. It must meet essential safety requirements, including fire performance, UV durability and mechanical strength, as outlined in SSbD Steps 1 and 3.

The irrigation hose and clamps make up a passive drip irrigation system that connects the green façade to the building's rainwater drainage system (HWA). This integration enhances water efficiency and plant vitality, particularly during periods of drought. The system's reliability under varying water pressure and exposure is also essential for ensuring occupant comfort and manageable maintenance cycles.

The substrate, a biobased growth medium, is a loose-fill organic material designed to support root development while retaining moisture. Fully biodegradable, it contributes to carbon sequestration but presents challenges in terms of long-term durability and potential leaching. It requires material testing to evaluate risks such as microbial growth, Volatile Organic Compound (VOC) emissions and decomposition over time, particularly in line with SSbD Steps 3 and 4.

The front plate, also constructed from a bamboo fibre composite, provides both structural support and visual framing for the plant system. Due to its constant exposure to sunlight, moisture and physical stress, this component must undergo rigorous testing for long-term durability and fire safety by standards such as EN 13501.

Finally, the plants themselves are selected based on criteria such as low maintenance requirements, ecological diversity and adaptability to local climate conditions. They contribute to enhanced biodiversity and improved air quality, while also affecting root interaction with structural elements and shading performance. This component is strongly linked to sustainability, aesthetic performance and occupant well-being, particularly as considered in SSbD Step 5.

The product emphasizes modularity, lightweight design and fast installation, as seen in the assembly mechanism and pre-formed containers. Use of bamboo composite supports sustainability goals but also introduces questions regarding its fire classification, recyclability and long-term weather resistance and requires targeted validation. The presence of a biodegradable substrate and living vegetation adds complexity in terms of moisture retention, microbial growth and maintenance cycles, calling for multi-criteria safety and exposure assessments under Step 3 of SSbD. The irrigation system demonstrates integration of building water infrastructure with façade functionality, creating dual benefits for plant health and occupant comfort, while also adding potential failure points (e.g., leaks, freezing).

## 4.2 Stakeholder Perspectives and Design Drivers for Responsible Façades

The successful implementation of SSbD principles in novel construction materials, particularly for complex systems like biobased green façades, is profoundly influenced by the perspectives and priorities of diverse stakeholders. Their insights are crucial for bridging the gap between high-level policy goals and operational realities, identifying critical design characteristics and addressing perceived barriers to market adoption. This section examines key stakeholder concerns and how they inform the definition of design drivers for both safety and sustainability in façade innovation.

### 4.2.1 Key Stakeholder Landscape

The stakeholders represent different domains across the construction value chain, from product development to installation and building operation. Identifying and engaging these actors is essential for aligning the panel's safety and sustainability objectives with real-world constraints and expectations. *Table 7* presents a stakeholder matrix that lists the roles, interests, level of influence and relevance of selected stakeholders to the SSbD framework, as determined through interviews, about Leafy's biobased façade panel development.

*Table 7: Stakeholder Overview for Leafy*

| Stakeholder | Primary Role | Expectation |
|---|---|---|
| Architect | Integrate safety & performance in design planning | Data for fire/wind performance, visual flexibility and regulations |
| Leafy | Product development and strategic direction | Balance innovation with compliance & durability |
| Professor | Structural design review and testing | Ensuring regulatory readiness & adaptability |
| Façade Expert | Research on facades | Validation for structural safety & SSbD value |
| Supplier 1 | Bamboo fibres provider and technical input | Transparent testing, market adoption |
| Supplier 2 | Panel manufacturing and using resin and bamboo fibres | Market adoption |

Figure 5 shows a power-interest grid illustrating the relative influence and level of interest of key stakeholders. The combination of these two factors informs Leafy's engagement strategy for each actor (van der Hoeven, 2023). Here, Bambooder is Supplier 1 and NPSP is Supplier 2.

Although no regulator is directly interviewed, the thesis thoroughly examines the regulatory landscape and its influence on façade design and the application of the SSbD framework. It is grounded in the European and specifically Dutch, context, assessing compliance with building codes, certification standards and evolving sustainability policies. Regulations are consistently described by stakeholders as essential and non-negotiable, directly shaping material and design decisions. Dutch laws such as the Arbowet, Arbobesluit and Bouwbesluit are discussed in relation to installation, maintenance and safety-by-design. While regulatory uncertainty isseen as a barrier to innovation, it also encourages future-proof design. The SSbD framework is highlighted as a policy-driven EU initiative that integrates safety and sustainability from the early stages of product development to meet both regulatory and market demands.

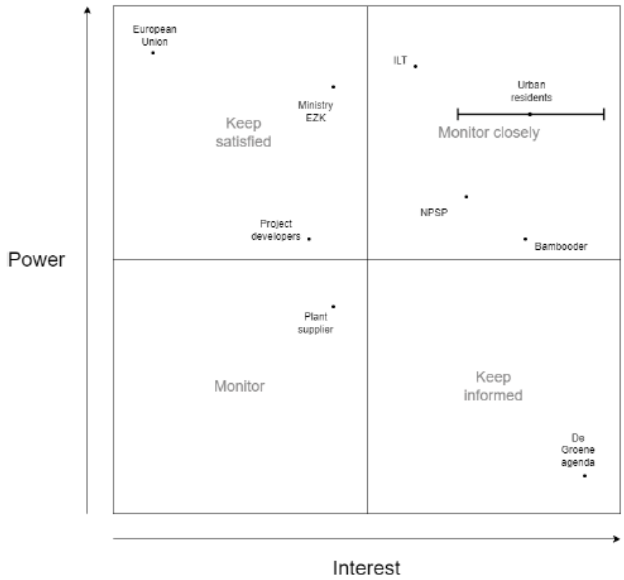


*Figure 5: Power-Interest Grid (van der Hoeven, 2023)*

Figure 6 illustrates the frequency of key stakeholder concerns, which inherently include aspects of performance alongside safety and sustainability. While 'Performance' itself was not coded as a standalone top-level theme in the interviews, its critical sub-elements such as structural integrity, thermal efficiency, acoustic control and long-term durability were consistently emphasized and are detailed in subsequent sections like the 'Façade performance domain' (Table 8) and Leafy's 'Key Design Characteristics for Safety and Sustainability' (Tables 9 & 10).

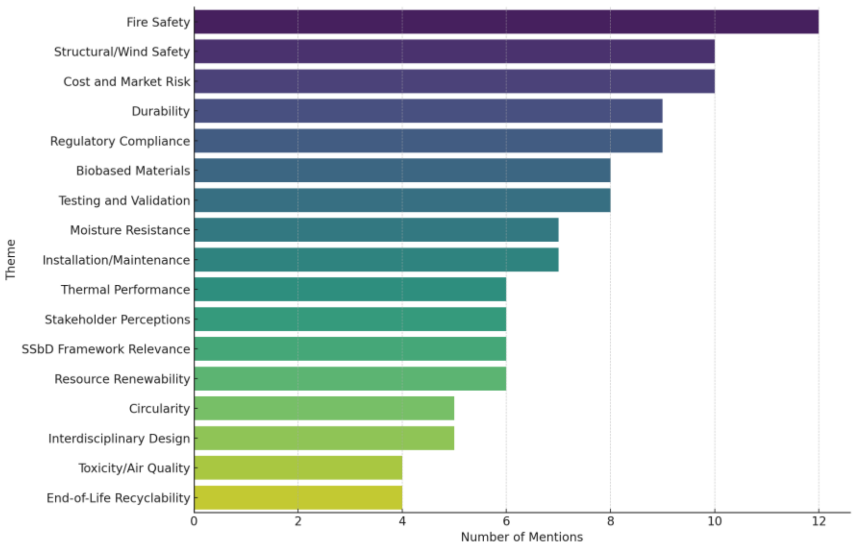


*Figure 6: Frequency of themes across stakeholder interviews*

The frequency of each topic was determined through a rigorous thematic coding process applied to the verbatim transcripts of the interviews. As outlined in the methodology, initial codes were developed around key themes identified during the familiarization phase and these were subsequently grouped into broader categories. The number of times a particular topic or code was mentioned across all interviews contributed to its frequency count, providing a data-driven basis for understanding stakeholder emphasis.

For instance, "Fire Safety" was mentioned 12 times, "Cost and Market Risk" 10 times and "Structural/Wind Safety" 10 times, consistently ranking as top concerns. This quantitative insight into frequency was then used to prioritize and frame the qualitative analysis, ensuring that the study's discussion of design characteristics, challenges and recommendations directly addresses the most salient issues identified by the experts in the field. The high-frequency topics were further merged into seven important themes (Safety, Sustainability, Maintenance & Durability, Stakeholder Concerns, Regulations, Trade-offs and SSbD Relevance), which formed the basis for in-depth analysis of their interrelations and implications for the SSbD framework. This approach ensures that the study is grounded in the perspectives of the interviewees and focuses on aspects they deemed most critical.

1. **Safety:** This emerged as a non-negotiable priority. Fire resistance, structural integrity and safe installation were key design drivers. Stakeholders emphasized system-level safety evaluations (not just materials), regular performance testing and avoiding toxic substances in production and use.

2. **Sustainability:** This was considered essential, but only after safety and performance were ensured. Stakeholders highlighted the importance of using biobased, recyclable, or locally sourced materials, conducting full LCA and designing for circularity (e.g., reusability, modularity). EPD and low-carbon design choices further supported this priority.

3. **Maintenance & Durability:** It was a dominant concern, particularly in public and commercial buildings. The façade system had to support easy upkeep, corrosion resistance and long-term functionality. Modular designs were preferred for easier maintenance and durability was directly tied to product acceptance, with warranties and lifecycle support viewed as critical.

4. **Stakeholder Concerns:** Stakeholders valued flexibility, cost-effectiveness and risk-sharing through clear roles in procurement and installation. Proof of real-world performance (via prototypes or pilots), collaboration and early benchmarking were key to building trust and enabling adoption in a conservative industry.

5. **Regulations:** Compliance with building codes, certification standards and evolving sustainability policies was essential. Fire safety, height restrictions, material approval and environmental performance scores (e.g., Dutch MPG) shaped design decisions. Regulatory uncertainty surrounding new materials posed barriers to innovation but also incentivized the adoption of future-proof design.

6. **Trade-offs:** Stakeholders often faced trade-offs between sustainability, performance, cost and compliance. While some compromises (e.g., using epoxy resin) were accepted for safety or feasibility, others stressed that sustainability must not undermine critical functions. The key was to balance client expectations, regulatory needs and technical feasibility within project constraints.

7. **SSbD Relevance:** The SSbD framework was widely seen as a helpful guide offering structure and foresight in product development. While the sequence of steps may need adaptation for biobased contexts, SSbD promoted holistic thinking by combining safety, sustainability and socio-economic considerations. It served as a common language across disciplines, helping to align innovation with regulatory and market expectations.

## Reflecting on Future Trade-offs and Prioritization in Façade Design

The analysis highlights several critical trade-offs and polarizations inherent in the development of safe and sustainable façade panels. These tensions currently exist between:

1. **Safety vs. Sustainability:** High safety standards (e.g., fire resistance) often require materials like epoxy resin with lower environmental performance, while biobased alternatives raise concerns about toxicity, fire safety or incomplete data. "Biobased" does not always mean "risk-free."

2. **Performance/Durability vs. Biobased Material Adoption:** Stakeholders prioritize durability and long-term performance over sustainability. Concerns about the lifespan of biobased façades remain a major barrier to adoption.

3. **Cost vs. Sustainability/Innovation:** The sector is conservative and cost-sensitive. Sustainability alone doesn’t drive adoption unless paired with clear cost or performance benefits, particularly for startups and SMEs.

4. **Regulatory Compliance vs. Innovation:** Outdated building codes and lack of SSbD standards or certifications continue to favor conventional materials, creating a conservative environment that delays approval for sustainable alternatives.

5. **Data Gaps & Uncertainty vs. Comprehensive Assessment:** Incomplete or early-stage material data makes it difficult to conduct reliable LCAs, limiting trust and market viability.

6. **Material-level vs. System-level Evaluation:** Stakeholders emphasized the need for system-level assessments of entire façade assemblies, especially for safety risks like fire, since component interactions cannot be captured through material-level evaluations alone.

7. **Integrated Trade-offs and SSbD Relevance:** Safety, sustainability, durability and stakeholder concerns are deeply intertwined. The SSbD framework helps balance these aspects by evaluating materials across LCA, toxicity and fire behavior.

8. **Maintenance & Lifecycle Concerns vs. Market Uptake:** Without long-term durability and easy maintenance, clients are unlikely to adopt green façades, even if they are environmentally friendly. Durability and low maintenance are critical for genuine sustainability, contributing to circularity and reduced lifecycle impacts by avoiding issues like plant die-off, VOC emissions, or microbial growth.

9. **Stakeholder Trust vs. Innovation Risk:** The conservative market favors proven, certified materials. New solutions must demonstrate clear advantages in cost or risk reduction to gain traction. As SSbD remains voluntary in most contexts, early adopters view it strategically as a way to future-proof their products and build trust with cautious stakeholders.

10. **SSbD and Policy Alignment:** Regulatory frameworks, including the EU SSbD guidance and Dutch MPG scoring systems, are beginning to incentivize sustainability practices. While SSbD is not yet mandatory, these emerging instruments suggest a shift toward integration of safety and sustainability at the policy level, reinforcing the relevance of SSbD in navigating complex trade-offs.

### 4.2.2 Functions of Building Facade

To effectively guide the development of safe and sustainable green façade panels, this study identifies and organizes key design requirements into five core performance domains. These domains represent a comprehensive framework for evaluating façade systems in terms of both technical feasibility and SSbD criteria.

Drawing on a combination of technical literature, regulatory standards and stakeholder insights from the Leafy case, each domain encompasses specific sub-criteria that influence how façade panels perform throughout the building lifecycle. These include measurable attributes such as fire resistance, modularity, carbon footprint and long-term durability, among others.

*Table 8* presents the complete list of domains and their associated sub-criteria, while *Appendix K* visually maps these relationships in a structured format. These components give rise to functional design principles that Leafy needs to incorporate in designing their façade panels, as shown in the next section. This framework serves as the foundation for design evaluation, supporting the integration of both qualitative and quantitative methods in the assessment process.

*Table 8: Facade performance domain*

| **Performance Domain** | **Design Characteristic** | **Description** |
|---|---|---|
| Protection and Safety | Fire resistance | Compliance with EN 13501 and treatments for bamboo |
| | Durability | Service life of 15-30 years outdoors |
| | Moisture resistance | Resistance to humidity, rain and biological degradation |
| | Impact and intrusion resistance | Performance under mechanical stress and security incidents |
| | Pollution control | Barrier to dust/pollutants; absence of hazardous emissions |
| Energy Efficiency | Thermal insulation | Insulation layers or natural ventilation integration |
| | Solar control | Shading elements or coatings to manage solar gain |
| | Ventilation optimization | Design supports passive or assisted airflow |
| | Material reuse and recyclability | Design-for-disassembly features or modularity |
| Sustainability | Biobased content | Use of renewable materials like bamboo with traceability |
| | Low embodied carbon | Materials with favorable LCA scores |
| | Recyclability | Materials can be reused, recycled, or composted |
| | Energy loop integration | Compatibility with on-site solar/thermal systems |
| | Local sourcing | Minimized emissions via local sourcing |
| Occupant Comfort | Acoustic control | Noise reduction and insulation for urban settings |
| | Indoor air quality | Low VOC materials and ventilation features |
| | Thermal comfort | Balanced indoor temperature regulation |
| | Visual comfort | Glare reduction, daylight access, outside views |
| Architectural Features | Visual integration | Site context, material palette, window ratio |
| | Access and connectivity | Design interaction with surrounding structures |
| | Modularity and adaptability | Flexibility for retrofitting or layout changes |

### 4.2.3 Design Principles of Leafy

In addition to broader performance domains and stakeholder insights, Leafy provided a structured list of functional design requirements to guide the development of their bamboo-based façade panels. These requirements are internally used to ensure alignment with safety regulations, sustainability goals, user expectations and market readiness.

*Appendix B* presents an overview of these design requirements, organized by theme, category, requirement, priority level (based on the MoSCoW method: Must, Should, Could, Won't Have) and validation method. The list reflects a comprehensive attempt to operationalize façade performance in quantifiable terms. The dataset is divided into several thematic clusters, each addressing specific aspects of the façade panel's design. Each requirement is assigned to a priority level:

- Must: Non-negotiable criteria necessary for regulatory compliance or product function
- Should: Strongly recommended features, often linked to performance or user satisfaction
- Could: Nice-to-have attributes, potentially optional depending on project phase or budget

Notably, most safety-related criteria (e.g., fire resistance, structural load, chemical safety) and core sustainability metrics (e.g., biobased content, recyclability) fall under the "Must" category, reinforcing the earlier findings that safety and sustainability form the central pillars of design.

Finally, the validation methods planned or applied by Leafy to ensure that each design requirement is met encompass a combination of quantitative, regulatory and qualitative approaches. Quantitative tests include LCA, thermal conductivity measurements, load-bearing simulations and UV exposure tests to evaluate material durability and performance under environmental stress. Regulatory certifications such as REACH compliance and CE marking are pursued to ensure adherence to industry and safety standards. Additionally, qualitative assessments such as visual inspections, user feedback and evaluations by key stakeholders are used to capture practical insights and ensure that the product aligns with both functional expectations and end-user needs.

This requirement list offers an internal lens into how a sustainability-oriented startup like Leafy translates abstract SSbD principles into technical specifications. It adds granularity to the broader functional categories described in earlier sections and reflects the multidimensional approach needed to design façade systems that meet regulatory, environmental and market expectations simultaneously.

### 4.2.4 Key Design Characteristics for Safety

From the above risks and interviews with stakeholders, we can identify several key safety-related design characteristics for façade panels. “Safety” here means protecting life, structural integrity and preventing hazards during the panel’s life cycle. The critical safety design characteristics are listed in *Table 9*.

*Table 9: Key Safety-related design characteristics*

| Design Characteristic | Description | Key Metrics / Standards |
|---|---|---|
| Fire Safety | Behavior in fire: combustibility, flame spread, smoke production, fire resistance. Includes use of fire-rated materials and cavity barriers. | • Euroclass (A2-s1,d0),<br>• Fire Resistance Rating EI30 meaning it can prevent fire passage for 30 minutes,<br>• NEN-EN 13501-1 |
| Structural Integrity & Wind Resistance | Ability to withstand dead loads, wind pressures and impacts without detachment or failure. | • Wind load capacity of ±2000 Pa meaning ~200 km/h wind gusts<br>• anchor pull-out strength (>1.5 kN)<br>• EN 1794 for impact resistance<br>• Eurocode/NEN standards |
| Moisture Management & Water Tightness | Prevention of water ingress and accumulation can lead to rot, mold, corrosion, or freeze-thaw damage. | • Withstand 95% RH EN 12467<br>• Water penetration resistance (no leakage at 300 Pa)<br>• cavity ventilation (≥20 mm)<br>• WRB presence, EN 12155 |
| Durability & Material Integrity | Resistance to environmental degradation over time (e.g., UV, freeze-thaw, corrosion, biological attack). | • Design life (30 - 100 years)<br>• freeze-thaw cycles (100+), corrosion class (ISO 12944)<br>• UV ≥ 10 years (ISO 4892-2)<br>• durability standards (EN 12467, EN 14782)<br>• no repainting or resealing for 20 years |
| Maintainability & Safety in Maintenance | Facilitation of safe inspection, access, replacement and initial installation by maintenance crews and construction workers throughout the panel's lifecycle. | • Presence of anchor points<br>• max panel weight for manual handling<br>• compliance with NEN-EN 365 and Dutch Building Decree<br>• Provision of PPE such as FFP2 dust masks<br>• Control of dust during on-site drilling |

In summary, safety-driven design characteristics for green façade panels revolve around fire performance, structural strength, moisture protection, durability and maintenance safety. These characteristics ensure that the panel system does not introduce hazards over its life.

### 4.2.5 Key Design Characteristics for Sustainability

Beyond safety, “green” façade panels are characterized by their sustainability-related features. These relate to the environmental impact of the panels over their life cycle and their contribution to an eco-friendly building. They are listed in *Table 10*.

*Table 10: Key Sustainability related design characteristics*

| Design Characteristic | Description | Key Metrics / Standards |
|---|---|---|
| Embodied Carbon & Environmental Footprint | Minimizing $CO_2$, emissions from material extraction to disposal. Prioritizes low-impact, bio-based, or recycled materials. | Global Warming Potential (GWP, kg $CO_2$„/m²), Embodied Energy (MJ/m²), EPD data |
| Thermal Performance & Energy Efficiency | Reducing operational energy use through high insulation and minimal thermal bridging. | U-value (W/m²K), thermal bridge Psy-value (W/mK), Solar Reflectance Index (SRI) |
| Resource Renewability & Biobased Content | Using renewable or recycled materials to conserve natural resources and reduce ecological impact. | Biobased content (%), ISO 16620-2 certification, recycled content (%) |
| Recyclability & End-of-Life Impact | Designing for reuse, recyclability, or biodegradability at end-of-life, avoiding landfill. | Recyclability rate (%), Cradle-to-Cradle certification, design for disassembly (yes/no) |
| Low Toxicity & Environmental Health | Avoiding hazardous substances (e.g., VOCs, heavy metals) that affect occupants or the environment. | VOC emission class (A+), Red List compliance, formaldehyde class (E1) |
| Climate Resilience & Adaptation | Ensuring performance under future climate conditions, including extreme heat or moisture. | SRI, hygrothermal modeling data, moisture resilience test results |

Many of these sustainability characteristics are intertwined with safety and performance. For instance, durability (discussed earlier) is both a safety and sustainability factor: a long-lasting panel means less frequent replacement (lower environmental impact) and sustained safety. Thus, design characteristics like durability, low maintenance and quality installation benefit both realms. Furthermore, *Appendix C4* presents a comparison of these metrics for biobased versus conventional façade panels.

To summarize the sustainability characteristics, a "green" façade panel has low embodied carbon, high energy efficiency contribution, uses renewable/recycled materials, is recyclable or reusable at end-of-life and avoids harmful substances. These are measured using various indicators, such as GWP (kg $CO_2$), U-value (W/m²K), recycled content (%) and service life (years), among others. The following section will compare how biobased panels versus conventional panels perform on these metrics and the summary table will map each characteristic to a measurable indicator for clarity. This mapping helps guide how SSbD can be translated into concrete, testable product criteria which will be elaborated in the next section through the complete SSbD framework application and audit of Leafy's panel.

These characteristics, directly shaped by stakeholder priorities and SSbD principles, guide the development of Leafy's façade panels towards a truly responsible design, aiming to balance environmental gains with user safety and regulatory compliance.

## 4.3 SSbD Evaluation: Integrating Qualitative Context with Quantitative Results

The practical application of the SSbD framework to Leafy's biobased green façade panels involved a comprehensive, multi-criteria assessment that systematically evaluated materials across their entire lifecycle. This section details the methodology employed for the SSbD evaluation. It presents the quantitative results for each of the four core steps: Hazard Assessment, Occupational Health and Safety (OSH), Use-Phase Impact and Environmental Sustainability. Crucially, these quantitative findings are integrated with the qualitative insights gathered from key stakeholders, providing a holistic understanding of how SSbD principles translate into real-world design drivers and reveal practical implementation challenges.

### 4.3.1 Material Mapping and Composition for Evaluation

As part of the case study, preliminary material mapping was conducted for each component of the Leafy Green Façade system. This mapping forms the basis for evaluating the materials through the SSbD lens. The current system configuration, as seen in Figure 4, comprises both conventional (eg. rubber, LDPE) and bio-based materials (eg. bamboo fibre, jute cloth) across six primary subsystems, as shown in *Appendix C1*. Leafy's growing medium is soil-free and composed of multiple biogenic and inert fractions. *Appendix C2* summarizes the assumed composition. Additionally, the Material Safety Data Sheet for all materials was consulted for use in the assessment. The majority of substrate materials are biobased and biodegradable, aligning with the goals of the circular economy. However, inorganic additives like perlite and pumice while non-toxic, do not biodegrade and must be assessed for end-of-life handling.

This system demonstrates a conscious effort to balance structural integrity, plant viability and material sustainability. While the use of SS and conventional polymers (e.g., LDPE, PP) provides durability and reliability, several materials are under active testing for potential biobased substitutions (e.g., jute, bamboo fibre composites). The comparison between Tricoya, MOSO and Accoya reflects an ongoing exploration of performance versus environmental safety. In the subsequent sections, each material or component category is evaluated against the SSbD criteria focusing on chemical safety (hazard classification), environmental impact (biodegradability, recyclability) and social aspects (sourcing, circularity potential).

Leafy primarily uses an NPSP bamboo fiber composite for both the substrate container and front plate. According to internal specifications and external reference data, the composite is classified as a natural fiber-reinforced biocomposite with an estimated biobased content of 70%, depending on the resin formulation used. The exact resin type remains under testing but is assumed to be a bio-based or partially bio-based thermoset resin. The presence of fire-retardant additives or coatings is confirmed which has direct implications for fire resistance and toxicity.

To contextualize the bamboo composite's safety and sustainability profile, a comparative review was conducted with three reference façade materials: Tricoya MDF, MOSO Bamboo X-treme and Accoya Modified Wood (see *Appendix C3*).

### 4.3.2 Methodology for SSbD Evaluation

The methodology employed for this study was a qualitative case study with quantitative aspects, drawing on abductive reasoning. The analysis integrates findings from each of the four assessment steps encompassing safety, exposure, application-phase risk and life cycle environmental impacts. For each criterion within these steps, a standardized scoring scale from 0 to 3 was used, where 0 indicated no alignment and 3 represented high alignment with SSbD principles. These scores were substantiated with evidence from product data sheets, safety assessments and regulatory references. The scoring system is primarily illustrative, supporting decision-making, stakeholder dialogue and comparative analysis, rather than implying a rigid regulatory judgment. The approach enables communication of complex risk and sustainability trade-offs in a structured and transparent manner, without implying a rigid or regulatory judgment. *Figure 7* illustrates the assessment methodology employed for all four steps.


*Figure 7: Assessment Methodology*

*Figure 8* illustrates the two main pillars of the SSbD framework: safety and environmental sustainability. Safety is assessed through hazard-based risks (Step 1), processing (Step 2) and use-phase impacts (Step 3), while environmental sustainability is evaluated across toxicity, climate change, pollution and resource use (Step 4).

The overall assessment methodology guides the process and the aggregation of safety and environmental aspects follows a hierarchical structure to ensure a comprehensive evaluation, as seen in *Figure 8.* This approach also incorporates scenario analysis to explore design choices under high-risk, real-world conditions, utilizing quantitative data for material performance and qualitative data for contextualizing practical challenges and trade-offs.

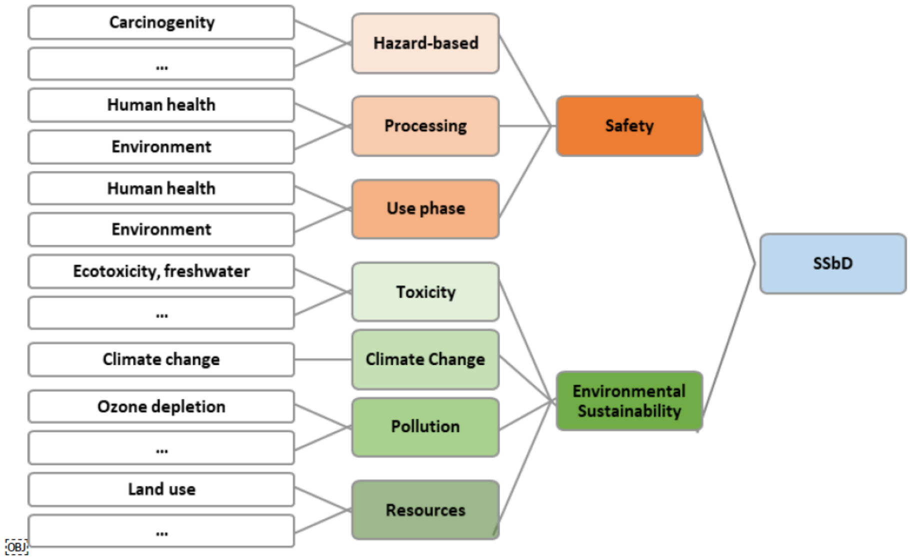


*Figure 8: Aggregation of safety and environmental aspects as a hierarchy*

## 4.3.3 Step 1 – Hazard Assessment

In the context of the SSbD approach, the focus is first on the intrinsic properties of chemicals and materials and identifying those that are inherently hazardous. In the EU chemicals legislation, three main hazard classes are described, i.e., human health hazards, environmental hazards and physical hazards and these classes are also included in the SSbD framework.

## Aspects & Indicators

Three main categories of aspects are defined and they are grouped in hazard categories as seen in *Appendix F.*

1. Intrinsic hazard properties relevant to human health (human health hazards).
2. Intrinsic hazard properties relevant to the environment (environmental hazards).
3. Physical properties (physical hazards).

## Criteria Definition

The methodology for defining criteria is based on the hazard classes and categories established within the CLP Regulation (Regulation (EC) No 1272/2008 (EU, 2008)) and REACH (Regulation (EC) No 1907/2006 (EU, 2006)). Three criteria (H1, H2 and H3) are defined in *Appendix F4.* It is divided into 3 parts: H1 which are the most harmful substances; H2 which are substances of concern and H3 includes other hazards.

## Evaluation System

Each chemical or material is assigned a safety level based on how it performs against the defined hazard criteria (H1, H2 and H3). This classification system includes four levels (0 to 3) which help determine the material's relative safety and inform its suitability for further use in product development, as shown in *Figure 9.*

- **Level 0:** Assigned to substances that fail Criterion H1, meaning they fall under the category of the most hazardous substances, such as those listed as SVHCs.
- **Level 1:** Indicates the material passes H1 but fails H2, suggesting it avoids the most harmful classifications but still belongs to the broader group of substances of concern due to potential chronic effects.
- **Level 2:** Given to materials that successfully meet both H1 and H2 but do not satisfy H3, implying they may still possess other hazard properties (e.g., flammability, acute toxicity).
- **Level 3:** The highest rating, for materials that meet all three criteria (H1, H2 and H3) and are thus considered to pose minimal intrinsic hazard. However, it's essential to note that even Level 3 substances may require additional risk assessment, depending on how and where they are used, particularly in scenarios involving significant exposure.

**Assumptions:**

- The data was collected from the interviews and MSDS of every material.
- Materials have been put into High, Medium, Low and Neg based on data collected from literature and MSDS and application of use.
- All criteria are initially weighted equally.
- NC material should automatically pass H1 and H2.
- The SSbD Score is defined by conditions related to hazard properties without involving any aggregation and therefore no MCDA methods are required in this step.
- The detailed chemical composition of the material wasn't considered.

*Table 11* presents the combined hazard classification for each material, evaluating them against three key SSbD criteria: Human Health, Environmental and Physical hazards.

*Table 11: Combined Hazard Classification Matrix (Human, Environmental, Physical)*

| Material | Human Health | Environmental | Physical | SSbD Level |
|---|---|---|---|---|
| **Epoxy Resin** | High | High | High | Level 0 |
| **Bio-Based Resin** | Neg | Low | Medium | Level 2 |
| **Bamboo Fibre** | Low | Neg | Low | Level 2 |
| **LDPE** | Neg | High | Medium | Level 1 |
| **PP** | Neg | High | Medium | Level 1 |
| **EPDM** | Neg | High | Medium | Level 1 |
| **SS** | Neg | Neg | Low | Level 2 |
| **Tricoya** | Low | Low | Low | Level 2 |
| **Jute Cloth** | Low | Neg | Low | Level 2 |

*Figure 9 below* shows the Step 1 workflow for epoxy resin. The left side indicates criteria for evaluation. The right side gives the 'Level' as described in the evaluation system. For epoxy resin, it fails the criteria and so we must stop the SSbD assessment on Step 1.

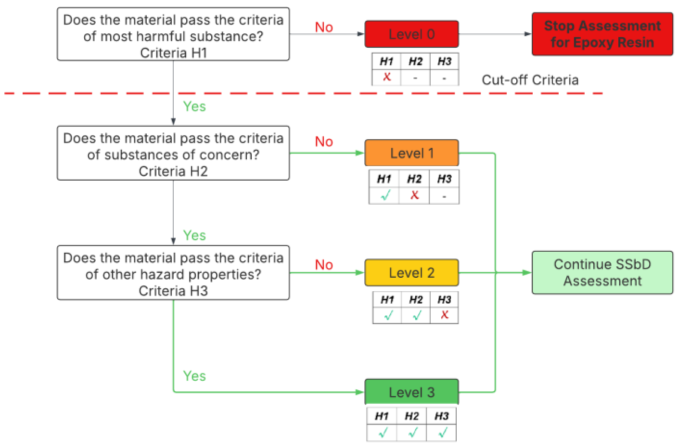


*Figure 9: Workflow for Step 1 for Epoxy Resin*

The Step 1 hazard assessment (see *Appendix F1, F2 and F3*) reveals varied safety risks across Leafy's material portfolio. Epoxy resin poses the highest concern, with multiple severe human health risks (e.g., carcinogenicity, reproductive toxicity), environmental hazards (e.g., PBT/vPvB, aquatic toxicity) and formulation-based flammability, making it the most hazardous material assessed.

In contrast, natural fibers like bamboo and jute exhibit minimal hazard classifications, primarily limited to skin and eye irritation from dust or mechanical processing. While not classified under GHS, they require standard safety precautions (e.g., dust masks). Bio-based resins appear safer than epoxy but lack comprehensive hazard data and should be used cautiously. Tricoya, although physically and environmentally moderate, raises health concerns due to its resin treatment and lacks sufficient environmental data. Petroleum-based plastics (LDPE, PP, EPDM) show few direct hazards but are flagged for flammability, potential SVHC classification and long-term microplastic risks. SS has the lowest risk profile, with no chemical hazards and only minor physical handling concerns.

These findings support prioritizing SS, bamboo, jute and bio-based resin for exposed or user-contact applications, while recommending epoxy and conventional thermoplastics be limited to low-exposure roles. The analysis also cautions that “biobased” does not equal “risk-free.” Minor issues, such as dust or incomplete toxicological data, still affect ratings.

Due to strict SSbD criteria where even mild concerns limit scoring, no material currently qualifies as Level 3. However, SS, jute and bio-based resin are close and may qualify with further data or formulation improvements. The absence of Level 3 ratings reflects the high SSbD safety threshold, not a lack of material progress.

### Qualitative Context & Implications

Stakeholders consistently emphasized safety as a non-negotiable priority, with specific concerns about fire resistance and the avoidance of toxic substances. The high stringency of SSbD's Step 1, which resulted in no material achieving Level 3, reflects this emphasis on intrinsic hazards without initially accounting for use conditions or risk mitigation measures. This highlights the trade-off inherent in material selection, where achieving optimal safety often requires careful consideration, even for "biobased" materials, as the evaluation emphasizes that biobased materials are not automatically benign and require further consideration of exposure routes, degradation mechanisms and data gaps.

### 4.3.4 Step 2 – Human Health & Safety Aspects in Production Phase

This step assesses the Occupational Safety and Health (OSH) risks associated with the production and processing of materials, as well as their on-site installation and handling, within the Leafy Green Façade System. It aims to identify potential hazards and exposures during upstream life cycle stages, especially in industrial and workshop settings and during active construction phases at the building site.

### Aspects and Indicators

This evaluation considers intrinsic hazards (toxicological properties, GHS classification) and exposure potential during production. Exposure is assessed by:

- Frequency and duration of processes
- Quantity handled
- Physical properties (volatility, dustiness, fugacity)
- Operational conditions (indoor/outdoor, open/closed systems)
- Exposure routes (inhalation, dermal, ingestion)

The effectiveness of Risk Management Measures (RMMs) (e.g., ventilation, PPE, closed systems) is included. A tiered approach is applied:

- Quantitative methods for established materials
- Tier 1 control banding for newer or less-studied materials, using qualitative/semi-quantitative scoring of hazard severity, exposure, physical form and RMM quality.

The output is a risk level categorization (low to high) to determine if current processes are safe or if further measures are needed.

## Criteria Definition

These criteria enable a structured evaluation of chemical/material hazards and exposure potential across all life cycle stages, including raw material extraction, manufacturing, processing, recycling and waste treatment.

Applying these criteria helps quantify occupational risk levels, supporting sustainable material choices and risk management decisions within the SSbD framework.

The main criteria are designed to apply across all phases of production and processing. They can be tailored to specific steps (e.g., extraction vs. end-of-life) depending on material type and data availability, as seen in *Appendix G2*. For emerging or under-tested materials (e.g., jute cloth, bamboo composites), these criteria enable Tier 1 qualitative assessments that can evolve into quantitative sub-criteria as more data becomes available.

## Evaluation System

Once the Step 2 criteria are defined, each material or process is assessed by assigning a numerical risk score (0–3) to each criterion, as seen in *Table 12.* Scores reflect both the intrinsic hazards of the material and the potential for worker exposure during production and processing.
The assessment covers five key criteria, including:

- Chemical hazard severity
- Exposure frequency and duration
- Physical characteristics (dustiness, volatility)
- Process operational conditions
- Effectiveness of Risk Management Measures (RMMs).

Scores are summed to calculate an overall Occupational Safety and Health (OSH) score (5–20), used to classify the occupational risk level as high, medium, low or negligible. This helps determine whether current practices are sufficient or if further safety measures or design changes are needed. Maximum scoring is 4 so that the total across 5 primary criteria is 20.

*Table 12: Evaluation Criteria for Step 2*

| Total OSH Score | OSH Level | Interpretation |
|---|---|---|
| 1-5 | Level 0 | High risk process |
| 6-10 | Level 1 | Medium risk process |
| 11-15 | Level 2 | Low risk process |
| 16-20 | Level 3 | Negligible risk process |

*Table 13* presents a scoring system for the Leafy Green Façade materials, illustrating how each material performs across five key OSH criteria. The total score and corresponding OSH Level give a clear picture of workplace safety risks during production and processing. *Note: Refer to Appendix G1 for scoring sources.*

**Assumptions:**

- Each criterion is scored individually and all criteria are initially weighted equally.
- OSH Score is considered the SSbD score for this step.
- The data was collected from the interviews and MSDS of every material.
- Risk Characterization Ratio method is not considered.

- To simplify the scoring, level 0-3 are only considered for consistency across other steps. Hence, a medium risk process can be considered closer to high risk.

*Table 13: OSH Scoring for Leafy materials*

| Material | Chemical Hazard | Exposure Freq | Physical Properties | Process Conditions | RMMs Effectiveness | Total Score | OSH Level |
|---|---|---|---|---|---|---|---|
| **Epoxy Resin** | 1 | 2 | 1 | 2 | 2 | 8 | Level 1 |
| **Biobased resin** | 3 | 3 | 3 | 3 | 3 | 15 | Level 2 |
| **Bamboo Fibre** | 2 | 3 | 3 | 3 | 3 | 14 | Level 2 |
| **Tricoya** | 2 | 2 | 3 | 2 | 2 | 11 | Level 2 |
| **LDPE** | 4 | 3 | 3 | 3 | 4 | 17 | Level 3 |
| **SS** | 4 | 4 | 4 | 4 | 4 | 20 | Level 3 |
| **PP** | 4 | 4 | 4 | 4 | 4 | 20 | Level 3 |
| **EPDM** | 4 | 4 | 4 | 4 | 4 | 20 | Level 3 |
| **Jute Cloth** | 4 | 3 | 2 | 2 | 3 | 14 | Level 2 |

*Figure 10* shows the Step 2 workflow for epoxy resin. The left side shows 5 criteria on which step 2 has been evaluated with scores given for each step. The middle section shows the overall OSH score by combining scores for all five criteria. The right side provides the OSH level.

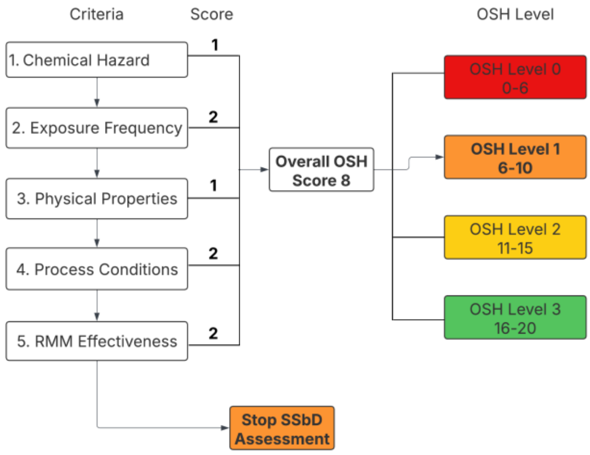


*Figure 10: Workflow for Step 2 for Epoxy Resin*

The OSH scoring in Step 2 reveals meaningful distinctions in occupational safety risk levels across the materials used in Leafy's green façade panel system. Most materials fall within Level 2 (Low Risk) or Level 3 (Negligible Risk), confirming that Leafy's material selection aligns well with safe-by-design principles in terms of worker health and safety during manufacturing and processing. Notably, epoxy resin is the only material that scored at Level 1 (Medium Risk), with a total OSH score of 8. This outcome is primarily driven by its high chemical hazard classification, low process safety profile and limited effectiveness of risk management measures (RMMs). Given its volatility and toxicity, this material poses a heightened occupational risk. It should either be phased out or limited to very controlled structural applications where worker exposure can be minimized through strict engineering controls, personal protective equipment (PPE) and ventilation systems.

In contrast, bamboo fibre composite, Tricoya, biobased resin and jute cloth all scored within the Level 2 (Low Risk) range. These are biobased or natural materials that, while generally safer, still involve moderate exposure risks particularly from dust inhalation or volatile organic compound (VOC) release during cutting or thermal treatment. These risks can be effectively mitigated through standard safety practices such as dust suppression, localized ventilation and protective clothing, making these materials viable for large-scale use with appropriate handling procedures in place.

The materials that performed best were LDPE, PP, EPDM and SS, all of which reached Level 3 (Negligible Risk). These materials are chemically stable, easy to process in closed systems and benefit from strong existing risk control measures. Their minimal impact on worker safety makes them ideal for roles in Leafy's design where extensive handling or long-term worker contact may occur.

## Qualitative Context & Implications

Stakeholders underscored the importance of safe installation and adherence to Dutch Occupational Health and Safety (Arbo) Regulations. Leafy's design emphasis on lightweight components (aiming for individual components not exceeding 10 kg) directly supports safe and easy installation, although mechanical aids may still be required for heavier panels. Supplier insights confirmed that while materials like bamboo can generate dust during production, these risks are typically well-mitigated through established safety protocols. However, a related concern highlighted during interviews and further evident in installation guidelines is the generation of dust during on-site activities such as drilling and cutting of panels and substructures. Despite general mitigation measures, this exposure remains a key aspect of worker health during the installation phase, necessitating strict adherence to PPE protocols (e.g., FFP2 dust masks for fibers) and proper ventilation. The findings validate Leafy's commitment to occupational safety, showcasing how design choices and industry practices align with SSbD principles in the production phase.

## Installation and Regulations

Leafy's innovative, self-sustaining bamboo-based façade panels, designed for their lightweight nature and modularity, must comply with stringent installation and safety regulations to ensure their responsible application, particularly in retrofitting existing buildings.

In the Netherlands, Leafy's installation and maintenance procedures are governed by the Working Conditions Act (Arbowet) and Working Conditions Decree (Arbobesluit). Key considerations for Leafy include:

- **Fall protection:** For work at heights over 2.5 meters, collective safety measures (e.g., scaffolding, guardrails) are mandatory. If not feasible, individual protection, such as harnesses, must be used, with collective measures prioritized.
- **Falling object prevention:** Leafy's panels and tools must be secured to prevent injury to workers or bystanders.
- **Ergonomics:** Employers must minimize manual lifting and awkward handling. While Leafy's design emphasizes lightweight components (with a total system weight of not more than 70 kg/m² and individual components ideally not exceeding 10 kg), mechanical aids are still required for heavy panels, given the standard safe lifting limit of 23 kg per person. A Risk Inventory & Evaluation (RI&E) and proper worker training are mandatory, as seen in *Appendix J*.
- **PPE Required Types:** Safety boots (steel toe); high-vis vest; hard hat; eye protection; gloves; fall-arrest gear; FFP2 dust mask for fibers. Crucially, the requirement for an FFP2 dust mask highlights the recognition of airborne particulate matter as a hazard during installation, particularly from cutting, drilling, or abrading activities involving materials like bamboo fibre composites or wood-based panels. Effective management of this dust, through local exhaust

ventilation or wet cutting methods, is essential to mitigate long-term respiratory health risks for workers.

Additionally, the Dutch Building Decree (Bouwbesluit) requires safety-by-design for façades. Sections 6.12 (Articles 6.53 and 6.54) mandate that new buildings incorporate safe maintenance solutions, such as roof anchors or façade access systems. Façade design must support safe installation and ongoing maintenance. *Appendix J* provides more details.

### Installation Workflow and Material Selection for Façade Systems

The installation process for Leafy is structured into five stages: pre-installation, material preparation, on-site work, panel installation and post-installation, as seen in *Appendix L1*, ensuring technical accuracy, regulatory compliance and long-term façade performance. This approach aligns with construction safety standards and SSbD principles, emphasizing durability, maintainability and worker safety throughout.

To support material choices, *Appendix L2* compares wooden and metal substructures for façade mounting, focusing on permit needs, durability, fire safety, height suitability and drainage.

For façades up to 13 meters, wooden battens can be used, provided they are treated and undergo a fire safety review. However, for buildings exceeding 13 meters or with an elevated fire risk, Leafy must use non-combustible subframes, such as SS, galvanized steel, or aluminum, to meet Euroclass B-s1,d0 standards.

### Impact of installation on external wall

Leafy's panels need to be adaptable to various existing wall types during retrofitting, with specific considerations for each substrate. When mounting façade panels onto an existing wall, the characteristics of the base wall (substrate) affect how panels are anchored, how loads are transferred and how the wall system handles thermal and moisture behavior. Different substrates: masonry, timber-frame, or concrete, each present unique consideration, as seen in *Appendix L3*.

These detailed considerations for installation and material compatibility are crucial for Leafy to ensure the safety, durability and long-term performance of its biobased façade panels, aligning with the core principles of the SSbD approach. They directly address stakeholder concerns regarding fire safety, structural integrity and long-term performance, reinforcing the feasibility and responsibility of Leafy's innovative solutions.

### 4.3.5 Step 3 – Human Health & Environmental Aspects in Application Phase

This step includes potential exposure to users (e.g., installers, particularly from dust generated during on-site cutting and drilling activities, maintenance workers, building occupants) and environmental emissions (e.g., leaching, degradation, or wash-off).

### Aspects & Indicators

Risk characterization during the use/application phase integrates material-specific properties with contextual use factors. Key inputs include:

- Intrinsic hazards (toxicity, environmental persistence, physical risks)

- Use conditions (frequency, duration, quantity used, open/closed systems, indoor/outdoor use)

This combined assessment estimates:
- Human exposure (inhalation, dermal contact)
- Environmental emissions (degradation, runoff during façade wash-off or irrigation)

This holistic evaluation supports the identification of safer use configurations and the development of targeted mitigation strategies within the SSbD framework.

## Criteria Definition

These criteria capture potential exposure scenarios and hazard outcomes for end users (workers, consumers) and the environment. Applying these criteria provides use-phase safety insights, complementing hazard (Step 1) and production-phase (Step 2) analyses within the SSbD framework.
The framework is flexible, accommodating:
- Different material types (polymers, natural fibres, metals)
- Varied applications (indoor cladding, outdoor façades, irrigation pipes, root barriers)

Criteria can be refined into sub-criteria as needed to ensure contextual relevance. While some criteria (toxicity, biodegradability) are universally applicable, others (inhalation exposure, wash-off potential) are context-dependent.
This approach ensures safety evaluations remain scientifically robust and practically relevant, reinforcing the integrity of the SSbD framework.

## Evaluation System

The evaluation system enables the quantification of risks based on defined safety thresholds, providing a structured approach to determine whether a material "passes" or "fails" concerning human health and environmental safety. Each material is evaluated against specific criteria and its position relative to the defined safe level is used to assign a score. *Table 14* outlines the scoring system.

*Table 14: Evaluation System for Step 3*

| Position to Safe Level | Score | Criteria Evaluation |
|---|---|---|
| Between safe level and 50% worse | 0 | Fail the criteria |
| Between 25% better and safe level | 1 | Further assessment needed |
| Between 50% better and 25% better | 2 | Pass the criteria |
| More than 50% better than safe level | 3 | Pass the criteria |

These thresholds enable a semi-quantitative risk classification, considering both hazard and exposure factors as outlined in the previous steps.

The combined outcome of the human health and environmental safety criteria determines the overall application-phase safety level of a material:
- Level 0: The material fails to meet both human and environmental safety criteria.
- Level 1: The material meets only one of the two safety criteria.
- Level 2: The material meets both safety criteria with certain restrictions.
- Level 3: The material meets both safety criteria without certain restrictions.

This multi-criteria system provides a clear framework to compare material alternatives, prioritize safer substitutes and integrate the findings into the overall SSbD decision-making process. It also helps accommodate data variability and uncertainty by allowing for graduated risk levels rather than binary outcomes. This can be found in *Appendix H.*

The findings from Step 3 reveal that SS stands out as the safest material across all evaluated criteria, achieving perfect scores in both human health (HH) and environmental exposure (EE) categories. Its inert properties, resistance to degradation and lack of emissions position it as an ideal material from both a health and sustainability perspective. Most polymeric and bio-based materials, including LDPE, PP, EPDM, bio-based resin and Tricoya, performed favorably as well, with average scores ranging between 3.0 and 4.0. These materials were classified as Level 2 (Passes Both), reflecting their relatively low volatility, durable nature and manageable risks during installation. However, polymers like LDPE and PP pose long-term environmental risks due to microplastic formation which warrants consideration in end-of-life strategies.
Natural fibres such as bamboo fibre and jute cloth, though biodegradable and low in emissions, scored moderately (around 3.0) in the human health dimension due to dust-related inhalation risks during handling. Despite this, they were still categorized as Level 2, indicating acceptable safety when paired with proper protective measures, such as PPE or prefabricated installations. In contrast, epoxy resin emerged as the least safe material during application, receiving the lowest scores in both HH and EE criteria. Its high VOC emissions, reactive chemical profile and toxic degradation products resulted in a Level 0 (Fails Both) classification, highlighting the need for strict controls or alternative materials when aiming for SSbD compliance.

This allowed for objective classification, where Level 2 materials can be confidently prioritized for application in façade systems and Level 1 or 0 materials indicate the need for risk mitigation, design revision, or substitution. These insights contribute to a more transparent and evidence-based decision-making process aligned with the SSbD principles.

**Assumptions:**

- Each criterion is scored individually and all requirements are initially weighted equally.

*Table 15: SSbD Scoring for Step 3*

| Material | Human Health Score | Environmental Score | Combined Score | SSbD Level |
|---|---|---|---|---|
| **Epoxy Resin** | 0.5 | 0.5 | 0.5 | Level 0 |
| **Bio-Based Resin** | 2 | 2 | 2 | Level 2 |
| **Bamboo Fibre** | 2.75 | 2.25 | 2.5 | Level 3 |
| **LDPE** | 3 | 2 | 2.5 | Level 3 |
| **PP** | 3 | 2 | 2.5 | Level 3 |
| **EPDM** | 3 | 2 | 2.5 | Level 3 |
| **SS** | 3 | 3 | 3 | Level 3 |
| **Tricoya** | 2 | 2 | 2 | Level 2 |
| **Jute Cloth** | 2.5 | 2 | 2.25 | Level 2 |

Note 1: Combined Score = Average of Human Health Score, Environmental Score. Find details in Appendix H

*Figure 11* shows the Step 3 workflow for epoxy resin. The left side shows 2 criteria for evaluation. The right side gives the level as based on criteria defined. For epoxy resin, it fails both criteria and so we stop the SSbD assessment.

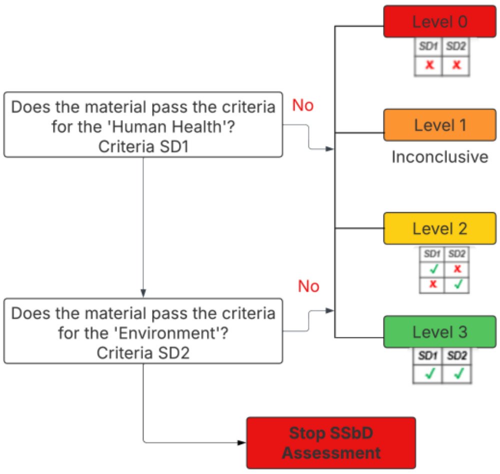


*Figure 11: Workflow for Step 3 for Epoxy Resin*

Overall scoring, as seen in *Table 15*, reveals significant variation among materials used in Leafy's façade system. Epoxy resin was identified as the material of highest concern, scoring Level 0 due to its high volatility, toxic degradation products and low environmental durability. This indicates that its use should be limited to internal or structural applications where exposure is tightly controlled. In contrast, SS, EPDM, LDPE and PP scored Level 3, reflecting negligible exposure concerns and strong environmental performance, thereby validating their use in external or exposed parts of the panel system. Materials like bio-based resin, bamboo fibre, jute cloth and Tricoya scored Level 2, suggesting low to moderate concerns, primarily related to dust generation during handling and especially during on-site cutting and drilling for installation, biodegradability, or susceptibility to moisture during use. While generally safe, the dust generated by these materials poses an inhalation risk to construction workers and would benefit from improved sealing, surface treatments, or refined installation procedures that minimize airborne particles and ensure proper respiratory protection to ensure safety and longevity.

## Qualitative Context & Implications

Stakeholders consistently emphasized durability and material integrity as critical for long-term safety, especially for materials exposed to the environment. Concerns about moisture management and long-term degradation (e.g., UV resistance, freeze-thaw cycles) were also prominent, reinforcing the need for materials that can withstand environmental degradation over time. The findings from Step 3 align with the design drivers for low toxicity, prioritizing materials that minimize hazardous substances impacting occupants or the environment, particularly highlighting the issues with epoxy resin.

## Systemic Impacts of Integrating Leafy Panels into Existing Buildings

When integrating novel biobased façade panels like Leafy's into existing building envelopes, stakeholders consistently raise concerns about their systemic impacts, which span structural integrity, fire resistance and environmental performance. These critical areas directly influence the long-term safety, durability and widespread adoption of such innovative solutions, requiring careful consideration beyond mere material composition.

The installation of Leafy's self-sustaining, bamboo-based façade panels on existing buildings introduces several key systemic impacts that align with primary stakeholder concerns identified in this study. Understanding and mitigating these impacts is crucial for ensuring the responsible deployment and market acceptance of these technologies.

1. **Structural Integrity:** The addition of Leafy's green façade panels, including their lightweight structures, plant systems and integrated irrigation components, adds weight to a building's structure. Stakeholders, particularly architects and façade experts, consistently emphasized the necessity of ensuring robust structural and wind safety to prevent failures, especially in multi-story or high-wind urban environments. This concern revolves around:

   - **Weight and Load-Bearing Capacity**: Green façade panels, especially those with extensive vegetation and irrigation, can strain the load-bearing capacity of existing building materials such as concrete and brick, potentially leading to structural issues over time. For Leafy, the weight of soil, plants and irrigation systems in green façades can impose additional stress on the building's foundation and walls (Manouchehri et al., 2024) (Flansbjer et al., 2018). For Leafy, while their panels are specifically designed to be lightweight, aiming for a total system weight not exceeding 70 kg/m² and individual components ideally not exceeding 10 kg, the underlying façade (substrate) must be rigorously inspected for structural integrity and checked for cracks to ensure it can safely carry the new load.

   - **Material Compatibility**: Integrating Leafy's panels with existing wall types like concrete and brick requires careful consideration of material compatibility. Leafy's click-on/click-off mounting interface for the substructure is a key design feature that facilitates easy installation and replacement without the need for adhesives. This design choice inherently reduces compatibility challenges often associated with chemical bonds while supporting rapid assembly and circularity goals (Shafaie et al., 2024). The panel components, made from bamboo composite and SS, are selected with long-term compatibility and thermal performance in mind, requiring thermally broken brackets and continuous insulation to prevent thermal bridging.

   - **Moisture Retention and Durability:** Leafy's integrated irrigation system and biobased growth medium can lead to increased moisture retention. This is a concern for materials like brick and concrete, which are prone to degradation from excessive moisture. Long-term performance and durability are the dominant stakeholder concerns for façades. To mitigate these risks, Leafy's installation procedures emphasize the provision of a ventilated air gap, the use of a weather-resistive barrier (WRB) and the installation of EPDM seals and drainage mats to prevent moisture buildup and ensure proper drainage. The design must also ensure resistance to humidity, rain and biological degradation over a service life of 15-30 years outdoors (Manso-Morato et al., 2024) (Nwokediegwu et al., 2024).

2. **Fire Resistance:** Fire safety consistently ranks as a top concern among stakeholders for novel biobased façade panels like Leafy's, mainly due to regulatory pressures and public safety implications. The combustibility of materials used in green façades, including vegetation and certain types of cladding, can pose a significant fire hazard. This concern involves:

   - **Combustibility of Materials**: The use of combustible materials in green façade panels, such as wood or certain types of insulation, can increase the risk of fire spreading. For Leafy, whose panels utilize a bamboo fiber composite for components like the substrate container and front plate, there is a confirmed presence of fire-retardant additives or coatings within the composite. While bio-based materials offer sustainability benefits, "biobased" does not automatically equate to "risk-free" in terms of fire performance. Traditional examples, such as ACP with combustible cores, highlight the fire hazards that can occur if materials are not adequately addressed. However, high-ignition-point insulation materials, like mineral fiberglass, can mitigate such risks (Dabous et al., 2022; Nguyen et al., 2016).

- **Fire Spread and Facade Design**: The design of green façade systems can significantly influence the spread of fire. Factors like the geometry of the façade, the presence of cavities and the use of cladding materials can all impact fire behavior. Architects highlighted the importance of incorporating fire breaks and vertical separation in green façade designs. For instance, deliberate gaps or access zones with no plants/panels can be included as fire prevention measures and unplanted bands at each floor level can act as fire breaks. Modern façade systems, including those with green elements, are more complex and potentially more flammable than traditional systems, emphasizing the need for improved fire-resistant design (Bonner & Rein, 2018; Nguyen et al., 2016).

- **Testing and Certification**: Ensuring that green façade panels meet fire resistance standards is essential. For Leafy, their panels must meet stringent fire safety requirements, such as EN 13501-1 Class B-s1,d0. For buildings exceeding 13 meters in height or in cases of elevated fire risk, non-combustible substructures (e.g., SS, galvanized steel, or aluminum) are essential to achieve higher Euroclass standards (A2-s1,d0). The design must also incorporate fire breaks and vertical separation to prevent the spread of fire. Testing protocols, such as those outlined in EN 13830:2015 for curtain wall systems, can provide valuable insights into the fire performance of green façade systems (Vandi et al., 2024). Additionally, the use of advanced materials, such as bio-based composites, has shown promise in improving fire resistance while maintaining sustainability (Pracucci et al., 2024).

## Extreme Failure Risk Events

The installation and long-term performance of Leafy panels are subject to a range of extreme conditions that can compromise both safety and sustainability. These events are not limited to weather-related phenomena but also include mechanical failures, fire propagation, vandalism and substrate-specific hazards. In line with the SSbD framework, it is crucial to identify such risks early and integrate mitigation strategies throughout the lifecycle from design and material selection to installation and maintenance. This approach ensures that the Leafy panels remain resilient, compliant with Dutch regulations (e.g., Bouwbesluit, Arbobesluit, NEN-EN standards) and fit for use in dynamic urban environments. Stakeholders, including architects, façade experts and Leafy's suppliers, consistently emphasized that safety is a non-negotiable priority, with concerns often revolving around fire safety, structural integrity and long-term durability.

## Weather-Related Risks

Leafy's panels, being bio-based and featuring a gravity rainwater irrigation system, must be robust against varying climatic conditions. Stakeholders repeatedly highlighted durability and maintenance as primary concerns, which significantly influence long-term performance and product acceptance. *Table 16* outlines significant weather-related risks that may impact the safety, durability and sustainability of Leafy Panels across their design, installation and use phase.

*Table 16: Extreme Weather Conditions During Façade Lifecycle*

| Failure Event | Risk Description | Mitigation Strategy | Justification / Source |
|---|---|---|---|
| Heavy Rain & Flooding | Moisture ingress behind panels may cause mold, wood swelling, or substrate erosion. | Provide ≥20 mm ventilation cavity; use EPDM sealants and drainage mats. | Pérez et al., 2011; NEN-EN 1991-1-4; Manso & Castro-Gomes, 2015 |
| Freeze–Thaw Cycles | Moisture in cracks or mounting cavities may freeze and expand, leading to cracking. | Use frost-resistant backing (Tricoya), pressure-treated battens, ensure sealed joints and breathable design. | EN 321; Building Research Establishment (BRE), UK |
| Heatwaves & UV | UV may degrade polymers (LDPE, EPDM); may cause cracking, fading, or brittleness. | Use UV-stable materials (Accoya, EPDM), apply reflective coatings, avoid dark surfaces on sun-exposed areas. | NEN-EN 927-6; Huijbregts et al., 2016 |
| Strong Winds & Storms | Panels may detach if wind load is underestimated or fixings are weak. | Design according to NEN-EN 1991-1-4 wind loads; use SS anchors and reinforced rails. | Bouwbesluit 2012; Eurocode; ISO 7892 |
| Drought | Vegetation dries out, damaging aesthetic value and dust control performance. | Use drought-tolerant plants; integrate drip irrigation with timer and moisture sensors. | Ottelé et al., 2011; USEPA Water Efficiency Guidelines |
| Hail & Debris Impacts | High-velocity hail can crack or dent panels, especially bamboo composites. | Use high-impact resistant laminated panels; add protective coatings in hail-prone regions. | ISO 7892:1988; Rockpanel Design Manual |

## Other Extreme Failure Scenarios

Beyond weather-related events, several non-weather-related factors pose significant risks. Stakeholder insights emphasized the importance of addressing these issues at a systemic level, acknowledging the practical challenges involved. *Table 17* captures these scenarios, such as mechanical collapse, vandalism, or fire and recommends proactive design and operational strategies specifically applicable to Leafy's bio-based façade systems.

*Table 17: Extreme Façade Failure Events*

| Failure Event | Risk Description | Mitigation Strategy | Source |
|---|---|---|---|
| Panel Detachment | Insecure anchors or corrosion may lead to panel falling from height. | Use CE-certified SS anchors, torque-check biannually and test fixings for wind load compliance. | NEN-EN 1991-1-4; ISO 898-1; façade collapse reports (Heijmans, 2019) |
| Structural Subframe Collapse | Failure of battens or brackets due to overload or decay. | Use Class 3.2 treated spruce; avoid timber subframes above 13 m; conduct visual inspections and strength tests. | Eurocode 5; Rockpanel Guidelines; Tricoya Design Guide |
| Vandalism or Theft | Intentional damage to green panels or irrigation systems in public buildings. | Use tamper-proof fixings, protect irrigation hardware, install motion sensors and CCTV near street level. | GGD Amsterdam Safety Guidelines (2018); ISO 10012 tamper resistance standards |
| Fire Spread via Cladding | If not fire-rated, façade may exacerbate fire propagation. | Use Euroclass B-s1,d0 materials (e.g., Tricoya + aluminium subframe) for all facades above 2.5 m. | Bouwbesluit 2012; NEN-EN 13501-1 Fire Classification |

| | | | |
|---|---|---|---|
| Equipment or Vehicle Impact | Forklift, crane, or vehicle strikes panel during use or maintenance. | Define no-go zones; install ground barriers or bollards; apply impact-resistant base panels. | ISO 7892; V&G-plan Construction Safety Protocol |
| Asbestos Substrate Hazard | If panels are fixed on asbestos cement, drilling can release hazardous fibers. | Perform SC-540 inspection; use SC-530 certified contractor for safe removal before installation. | Dutch Asbestverwijderingsbesluit; Inspectie SZW Guidelines |
| Design Integration Failure | Engineering oversight causes unexpected load paths or unverified fastening. | Ensure peer review of all structural drawings; document all façade-specific load tests and assumptions. | Hyatt Walkway Failure Case Study; Eurocode QA Protocol |

*Figure 12* provides an overview of the extreme events that may occur during the lifecycle of a façade.

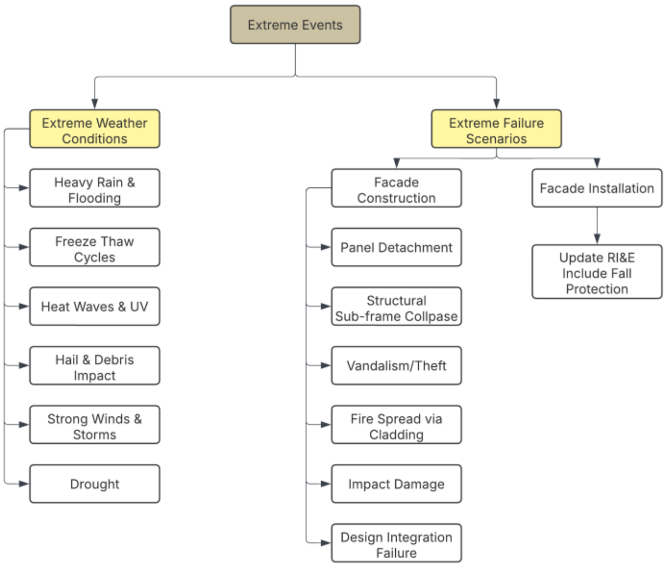


*Figure 12: Extreme Event Scenarios (Weather & Non-weather)*

We find that while Leafy Panels offer significant sustainability benefits through their bio-based composition, their design and installation must equally prioritize environmental resilience and structural safety. Proper detailing of drainage and anchoring systems is crucial to prevent moisture accumulation and potential panel detachment, particularly in varying weather conditions. Additionally, the use of durable, fire-rated and impact-resistant materials is essential not only for long-term performance but also for meeting regulatory compliance and ensuring public safety. To maintain reliability throughout the product's lifecycle, regular inspections, thorough documentation and comprehensive risk audits are necessary to anticipate and mitigate the risk of extreme failure events. These strategies align with Dutch Bouwbesluit, Arbo and Eurocode requirements and ensure Leafy's façades are safe and sustainable by design. Each of these risks corresponds to design characteristics and metrics that can be measured and specified, as seen in the next section.

### 4.3.6 Step 4 – Environmental Sustainability Assessment

This assessment evaluates 1 m² façade panels made of different materials under a cradle-to-cradle scope (raw extraction through end-of-life), using ReCiPe/CML-type impact categories relevant in the EU (e.g., GWP/climate, toxicity, eutrophication, resource depletion). Each material's goal, scope, system boundaries and assumptions are summarized, followed by impact results (scored 0–3) and discussion of critical categories. To evaluate all the materials, literature and desk research are conducted to check the LCA of each material. Based on this, scoring is provided. *Appendix I* includes the goal, boundaries, assumptions and indicators used in each material.

## Aspects & Indicators

The Environmental Footprint method covers 16 impact categories, grouped into four clusters:

- Toxicity: human toxicity (cancer, non-cancer), freshwater ecotoxicity
- Climate change: global warming potential
- Pollution: acidification, eutrophication, ozone depletion
- Resource use: water, energy, minerals

Specific metrics for each aspect. E.g., GWP (kg $CO_2$-eq) for climate, human toxicity potential (HTP) for toxicity, acidification potential (kg $SO_2$-eq), eutrophication (kg $PO_4$-eq) and abiotic depletion (MJ or kg Sb-eq) for resources.
Unlike earlier steps focusing on direct exposure, Step 4 emphasizes indirect environmental impacts from emissions and resource consumption across the life cycle, considering chemical fate, transport, bioaccumulation and soil contamination. Indicators align with the CSS supporting climate action, biodiversity protection and resource efficiency. While the EF method enables aggregation, disaggregated scores across all categories are maintained to identify trade-offs and hotspots.

## Criteria Definition

For each indicator, we set thresholds to assign scores from 0 (worst) to 3 (best). For example, high GWP or high fossil energy use: score 0–1; moderate: 2; near-zero/positive (carbon uptake): 3. Similar ordinal scales apply to toxicity (e.g., presence of known carcinogens lowers the score) and pollution. These thresholds should be defined based on relative performance (e.g., compared to reference materials). This approach reinforces SSbD principles, prevents burden-shifting and supports the design of truly safe and sustainable materials.
0 = High Risk (e.g., GWP >20 kg $CO_2$-eq/m²)
1 = Medium (e.g., 10–20 kg $CO_2$-eq/m²)
2 = Low Risk (e.g., 2–10 kg $CO_2$-eq/m²)
3 = Negligible Risk (<2 kg $CO_2$-eq/m² or net negative)

## Evaluation System

The scores per category are aggregated. Here, we define the *overall LCA score* as follows: 0 if no category scores greater than 1 and up to 4 if all categories score 2 or higher. This rule simplifies assessment (materials with multiple low-impact categories rate highest). In this thesis, one might elaborate using weighted multi-criteria analysis or adding normalization (e.g., dividing impacts by reference loads) to justify thresholds. The Standard LCA methodology (ISO 14040/44, EN 15804) underpins the approach, which aligns with the PEF/CML guidance.

A material is considered to have passed a level if it meets the minimum improvement threshold (Score ≥ 2) in all categories within that level. The overall LCA level is then calculated by counting the number of levels that are fully passed. Unlike earlier steps, there is no cut-off criterion at the impact level; all materials are evaluated across all categories and performance is reported as a combination of scores and an overall LCA level.

In practice, this means we evaluate each material's performance in key indicators (per ReCiPe/CML) and then apply the scoring rubric. *Table 18*, the comparative table, exemplifies this: it condenses complex LCI results into intuitive scores (with sources) for informed decision-making. All impact statements and scores above draw on LCA literature and EPD data to ensure the assessment is evidence-based.

**Assumptions:**

- Each criterion is scored individually and all criteria are initially weighted equally.
- Reflect average EU market conditions, typical panel thickness and standard disposal scenarios.
- SSbD score is the average of all 4 category scores.
- SSbD score is included to have consistency.

*Table 18: Step 4 Summary*

| Material | Toxicity (ES1) | Climate Change (ES2) | Pollution (ES3) | Resources (ES4) |
|---|---|---|---|---|
| Epoxy Resin | Yes | Yes | Yes | Yes |
| Bamboo Fibre | No | No | No | No |
| LDPE | No | Yes | No | Yes |
| PP | No | Yes | No | Yes |
| EPDM | No | Yes | No | Yes |
| SS | Yes | Yes | Yes | Yes |
| Tricoya | No | No | No | No |
| Jute Cloth | No | No | No | No |

*Table 19: Step 4 Scoring*

| Material | Toxicity | Climate | Pollution | Resource | LCA | SSbD Score |
|---|---|---|---|---|---|---|
| **Epoxy resin** | 1 | 1 | 1 | 0 | 0 | **1** |
| **Bamboo fiber** | 3 | 3 | 3 | 3 | 4 | **3** |
| **LDPE** | 2 | 2 | 2 | 1 | 2 | **2** |
| **PP** | 2 | 2 | 2 | 1 | 2 | **2** |
| **EPDM** | 2 | 1 | 2 | 1 | 2 | **1** |
| **SS** | 2 | 1 | 1 | 0 | 1 | **1** |
| **Tricoya** | 2 | 2 | 2 | 2 | 3 | **2** |
| **Jute cloth** | 3 | 3 | 3 | 3 | 4 | **3** |

*Figure 13* shows the Step 4 workflow for epoxy resin. The left side shows four criteria for evaluation. The right side provides the Level of LCA based on the defined criteria. For epoxy resin, it fails both criteria and so we stop the SSbD assessment.

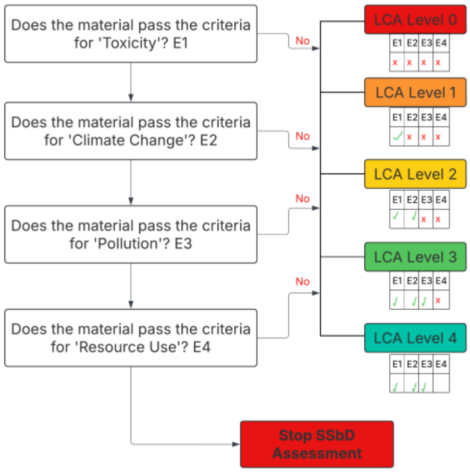


*Figure 13: Workflow for Step 4 for Epoxy Resin*

The comparative cradle-to-cradle LCA in *Table 19* for 1 m² façade panels under EU conditions revealed apparent differences in environmental performance among the eight materials. Epoxy resin showed high impacts, with a global warming potential (GWP) of ~5–9 kg $CO_2$-eq/kg resin, high fossil resource use and concerns over toxicity from bisphenol A and epichlorohydrin precursors, resulting in an overall poor sustainability score. Bamboo fibers demonstrated excellent environmental performance, with net negative or near-zero GWP due to biogenic carbon uptake, negligible toxicity, low pollution and renewability, making them one of the most favorable materials. EPDM rubber exhibited moderate to high impacts, with ~8.9 kg $CO_2$-eq/m² and fossil resource dependency, though end-use toxicity remained low due to the inert nature of the cured rubber. SS panels showed the highest climate and resource burdens, with ~54 kg $CO_2$-eq/m² (2 mm thick), significant acidification potential due to $SO_2$/NOx emissions during smelting and high fossil energy use despite high durability and recyclability. Jute cloth scored very favorably, with low or neutral GWP, negligible toxicity and minimal pollution while being fully renewable, making it an ideal biobased option. LDPE and PP panels exhibited moderate climate impacts, with GWP values of ~2.3–2.7 kg $CO_2$-eq/m² at typical thicknesses, low toxicity and pollution, but low scores in resource use due to their petrochemical origin. Finally, Tricoya wood exhibited low to moderate climate impacts (~50–150 kg $CO_2$/m³ after biogenic carbon credits), moderate toxicity due to MDI resin used in manufacturing, low pollution and higher resource use than pure wood due to chemical processing yet remained a sustainable alternative overall. These results indicate that bamboo fibers and jute cloth are strongly preferable for low-impact façade panels, while epoxy resin and SS should be avoided where lower-impact biobased options are viable.

## Qualitative Context and Implications

Sustainability was seen as essential, but only after stakeholders had assured safety and performance. They highlighted the importance of biobased, recyclable, or locally sourced materials, conducting full LCA and designing for circularity. The strong performance of biobased materials, such as bamboo and jute, in terms of embodied carbon and renewability directly aligns with Leafy's design principles and the broader EU sustainability goals, as they contribute to a low-carbon footprint and resource efficiency. However, the study reiterates that "biobased" does not automatically equate to "risk-free," particularly in terms of fire performance and other hazard profiles. Leafy's active assessment and disclosure of environmental impacts, as mentioned by a supplier, demonstrate its commitment to rigorous environmental evaluation.

## Systemic Impacts of Integrating Leafy Panels into Existing Buildings

The environmental impact of integrating green façade panels with traditional building materials is a key consideration. While green façades offer several environmental benefits, such as improved thermal performance and reduced energy consumption, their long-term environmental impact requires careful evaluation.

Note: The general information below on energy efficiency, thermal performance and LCA is drawn from academic literature and research on green facades in the built environment, as cited and is then tailored to Leafy's context, rather than being direct feedback from stakeholder interviews. The stakeholders mentioned the points of discussion here.

1. **Energy Efficiency and Thermal Performance**: Green façade panels can significantly improve the thermal performance of buildings, reducing the need for heating and cooling. For example, the use of stone cladding systems has been shown to reduce cooling loads by up to 4% compared to aluminum composite panels (Dabous et al., 2022). Additionally, the use of bio-based materials, such as cork, has been shown to improve thermal insulation and reduce energy consumption (Malanho et al., 2021). In the context of Leafy, their bamboo-based façade panels are designed to enhance insulation in dense urban settings, directly contributing to improved thermal performance and energy efficiency of buildings. Leafy's materials, such as bamboo, are valued for their thermal regulation and low environmental impact. The design characteristics for sustainability in façade panels include thermal performance and energy efficiency, aiming to reduce operational energy use through high insulation and minimal thermal bridging.

2. **Life Cycle Assessment (LCA)**: The environmental impact of green façade panels should be assessed using LCA methodologies. It considers the entire life cycle of a material, from raw material extraction to disposal and can provide valuable insights into the environmental benefits and drawbacks of green façade systems. For instance, the use of fiber-reinforced concrete has been shown to reduce the carbon footprint of concrete structures by up to 94% (Manso-Morato et al., 2024). For Leafy, this assessment helps determine the overall environmental footprint and guides material selection. Leafy's product development aims to reduce carbon emissions and capitalize on the carbon sequestration capacity of bio-based materials, such as bamboo. The sustainability goals for Leafy's panels include minimizing $CO_2$ emissions from material extraction to disposal, prioritizing low-impact, bio-based, or recycled materials and assessing their Global Warming Potential (GWP). A supplier to Leafy explicitly stated that they are "in the process of making a new LCA that will cover all facets again," demonstrating Leafy's commitment to evaluating their environmental impact rigorously. The SSbD framework's Step 4, "Environmental Sustainability Assessment," directly applies LCA to evaluate impacts across 16 categories, grouped under toxicity, climate change, pollution and resource use. In the quantitative assessment, bamboo fibers demonstrated excellent environmental performance with net negative or near-zero GWP due to biogenic carbon uptake, making them highly suitable for sustainable façade systems.

3. **Material Sustainability**: The sustainability of materials used in green façade panels is a critical factor in determining their environmental impact. The use of recycled and bio-based materials, such as recycled polymers and natural fibers, can significantly reduce the environmental footprint of green façade systems (Nwokediegwu et al., 2024) (Tazmeen & Mir, 2024). Additionally, the use of agricultural waste to produce bio-bricks has been shown to improve the thermal properties of building materials while reducing greenhouse gas emissions (El-Hady & Mohamed, 2023). For Leafy, material sustainability is central to their product design and vision. Leafy's façade panels are

bamboo-based, designed to enhance biodiversity, air quality and insulation in urban settings and they emphasize renewable and recyclable materials. Their substrate container and front plate primarily use an NPSP bamboo fiber composite, with an estimated 70% biobased content. The growing medium itself is soil-free and incorporates multiple biogenic fractions, including coconut fibers, crushed coconut chips, biochar, compost and wood fibers.

### 4.3.7 Overall SSbD Assessment and Stakeholder Opinions

*Table 20* presents the decision matrix, which visually summarizes the SSbD evaluation of all Leafy materials across all four steps. This chart highlights which materials consistently perform well (e.g., Bio-Based Resin, Jute Cloth, Bamboo Fibre) and which fall short (e.g., Epoxy Resin, LDPE, PP) across the different sustainability and safety dimensions.

The MCDA approach is used to aggregate scores from Steps 1 through 3 into a single Hazard and Safety Level and subsequently combine this with the environmental performance score from Step 4. To avoid compensating for poor performance in one area with high scores in another, a minimum threshold logic is applied. Specifically, achieving SSbD Level 2 would require a minimum of Level 1 in each of Steps 1–3, while reaching SSbD Level 3 would require a minimum of Level 2 across all three safety-related steps. A stricter, non-compensatory approach could also be applied, where the lowest level obtained across Steps 1–3 determines the overall safety level. This aligns with the foundational principle of the SSbD framework: materials or chemicals failing to meet minimum safety criteria at any stage should not be classified as safe and sustainable by design (Caldeira et al., 2022b).

*Table 20: Overall SSbD scoring Matrix*

| Material | Step 1: Hazard | Step 2: OSH | Step 3: Use Phase | Step 4: LCA |
|---|---|---|---|---|
| **Epoxy Resin** | 0 | 1 | 0 | 1 |
| **Bio-Based Resin** | 2 | 2 | 2 | 3 |
| **Bamboo Fibre** | 2 | 2 | 3 | 2 |
| **LDPE** | 1 | 2 | 3 | 2 |
| **PP** | 1 | 3 | 3 | 1 |
| **EPDM** | 1 | 3 | 3 | 1 |
| **SS** | 2 | 3 | 3 | 2 |
| **Tricoya** | 2 | 3 | 2 | 3 |
| **Jute Cloth** | 2 | 2 | 2 | 1 |

Finally, the integration of the hazard and safety level (derived from Steps 1–3) with the Environmental Footprint (EF) score from Step 4 can be performed using a straightforward two-dimensional aggregation approach as seen in *Table 21*. This method assumes that both dimensions follow a uniform four-level scale and prioritizes safety in the final assessment. In this structure, a material that achieves a higher score in safety and a slightly lower score in environmental performance is considered preferable to one with the reverse profile.

*Table 21: Two-way aggregation for final scoring*

<table>
<tr><td></td><td></td><td colspan="4">Environmental Rating</td></tr>
<tr><td></td><td></td><td>0</td><td>1</td><td>2</td><td>3</td></tr>
<tr><td rowspan="4">Safety Rating</td><td>3</td><td>L1</td><td>L2</td><td>L3</td><td>L3</td></tr>
<tr><td>2</td><td>L1</td><td>L2</td><td>L2</td><td>L2</td></tr>
<tr><td>1</td><td>L1</td><td>L1</td><td>L1</td><td>L1</td></tr>
<tr><td>0</td><td>L0</td><td>L0</td><td>L0</td><td>L0</td></tr>
</table>

*Table 22: Overall SSbD Assessment*

| Material | Hazard | Processing | Use Phase | SR | Toxicity | Climate Change | Pollution | Resources | ER | SSbD Level |
|---|---|---|---|---|---|---|---|---|---|---|
| **Epoxy Resin** | 0 | 1 | 0 | 0.3 | 1 | 1 | 1 | 0 | 0.75 | **0** |
| **Bio-Based Resin** | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | **2** |
| **Bamboo Fibre** | 2 | 2 | 3 | 2.3 | 3 | 3 | 3 | 3 | 3 | **2** |
| **LDPE** | 1 | 2 | 3 | 2 | 2 | 2 | 2 | 1 | 1.75 | **2** |
| **PP** | 1 | 3 | 3 | 2.3 | 2 | 2 | 2 | 1 | 1.75 | **2** |
| **EPDM** | 1 | 3 | 3 | 2.3 | 2 | 1 | 2 | 1 | 1.5 | **2** |
| **SS** | 2 | 3 | 3 | 2.7 | 2 | 1 | 1 | 0 | 1 | **2** |
| **Tricoya** | 2 | 3 | 2 | 2.3 | 2 | 2 | 2 | 2 | 2 | **2** |
| **Jute Cloth** | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | **2** |

Note 1: SR= Safety Rating = Average of Hazard, Processing and Use Phase

Note 2: ER= Enviro Rating = Average of Toxicity, Climate Change, Pollution, Resources

Note 3: 1.5 is rounded off to 1, others to the nearest whole number for final scoring

The final SSbD assessment reveals a nuanced but actionable material selection strategy for Leafy's façade system. Epoxy resin scores the lowest overall, achieving only Level 0, due to its high application-phase risks and poor environmental performance, as reflected in its low Environmental Footprint (EF) score. Its use should be phased out. In contrast, bio-based resin, bamboo fibre, jute cloth and SS consistently perform well across safety and environmental dimensions, achieving a robust SSbD Level 2, making them strong candidates for visible and exposed façade applications. Thermoplastics such as LDPE, PP and EPDM also reached Level 2, primarily due to low worker exposure risks and stable use-phase properties; however, their environmental burdens, particularly in resource depletion and end-of-life impact, suggest they should be confined to internal or easily replaceable elements. Tricoya, while acceptable at Level 2, shows moderate environmental and health trade-offs, making it best suited for areas with limited human contact or external exposure. Notably, no material achieved SSbD Level 3, indicating that even promising alternatives fall short of the stringent criteria and reinforcing the importance of continuous improvement in both material innovation and data quality. Overall, this step enables Leafy to adopt a hybrid material strategy that prioritizes bio-based and durable materials for high-visibility elements while transparently managing the risks of conventional options through controlled application and robust design guidelines.

## Stakeholder Perspectives on SSbD Application

Stakeholders across the interviews provided straightforward, actionable suggestions to improve the SSbD framework for construction and biobased panels. A key recommendation was to adopt a system-level perspective, evaluating the safety and sustainability of the whole façade assembly rather than just individual materials, particularly important for risks like fire, where the panel, air gap and vegetation interact. Also, the steps in the framework should be flexible enough to accommodate their type of product. For example, LCA should be the first step, then hazard assessment. Another central improvement point is the emphasis on maintenance and end-of-life planning. Stakeholders stressed that durable, low-maintenance design and clear end-of-life strategies (e.g., reuse, recyclability) must be explicitly addressed in SSbD to ensure long-term safety and sustainability.

The need to bridge sustainability and market viability was also highlighted. Stakeholders noted that sustainability alone is not enough; designs must also be both cost-effective and high-performing. SSbD could be improved by requiring socio-economic analysis and encouraging value-driven design features (e.g., ease of installation, thermal performance). A fourth suggestion is to embed testing and transparency as core principles, requiring third-party validation (such as EPDs and fire tests) to substantiate claims and foster trust. Moreover, stakeholders advocated for early integration of SSbD thinking, making it part of the design process from the outset and building awareness across teams. Finally, in the context of biobased panels, the interviews revealed a systemic issue with outdated certification pathways. SSbD could promote faster approval processes and encourage collaboration across the sector, including the standardization of test methods and the sharing of LCA data. Overall, while no stakeholder rejected SSbD, they emphasized the need to make it more holistic, practical and attuned to the realities of construction product development.

Stakeholders affirmed the relevance of the framework, even if not all were familiar with it by name. While some intuitively applied its principles, others appreciated its structured approach once introduced. SSbD proved to be a unifying tool that allowed professionals from different roles: suppliers, architects, founders and academics to connect their domain-specific concerns (e.g., safety, sustainability, usability, business case) under a common framework. Stakeholders did not criticize the framework itself, but instead offered insights to improve its application, particularly in construction contexts where system-level evaluation and economic feasibility are crucial. Overall, SSbD was seen as practical, adaptable and increasingly important in both regulatory and market contexts.

This structured presentation enables stakeholders with diverse interests, ranging from regulatory compliance to market acceptance, to draw comprehensive and interconnected conclusions by reviewing how quantitative assessments address the qualitative concerns raised during stakeholder engagement. The framework thus serves as a decision-support and validation model, bridging the gap between abstract SSbD principles and practical product development in sustainable construction.

## 4.4 Conceptual Framework for SSbD Assessment

The framework developed in *Figure 14* visually maps the operationalization of the SSbD framework in the context of Leafy's bamboo-based façade panels. It aligns with the core research question: "*How can the Safe and Sustainable by Design (SSbD) framework be applied to arrive at a responsible green facade panel design?"* and integrates all key sub-questions through a structured, stepwise evaluation approach. It provides a structured lens to evaluate safety, sustainability and responsible innovation in façade design, grounded in both European policy priorities and practical implementation challenges observed in startups.

The framework begins by identifying the design characteristics that define safety and sustainability in façade panels, addressing sub-question 1. Also, they serve as functional requirements that need to be considered by Leafy while designing their panels in alignment with EU regulations. This forms the foundation for assessing how well such products meet the SSbD criteria.

This sequential process reflects the SSbD lifecycle approach and links directly to Sub-question 2, which explores the integration of quantitative (e.g., LCA) and qualitative tools (e.g., expert interviews) across these steps. A parallel pathway in the framework connects the SSbD evaluation to the real-world application of Leafy's façade system, helping identify practical limitations of the framework in construction contexts (sub-question 3). This includes issues like a lack of harmonized testing methods, unclear compliance routes and gaps in standardization. Informed by these findings, the final stage of the framework provides targeted recommendations for SMEs and startups, such as Leafy. These recommendations are grounded in both empirical findings and stakeholder input, supporting the development of feasible and responsible biobased façade systems.

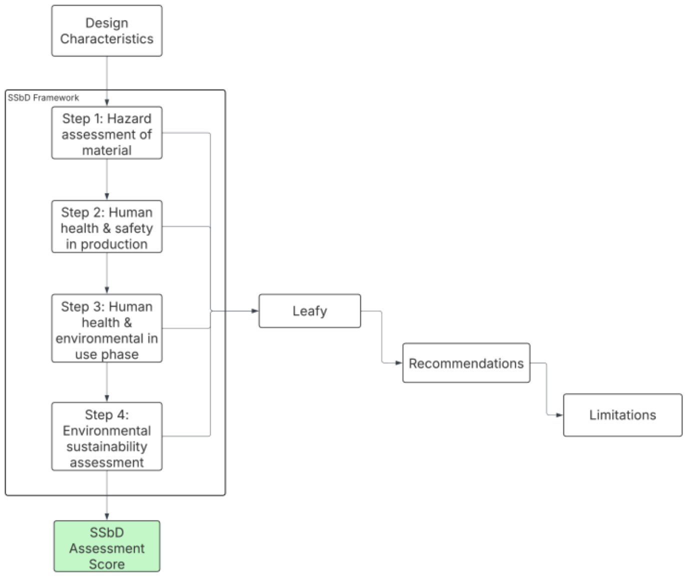


*Figure 14: Conceptual Framework for SSbD Assessment on Leafy*

## 4.5 Step 5: Socio-Economic Assessment

For Leafy, integrating the optional socio-economic assessment within the SSbD framework can enhance the robustness and market readiness of its façade panels. Here's how Leafy can apply the suggested approaches:

1. **Social Assessment:** Reference Scale Method: Leafy can use the Reference Scale method to assess social impacts across the product life cycle, covering worker safety, fair salary, working hours, equal opportunity, local employment, community engagement, product safety and responsible communication. These are rated on a scale of 1-4 and the maximum score is 32. This helps identify ethical risks in the supply chain and installation process, aligning with stakeholder expectations for socially responsible innovation.

2. **Critical Raw Materials (CRMs) Screening:** By screening life cycle inventories, Leafy can flag the presence of Critical Raw Materials (CRMs), identifying supply chain and geopolitical risks early. This supports more resilient material choices and aligns with EU priorities for reducing CRM dependency.

3. **Economic Assessment LCA Monetisation:** Leafy can apply monetisation factors to LCA results to quantify environmental impacts in economic terms (e.g., cost of $CO_2$ emissions). The dimensions are lifespan, resource efficiency, carbon cost saving, health cost saving, circular economy potential, recyclability, local supply chain and market differentiation. The scale is similar to social assessment. This enables lifecycle-based cost-benefit analysis, strengthening the business case for sustainable materials and informing investment decisions.

4. **Alignment with Corporate Strategies:** Integrating these assessments into broader ESG and sustainability goals ensures consistency and transparency. It positions Leafy as a responsible innovator, aligning product development with societal and regulatory expectations.

# 5 Discussion

## 5.1 Interpretation of Findings

The results from the SSbD evaluation across all four steps provide a comprehensive view of the safety and sustainability performance of the materials used in Leafy's bio-based façade panel system. The evaluation reveals a clear distinction between recyclable materials (e.g., bamboo fibre, bio-based resin, jute cloth, SS) and conventional synthetic materials (e.g., epoxy resin, LDPE, PP, EPDM) in terms of hazard profiles and environmental impacts.

In Step 1 (Hazard Assessment), none of the materials achieved Level 3, indicating that the high threshold set by SSbD for a material to be considered free of concern was not met. However, materials like bio-based resin, SS and jute cloth were close to meeting this standard, with only minor concerns such as inhalable dust or incomplete toxicity datasets limiting their scores. This outcome reflects both the conservative nature of the SSbD framework and the challenges in data availability for emerging materials. From the process perspective, the toolbox and supporting documentation provided clear criteria for assessing hazard classes; however, aligning them with façade-specific concerns (e.g., weathering emissions, degradation products) required additional interpretation, indicating a potential gap when applying the framework directly to building materials.

Step 2 (Human Health and Safety in Production) demonstrated the strongest overall performance, with most materials achieving a Level 3 rating. This highlights the maturity of industrial safety measures such as PPE, ventilation and controlled processing environments, especially for SS and thermoplastics. Even epoxy resin scored Level 1 due to established safety protocols, despite its known chemical hazards. The structured approach of the SSbD toolbox effectively guided the evaluation in this step and the criteria were generally aligned with the realities of production environments in construction material manufacturing.

In Step 3 (Safety in Use Phase), the spread in scores widened. SS, EPDM, LDPE and PP showed excellent performance (Level 3), while bamboo fibre, jute cloth and bio-based resin achieved Level 2 due to moderate concerns such as dust or wear-off during handling. Epoxy resin was the only material to score Level 0, validating concerns about its volatility, user exposure risks and emissions during application. The SSbD step-by-step process was logical and clear here; however, some limitations were noted regarding the systematic inclusion of durability and lifecycle safety, which are essential for façade systems where materials are exposed to weathering and mechanical stresses over decades.

In Step 4, biobased materials such as bamboo fibers and jute cloth scored best in the comparative LCA (Level 4), driven by their carbon uptake during growth and renewability. These materials exhibit negligible toxicity, low pollution and minimal resource use, making them highly suitable for sustainable façade systems. In contrast, synthetic materials like epoxy, EPDM, LDPE and PP should be minimized due to their reliance on fossil feedstocks, which results in significant greenhouse gas emissions and resource depletion. Epoxy involves toxic precursors during its production and curing processes, adding to its environmental and health burdens. Although SS offers high durability, it has a very high embodied energy footprint throughout its lifecycle, making it less preferable where lower-impact alternatives exist. In terms of critical categories, climate change (carbon balance) is the key factor for natural fibers, often showing positive or neutral impacts due to biogenic carbon storage. For plastics and rubbers, resource use and climate impacts are most critical due to fossil origin and emissions during production. For metals, resource depletion and pollution (especially acidification) dominate, underscoring the importance of considering these categories when selecting materials for SSbD-aligned façade designs.

Finally, the aggregated SSbD level showed that none of the materials reached Level 3, but many achieved Level 2 and epoxy failed the assessment. This underscores the value of a mixed-material strategy for Leafy: utilizing bio-based and recyclable materials in visible, exposed, or high-impact areas, while limiting the use of high-risk materials, such as epoxy resin, to structural or internal elements with strict controls.

The overall stepwise process of SSbD is logically structured to follow the progression of product development, from early-stage ideation to commercial deployment. This stage-gate approach allows for critical decisions to be made at each "Gate" to assess if the innovation meets predefined safety, sustainability and technical criteria before advancing. The framework's core principle, that a product cannot be deemed safe and sustainable if it poses a critical hazard or exposure risk, regardless of its strengths in other areas, is enforced by rules such as the minimum threshold logic. This ensures a precautionary approach where safety is non-negotiable.

For bio-based materials, the sequence of steps can be adjusted, for example, with LCA (Step 4) preceding hazard assessment (Step 1). This suggests that, while the framework is generally sound, its flexibility for different product types and innovation processes may require further refinement. The "fail-fast" or agile approach often followed by startups can complicate the rigid stage-gate process of SSbD. While the framework allows for reiteration, this iterative nature for startups might require more seamless integration than a strict linear progression.

### 5.1.2 Future Evolution of Trade-offs and Shifting Priorities

Future developments in sustainable façade systems will be strongly influenced by several converging trends. Policy and regulatory pressure will intensify, with frameworks like the European Green Deal and SSbD embedding sustainability as a core requirement. This will lead to stricter mandates around embodied carbon, material circularity and full lifecycle performance, as seen in recent updates to the CPR. At the same time, technological improvements in biobased materials, such as more durable bio-resins and treated natural fibers, will help overcome current limitations related to fire safety, durability and structural integrity. The need for long-term environmental and performance data under real-world conditions will remain essential to gaining stakeholder trust, with digital twins and AI-based models offering potential solutions for filling existing data gaps.

Market dynamics are also evolving, with increasing demand for green buildings, investor-driven ESG reporting and greater consumer awareness positioning sustainability as a competitive advantage. Financial mechanisms such as carbon pricing, subsidies and tax incentives could further tip the balance, making sustainable materials more economically attractive over their lifecycle. Meanwhile, the development of harmonized SSbD standards and PEFCR is expected to reduce regulatory uncertainty and streamline approvals for innovative materials. Importantly, the focus is shifting from evaluating individual materials to assessing the performance and resilience of whole façade systems. This reflects the growing need to address complex risks such as fire spread and extreme weather impacts. In this context, durability and low maintenance are critical to achieving long-term sustainability. The SSbD framework's “minimum threshold rule” reinforces this by ensuring that weaknesses in one area cannot be offset by strengths in another, supporting a more balanced and robust approach to sustainable innovation.

### 5.1.3 Prioritization Among Trade-offs in the Future

The future of façade design, guided by the SSbD framework, will be shaped by a clear hierarchy of priorities. Safety will remain the non-negotiable foundation, materials must meet strict thresholds for fire resistance, structural integrity and non-toxicity, regardless of their sustainability credentials. Performance and durability are essential enablers, with stakeholders demanding long-term functionality and manageable maintenance. Biobased materials must match or exceed conventional standards to gain market trust. Once safety and performance are secured, environmental sustainability, including low embodied carbon, circularity and ecological impact becomes the core objective. The SSbD framework supports this shift, encouraging lifecycle thinking and system-level innovation. Finally, economic viability and regulatory alignment act as enabling conditions. The definition of cost-effectiveness will expand to include lifecycle costs and carbon pricing, while evolving regulations and harmonized standards will help remove adoption barriers. In this trajectory, initial trade-offs will give way to integrated solutions that deliver on safety, performance and sustainability together, supported by economic and regulatory structures that reward responsible innovation.

### 5.1.4 Defining 'Right Innovation' through SSbD for Façade Design

For Leafy, the "right innovation" is a façade panel design that not only meets stringent safety and sustainability standards (SSbD principles) but also effectively addresses market needs, stakeholder concerns and long-term societal value in the built environment. This involves several key dimensions:

1. **Integrating Safety and Sustainability:** The innovation must genuinely aim for low hazard profiles, safe production and application and strong environmental performance across its lifecycle. No material fully achieved Level 3 SSbD, emphasizing the framework's stringency and the need for continuous improvement.

2. **Addressing Market Viability and Stakeholder Needs:** Stakeholders prioritize safety and performance before sustainability, affirming that a "right" innovation must be cost-effective, high-performing, durable and easily maintainable to gain market acceptance.

3. **Navigating Trade-offs:** Achieving the "right" innovation often requires a hybrid material strategy, balancing ideal sustainability with practical performance, cost and safety requirements. For instance, conventional materials like epoxy resin might be used for structural, non-visible applications where safety cannot be compromised, despite environmental drawbacks.

4. **Continuous Improvement and Transparency:** SSbD is an ongoing process that supports iterative refinement and transparent decision-making regarding material choices and their associated risks and benefits throughout the product's development and lifecycle.

### 5.1.5 SSbD Standards vs. CE Marking for Building Materials

SSbD and CE marking are both relevant frameworks within the European construction materials landscape, particularly for innovative products such as biobased façade panels. While CE marking ensures compliance with established EU safety, health and environmental regulations, SSbD provides a more comprehensive, proactive approach that integrates sustainability and safety considerations from the earliest design stages. Table 23 below outlines their key overlaps and gaps.

*Table 23: Comparison of SSbD and CE Marking – Overlaps and Gaps*

| Dimension | SSbD | CE Marking | Overlap / Gap |
|---|---|---|---|
| Safety and Health | Integrates safety from earliest design stages, covering material, occupational and use-phase safety. | Confirms compliance with EU safety, health and environmental regulations. | **Overlap:** Both address safety, including EN 13501-1 fire safety for façade panels. |
| Environmental Compliance | Includes a dedicated “Environmental Sustainability” step using LCA across 16 impact categories (e.g., climate change, pollution). | Covers environmental requirements as part of EU directives. | **Overlap:** Both address environmental compliance, but SSbD applies a broader LCA approach. |
| EU Regulatory Context | Aligns with EU regulatory objectives for a low-carbon built environment. | Operates under EU regulations for market conformity. | **Overlap:** Both support broader EU sustainability goals. |
| Proactive vs. Reactive Design | Proactively prevents harm by embedding safety and sustainability in early design. | Primarily reactive, focusing on risk management and post-development compliance. | **Gap:** SSbD anticipates hazards; CE marking verifies after design completion. |
| Holistic Lifecycle Approach | Considers safety, functionality, circularity and sustainability from raw materials to end-of-life, avoiding burden-shifting. | Relies on fragmented technical protocols (e.g., EN 13501, EN ISO 14040/44). | **Gap:** SSbD integrates full lifecycle; CE marking focuses on specific compliance aspects. |
| Novel Materials and Data Gaps | Addresses data gaps for fire safety, durability and performance in biobased materials (e.g., Leafy’s bamboo panels). | Does not directly address novel material unfamiliarity or data gaps. | **Gap:** SSbD supports innovation readiness; CE marking follows established testing norms. |
| Stringent Criteria | High thresholds; few materials achieve Level 3 due to strict safety/data requirements. | Meets baseline compliance standards for market entry. | **Gap:** SSbD is more demanding than CE marking. |
| Socioeconomic Dimensions | Optional step includes Social LCA and Life Cycle Costing. | Does not cover socioeconomic impacts. | **Gap:** SSbD addresses broader impacts beyond technical compliance. |
| Integration with Innovation | Embedded in early R&D, enabling “fail-early-fail-cheap” strategies. | Applied post-development for market compliance. | **Gap:** SSbD shapes innovation; CE marking validates final products. |

While CE marking ensures that a product meets the minimum legal requirements for safety, health and environmental compliance in the EU, SSbD provides a forward-looking, integrated framework that guides product developers in embedding safety and sustainability throughout the entire lifecycle. For novel biobased construction materials, SSbD can address the unique challenges of data gaps, unfamiliarity and stricter performance expectations, often going beyond the baseline compliance assured by CE marking.

### 5.1.6 Comparative Toxicity of Epoxy Resin, Cyanide, PFAS and Furan in Building Materials

In building materials, epoxy resin is hazardous but ranks lowest in overall toxicity among the substances compared. Its main risks are skin sensitization, irritation and aquatic toxicity, without the extreme acute lethality of cyanide, the global persistence of PFAS, or the carcinogenic classification of certain furan monomers. Cyanide poses immediate life-threatening risks but is not used in building products and leaves no lasting environmental footprint if controlled. PFAS are chronic hazards, linked to cancer, endocrine disruption and persistent global pollution. Furan resins present notable worker health risks and suspected carcinogenicity but have low environmental persistence. Properly cured epoxy is inert for occupants, with hazards mainly to applicators and aquatic systems if mishandled. In construction, the hazard hierarchy places epoxy below cyanide, PFAS and furans, yet it still requires strict handling precautions. For more details, check *Appendix M*.

### 5.1.7 Balancing Stakeholder Values and Uncertainty in SSbD Hazard Scoring

The SSbD framework requires carefully balancing multiple stakeholder values (such as safety, cost, sustainability and durability) in material selection while also dealing with uncertainties in hazard data. The thesis case study demonstrates how these sometimes-competing priorities are weighed and how the scoring approach reflects uncertain information.

**Weighing Stakeholder Values:** Safety is a non-negotiable priority, covering fire resistance, structural integrity and avoidance of toxic substances. Sustainability (e.g., biobased, recyclable materials, low-impact LCA results) is important but secondary to safety and performance. Durability and ease of maintenance are critical for real-world adoption, with preference for materials lasting 15–30 years and supporting modular replacement. Cost and market viability influence decisions, with compromises accepted if safety and feasibility are maintained (e.g., using epoxy resin for structural performance). In the SSbD framework, stakeholder priorities are balanced through a multi-criteria, non-compensatory approach, ensuring safety, sustainability and other criteria are co-equal but with safety as the gatekeeper. Materials must meet minimum safety thresholds (Steps 1–3) before environmental performance (Step 4) can raise their rating; for a Level 3 overall score, at least Level 2 is required in all safety categories. The final scoring matrix favors higher safety over higher environmental scores, reflecting both stakeholder consensus and regulatory realities. Once safety is secured, the framework promotes sustainability improvements. There is a socio-economic step to formally integrate cost, supply chain maturity and market acceptance into decisions, bridging sustainability goals with practical viability.

**Managing Uncertainty in Hazard Scoring:** Data gaps are flagged as “MISS” and visualized to guide further testing. Incomplete hazard data prompts conservative, worst-case assumptions, which may lower scores but align with the precautionary principle, absence of evidence is not treated as evidence of safety. The framework applies qualitative and semi-quantitative methods (e.g., control banding, hazard classes) when precise toxicological data are lacking, refining these scores as new data emerge. Unresolved uncertainties cap achievable safety scores; in the case study, no material reached the highest safety level due to mild concerns or missing data. Even greener materials (e.g., bio-resins) were rated cautiously until hazards were fully verified.

SSbD ensures safety, sustainability, durability and cost are integrated into material decisions, with safety as a gatekeeper. Uncertainty is handled transparently and conservatively, incentivizing data generation. This approach maintains a high safety bar while accommodating innovation, guiding designs toward safe, sustainable and market-viable outcomes.

## 5.2 Practical Implications for Leafy

The SSbD assessment, conducted across four key steps, offers critical strategic insights for Leafy as it advances the development and commercialization of its bio-based façade systems. The results of the SSbD assessment suggest that Leafy's material strategy appears to be broadly aligned with SSbD principles. Materials such as bio-based resin, bamboo fibre, jute cloth and SS were observed to perform strongly across human health, safety and environmental dimensions during the evaluation. These findings reinforce Leafy's commitment to circular material use and provide evidence-based validation that can support product positioning in sustainability-conscious markets.

Conversely, the assessment also revealed areas of concern. Epoxy resin, although manageable under tightly controlled industrial conditions, scored significantly lower in both use-phase safety and environmental life cycle impact. Its volatility, toxicity and low durability make it unsuitable for applications involving direct user exposure or long-term environmental interaction. Based on the assessment, it is suggested that Leafy consider restricting epoxy resin use to non-visible, structural applications and explore alternative resin systems.

The assessment also emphasized the importance of a functional-material match strategy, recognizing that no single material achieved a Level 3 rating across all SSbD steps. For instance, thermoplastics like LDPE and polypropylene scored well in safety-related criteria but performed poorly in environmental categories due to their fossil origin and microplastic risk. These materials may still be suitable for secondary, non-visible components such as internal supports or irrigation tubing but should not be used as primary façade elements. This trade-off-driven material allocation strategy will allow Leafy to maintain high sustainability standards while addressing the practical requirements of performance and durability.

Operationally, the SSbD framework provides a structure for integrating safety and sustainability metrics into Leafy's design and procurement processes. The insights from Step 2, for example, can inform supplier audits and occupational risk assessments, while the results of Steps 3 and 4 can guide material selection in installation protocols and end-of-life planning. Embedding this evaluation system into Leafy's ongoing product development, risk documentation (RI&E) and compliance practices (e.g., V&G plans) can ensure continued alignment with evolving EU regulatory frameworks.

Ultimately, the results lay the groundwork for effective strategic communication and differentiation. Scoring Level 2 across most materials enables Leafy to credibly communicate its sustainability efforts to clients, certification bodies and investors. These outcomes can also support ESG reporting, green building certification (e.g., BREEAM, LEED) and future grant or funding proposals. Looking ahead, the assessment identifies specific areas for improvement, such as enhanced toxicological data for bio-resins, dust suppression strategies for natural fibres and further process optimization for Tricoya that could elevate several materials to SSbD Level 3. By acting on these findings, Leafy can continue to innovate while aligning its operations with the highest safety and sustainability standards.

### 5.2.1 SSbD Dashboard

The result of the evaluation can be expressed either as a class of SSbD (poor, good, very good) or with a numerical score derived from the combination of the individual scores in each aspect (subject to, e.g., weighting). To simplify this, Leafy can utilize a dashboard, as shown in *Table 24.* Linking this with *Figure 15*, where the stage-gate innovation process can prove to be a helpful checklist.

*Table 24: SSbD Dashboard*

| Dimension | Aspect | Level | Score |
|---|---|---|---|
| **Hazard Properties** | H1 | Yes/No | 0-3 |
| | H2 | | |
| | H3 | | |
| **Human Health & Safety aspects (production & processing phase)** | OSH1 | | |
| | OSH2 | | |
| | OSH3 | | |
| | OSH4 | | |
| **Human Health & Environmental aspects (Use phase)** | SD1 | | |
| | SD2 | | |
| **Environmental Sustainability** | E1 | | |
| | E2 | | |
| | E3 | | |
| | E4 | | |

## 5.3 Representativity of Leafy in the Biobased Construction Sector

Leafy, a startup producing bamboo-based façade panels, is a representative example of the opportunities and challenges faced by novel biobased materials in the built environment. Selected for its theoretical relevance and innovation-driven context, it enables practical exploration of the SSbD framework.

Leafy embodies current bio-architecture trends by integrating natural materials to enhance urban biodiversity, air quality and insulation, reflecting the sector’s shift toward transformative, sustainable design. However, it faces common adoption barriers for emerging biobased materials, including fire safety, durability and long-term performance concerns. Existing regulations and certifications offer partial guidance but remain fragmented, treating structural, environmental and health metrics in isolation.

Regulatory and standardization gaps further hinder adoption, with SSbD underdeveloped for façade systems and no materials meeting its stringent Level 3 criteria, often due to incomplete data. For startups like Leafy, resource constraints limit capacity for comprehensive SSbD assessments, underscoring the need for standardized implementation pathways.

Leafy’s hybrid material strategy, combining biobased and conventional components, illustrates the trade-offs between safety and sustainability. Its case highlights the need for holistic assessment frameworks integrating safety validation and environmental performance, advancing SSbD discourse and offering practical insights for scaling responsible innovation in the biobased construction sector.

## 5.4 Guidelines for Tailored Approach

### 5.4.1 SSbD Assessment within Stage-Gate innovation process

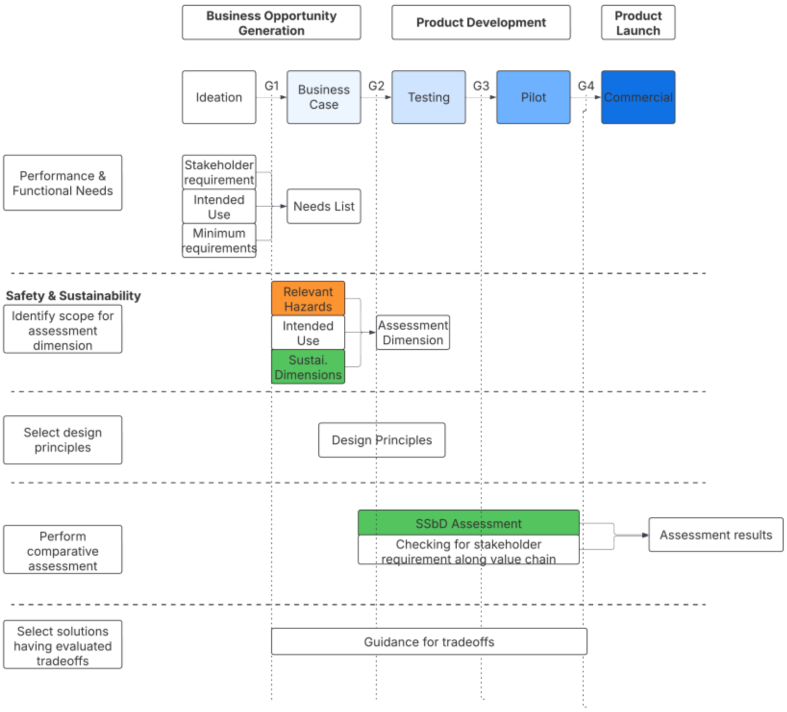


*Figure 15: SSbD Assessment within the innovation process*

1. **Define Performance & Functionality Needs:**
For Leafy, defining performance and functionality needs involves a comprehensive process that integrates safety, sustainability and intended use across the entire value chain. This requires engaging multiple stakeholders to identify both primary and secondary requirements, ensuring that no trade-offs inadvertently undermine the sustainability goals outlined by initiatives like the EU Green Deal. They will do this by defining core vision, protection and safety (non-negotiable) requirements, sustainability requirements and fulfilling stakeholder expectations.

2. **Define Assessment Dimensions:**
Assess safety dimensions for Leafy's panels based on human health (e.g., toxicity, sensitization, mutagenicity), environmental (e.g., PBT/vPvB, aquatic toxicity) and physical hazards (e.g., flammability, reactivity). Consider intended use (consumer vs. industrial) since it affects exposure and risk management needs. Assess sustainability using environmental (e.g., recycling, climate, biodiversity), social (e.g., worker and consumer health, community impact) and economic (e.g., profitability, resilience) criteria. Include corporate requirements as additional minimum thresholds.

3. **Design Principles**:
The design principles for Leafy focus on guiding innovation to deliver measurable improvements in safety and sustainability without causing significant harm elsewhere, ensuring all innovations meet minimum legal and regulatory requirements. These principles support iterative, continuous improvement and apply to startups as well. Emphasizing hazard and exposure reduction early in development enables a fail-fast approach and informed trade-off decisions in later stages. For Leafy, these principles translate into:

- SSbD1: Material efficiency: Modular, click-on/click-off design supports circularity and reduced waste.
- SSbD2: Avoid hazardous chemicals: Eliminate or minimize hazardous substances while maintaining performance.
- SSbD3: Energy efficiency: Use lightweight materials to reduce production and transport energy.
- SSbD4: Renewable sourcing: Prioritize bamboo and biobased substrates over fossil-based materials.
- SSbD5: Prevent hazardous emissions: Manage VOCs and emissions across the lifecycle.
- SSbD6: Reduce exposure: Minimize installer, user and environmental exposure to hazards.
- SSbD7: Design for end-of-life: Enable separation, reuse, recycling, or biodegradation of components.
- SSbD8: Whole lifecycle approach: Apply principles across the value chain, ensuring system-level safety and sustainability.

4. **Comparative Assessment:**
   Involves evaluating multiple materials against predefined safety, sustainability and performance requirements. The goal is to enable early, informed decision-making using a "fail-early-fail-cheap" approach, progressively narrowing down candidates as TRL increases. An individual assessment strategy should prioritize essential criteria (e.g., toxicological risks, climate impact, recyclability, resource use, life cycle cost), while optional “good-to-have” criteria may be added later. This process helps identify the most promising SSbD-aligned materials efficiently.

5. **Trade-offs:**
   Trade-offs are inherent in Leafy’s innovation process, requiring careful balance between safety, sustainability, performance and cost across the life cycle. Safety remains non-negotiable, especially for fire resistance and structural integrity, which sometimes necessitates the use of less sustainable materials, such as epoxy resin, in non-visible structural elements. While biobased materials align with sustainability goals, they may increase costs and maintenance needs, which can challenge their adoption in cost-sensitive markets. Leafy’s pursuit of modular, click-on/click-off designs support circularity but requires careful design to ensure long-term durability without compromising recyclability at the end of life. Regulatory compliance can also limit innovation, as building codes may favor conventional materials, delaying approval for sustainable alternatives. MCDA can help Leafy navigate these trade-offs, ensuring that critical safety and performance needs are met while advancing sustainability, thereby allowing for informed and transparent decision-making throughout product development.

### 5.4.2 Adapting SSbD for Startups: Simplified and Phased Approaches

To make SSbD more practical for small companies, experts propose a tiered, phased model aligned with a startup’s growth stage. Early in R&D, lightweight qualitative checks, such as SUNSHINE Tier 1 self-assessments, can flag hazardous materials, basic safety gaps and sustainability “red flags” without extensive data needed (Harmless Project, EU). This acts as an early warning system, enabling design pivots before costly commitments.

In mid-stages (product refinement, pilot production), semi-quantitative tools like LICARA NanoSCAN can provide simplified carbon, toxicity and cost assessments. Final stages (demo/market readiness) would use full SSbD methods, including detailed LCA and risk modeling, ideally with expert support.

The Leafy case study recommends a more flexible SSbD for SMEs, allowing for temporary data gaps, sector-specific checklists and recognition of improvements even without reaching absolute “Level 3” safety. An official phased compliance pathway could encourage adoption, enabling startups to begin with self-audits and scale to full compliance over time, maintaining SSbD’s core safety and sustainability values while fitting resource constraints.

### 5.4.3 Benefits of a Tailored SSbD Version for Startups

A tailored, phased SSbD approach can help startups integrate safety and sustainability from the outset without overwhelming resources. By encouraging early hazard identification and sustainable design choices, SSbD can drive innovation, reveal safer material alternatives and turn sustainability constraints into opportunities (Cefic, 2023). The Leafy case study showed that SSbD assessments, though demanding, helped identify critical risks, guide material selection and support responsible innovation.

From a compliance perspective, early SSbD adoption positions startups ahead of tightening regulations, smooths certification processes and reduces the risk of costly redesigns or market delays (Harmless Project, EU). It can act as a compliance roadmap, flagging regulatory red flags early (e.g., potentially restricted substances) and aligning with eco-label or safety certification requirements.

The approach also mitigates business risk, as design flaws are far cheaper to address at the concept stage. As noted in the HARMLESS SME workshop, SSbD at ideation can prevent investment in unsafe or unsustainable products, saving significant costs later. Additionally, visible commitment to safety and sustainability enhances brand credibility with investors, customers and partners.

In essence, a startup-friendly SSbD bridges the gap between ambition and capacity by providing the right-sized tools and stepwise milestones. This enables SMEs to grow toward full compliance while delivering safer, market-ready innovations that align with EU sustainability goals, a win for both business and society.

## 5.5 Integration of Qualitative & Quantitative Tools

Integrating qualitative and quantitative tools within the SSbD framework involves a multifaceted approach, combining an understanding of stakeholder needs and material properties with a rigorous assessment of safety and sustainability across the product lifecycle. This integration was achieved by using qualitative data to inform the design phase, develop safety and sustainable characteristics and identify key factors, while quantitative data provided the numerical evidence for assessing and optimizing performance across the materials.

### 5.5.1 Informing and Validating the Framework

- **Qualitative data informing quantitative assessment:** Qualitative research, particularly through semi-structured interviews with key stakeholders (architects, façade experts, suppliers, Leafy's founder, academic researchers), was crucial in informing the design phase and identifying key safety and sustainability characteristics. For example, stakeholder interviews helped reveal that fire safety, low environmental impact and high durability were top priorities. These qualitative insights then guided the focus of the quantitative assessments within the SSbD framework.

- **Quantitative data validating qualitative insights:** The quantitative data, derived from the SSbD framework (Hazard Assessment, Occupational Health and Safety, Use-Phase Impact, Environmental Sustainability), provided numerical evidence to assess and optimize performance across materials. For instance, stakeholder concerns about fire safety were validated by the quantitative scoring of materials like epoxy resin at Level 0 in Step 1 (Hazard Assessment) and Step 3 (Use Phase), due to its flammability, high VOC emissions and toxic degradation products. This quantitative evidence reinforced the qualitative concerns expressed by stakeholders regarding this material.

- **Triangulation for validity:** The integration was further strengthened by triangulating findings from multiple data sources: the quantitative framework scoring, qualitative insights from interviews and secondary literature. This cross-validation helped confirm recurring patterns and identify inconsistencies or gaps between the theoretical SSbD framework and its practical application.

### 5.5.2 Joint Displays for Communicating Findings

While this thesis does not present a single, explicit "joint display" table merging qualitative and quantitative data, it intentionally structures separate qualitative and quantitative presentations to allow stakeholders to interpret them in conjunction, ensuring a comprehensive understanding of the assessment outcomes.

Joint displays in mixed-methods research serve to visually and analytically connect stakeholder perspectives (qualitative) with measurable performance data (quantitative), facilitating precise and actionable insights for informed decision-making. For Leafy, this approach ensures that stakeholder concerns (e.g., fire safety, cost, regulatory compliance) are not evaluated in isolation but are systematically connected to measurable SSbD performance, bridging the gap between "what matters" and "how it performs."

### How Qualitative and Quantitative Results Align

Stakeholder Priorities (Qualitative): The Stakeholder Overview (Table 7) and Frequency of Themes (Figure 6) summarize key concerns, including fire safety, market risk, cost, durability, structural safety and regulatory compliance, which are critical drivers for product acceptance and market viability.

Material Performance (Quantitative): The Overall SSbD Scoring Matrix (Table 23) and Overall SSbD Assessment (Table 25) systematically quantify material performance across the four SSbD steps, offering clear comparative insights on hazard profiles, production safety, use-phase safety and environmental sustainability for each material.

When stakeholders emphasize durability and maintenance, these concerns are linked with Step 3 durability scores in Table 20, which show that SS, LDPE, PP and EPDM scored Level 3 (high durability). In contrast, bamboo and jute scored Level 2. This quantitative evidence supports stakeholder perceptions that while biobased materials are environmentally preferable, they may require additional design considerations or warranties to address long-term performance concerns.

For regulatory compliance, identified as a critical stakeholder priority, the quantitative SSbD assessment incorporates compliance with REACH (hazardous substance restrictions in Step 1) and Euroclass fire ratings (addressed in Step 1 and Table 14). The qualitative findings further contextualize these regulatory needs, emphasizing that while compliance with existing standards is essential for market entry, regulatory pathways for novel biobased materials remain uncertain, requiring proactive testing and certification strategies.

This structured presentation enables stakeholders with diverse interests, whether focused on regulatory readiness, technical performance, or market acceptance, to draw comprehensive and interconnected conclusions by reviewing how quantitative assessments address the qualitative concerns raised during stakeholder engagement. While not a single merged table, the framework enables practical, decision-focused integration of data, aligning stakeholder needs with Leafy's SSbD-aligned material selection and design process. For future work, developing a visual "traffic light" or matrix-style joint display could further enhance clarity in stakeholder workshops or investor communications.

### 5.5.3 Scenario Analysis

This thesis employs scenario analysis to examine how design choices influence safety and sustainability under high-risk, real-world conditions, integrating quantitative data to evaluate material performance and qualitative data to contextualize practical challenges and trade-offs.

### Defining Scenarios through Extreme Failure Risk Events

Key extreme failure risk events *(Table 16, Table 17, Figure 9)* identified include heavy rain, heatwaves, strong winds, panel detachment, fire spread and impact events. These serve as structured scenarios to evaluate the façade system's robustness and compliance with safety and sustainability goals under stress conditions.

Quantitative data gathered from stakeholder interviews (e.g., wind load capacity of ±2000 Pa, fire resistance rating, UV resistance ≥10 years, 95% RH tolerance) are applied within SSbD steps to measure whether materials and design configurations can withstand these scenarios. For example, SS and EPDM demonstrated high resilience to wind and moisture, whereas bamboo-based panels required additional treatment to maintain their fire safety ratings under extreme conditions.

Stakeholder feedback provides critical insights by highlighting practical challenges and trade-offs in these scenarios (Tables 4 and 8, Appendix E6). For example, while epoxy resin presents apparent environmental and health drawbacks, it may still be considered for specific high-risk zones due to its superior fire performance, illustrating a trade-off between fire safety and sustainability in critical scenarios. Similarly, stakeholders' concerns about the "unproven" nature of biobased materials under prolonged heat or moisture exposure add a qualitative layer of uncertainty, emphasizing the importance of prototypes, warranties and extended field testing to validate these systems in extreme conditions.

By combining quantitative performance measurements with qualitative stakeholder perspectives, the scenario analysis ensures that Leafy's design decisions are not only technically sound under stress conditions but also aligned with real-world concerns about durability, market risk and regulatory compliance. This structured, scenario-based approach supports Leafy's SSbD strategy by anticipating potential failures early, enabling risk-informed design improvements while maintaining transparency in trade-offs required for market readiness.

### Design Choice Scenarios through SSbD Assessment

The comprehensive four-step SSbD assessment for Leafy's materials provides a clear pathway for strategic material selection and design refinement. By categorizing materials into different SSbD levels (0-3), Leafy can make deliberate choices that prioritize safety and sustainability across the product's lifecycle.

1. **Prioritizing High-Performing Materials:** Bio-based resin, bamboo fibre, jute cloth and SS consistently performed well (SSbD Level 2+), showing low hazard profiles, manageable occupational risks, safe application and strong environmental performance. These findings align with EU goals and the literature advocating for bio-based and circular materials in construction, supporting Leafy in prioritizing these materials for visible and load-bearing components while enhancing biodiversity and reducing environmental impact.

2. **Restricting Problematic Materials:** Epoxy resin scored lowest due to high toxicity and poor environmental durability, while LDPE, PP and EPDM, despite use-phase safety, had lower environmental scores due to fossil origins. Literature confirms that bio-based does not always equate to benign, requiring a case-by-case assessment. Leafy should avoid epoxy in exposed areas, limit thermoplastics to secondary components and seek safer alternatives where feasible.

3. **Driving Continuous Improvement:** No material reached Level 3, reflecting the framework's high standards. Leafy should invest in further data collection (e.g., bio-resin toxicity, fibre dust suppression) and long-term performance monitoring to improve material scores. This supports SSbD as a continuous improvement tool and aligns with calls in the literature for sector-specific adaptation and data-driven refinement.

4. **Integrating SSbD into Innovation:** The SSbD assessment can be embedded into Leafy's stage-gate process, enabling "fail-early-fail-cheap" decisions and iterative design improvement. Developing an SSbD dashboard would facilitate tracking materials against safety and sustainability criteria at each TRL, aligning with literature on integrating SSbD within innovation processes for SMEs.

5. **Informing Policy and Contextual Adaptation:** Findings highlight the need for sector-specific SSbD thresholds and clearer compliance pathways for bio-based façades, supporting calls in the literature for contextual adaptation. Leafy can utilize its learnings to advocate for PEFCRs that reflect biogenic carbon and long-term performance, while promoting durability within SSbD hazard assessments for construction.

# 6. Conclusion

This thesis aims to investigate how the SSbD framework can be effectively applied to enable responsible green façade panel design, using Leafy's biobased façade panel as a case study. By integrating multi-criteria assessment tools, stakeholder perspectives and real-world implementation constraints, the research offers a comprehensive view of how SSbD can serve not just as a theoretical framework but as a practical decision-making aid in sustainable construction. The study's findings are organized around three core sub-questions, which together guide the response to the main research question.

**Sub-question 1: What are the design characteristics that define safety and sustainability in green façade panels?**

This question was addressed through an exploratory review of material choices, environmental indicators and safety parameters relevant to façade panels. Safety was interpreted through multiple lenses, including material hazards, occupational health risks and application-phase exposure, while sustainability was examined via life cycle indicators such as carbon emissions, resource depletion, recyclability and biodegradability. Materials like bio-based resin, bamboo fibre, SS and jute cloth consistently demonstrated favourable safety and environmental performance across Steps 1–4 of the SSbD assessment. Meanwhile, materials like epoxy resin and thermoplastics revealed trade-offs, scoring high on safety during manufacturing but low on environmental footprint or use-phase emissions. The study also found that *no single material achieved an SSbD Level 3*, underlining the stringency of the framework. Thus, the responsible design of green façade panels must embrace a hybrid material strategy that carefully balances trade-offs across dimensions of safety and sustainability.

**Sub-question 2: How can qualitative and quantitative tools be integrated within the SSbD framework to assess when biobased façade panels are safe and sustainable enough to be considered responsible?**

This research demonstrated that quantitative tools like Occupational Safety and Health (OSH) scoring can be meaningfully integrated with qualitative assessments such as stakeholder interviews, design guidelines and regulatory mapping to form a cohesive SSbD evaluation. The multi-step scoring system (Steps 1–4) and the final MCDA aggregation logic (including minimum score requirements to avoid compensatory effects) allowed the framework to evaluate safety and sustainability holistically. The research found that 'safe enough' in this context means meeting minimum thresholds across hazard, human exposure and environmental impact, reinforcing the non-compensatory, precautionary ethos of the SSbD framework. Additionally, stakeholder interviews with Leafy and material suppliers revealed that contextual factors, such as supply chain maturity or the distinction between indoor and outdoor use, shape what constitutes "responsible" in practice. This integration of tools helped to quantify abstract concepts like safety, while also ensuring that the results remain grounded in practical realities. Integrating Step 5 (Socioeconomic Assessment) would expand the concept of "safe and sustainable enough" to include broader societal and economic responsibility. Quantitatively, this would involve LCC to assess economic viability and S-LCA for social impacts. Qualitatively, it would draw on stakeholder insights regarding market acceptance, supply chain labor practices, wages, human rights and community impacts.

**Sub-question 3: What are the limitations in SSbD framework implementation, as identified through the case study with Leafy?**

Applying the SSbD framework to Leafy's biobased façade system uncovered several implementation challenges. Data gaps, particularly for emerging materials like bio-resins and natural fibres, limited hazard scoring and resulted in cautious assumptions that sometimes underrepresented material performance. Moreover, regulatory alignment issues (e.g., lack of facade-specific SSbD standards or ambiguous Arbo compliance paths for novel installations) revealed the need for greater sectoral calibration. Leafy's startup status also highlighted the resource-intensiveness of conducting full-scale SSbD evaluations, especially in terms of LCA, risk modelling and compliance documentation. The analysis suggested that the outcome of no materials achieving Level 3 was related to the stringency and rigidity of the current SSbD criteria, rather than indicating inherently poor design. These limitations highlight the need for a more adaptable, context-sensitive version of SSbD tailored to SMEs and the building sector, without compromising core safety and sustainability values. While this study demonstrated the effective integration of quantitative tools, such as OSH scoring, with qualitative assessments to deliver a cohesive SSbD evaluation, it primarily focused on the first four steps of the framework. The optional Step 5, which evaluates social and economic impacts using tools like Social LCA and LCC, can present significant challenges for Leafy. Unlike the earlier steps, Step 5 lacks clear, standardized guidelines and user-friendly tools, making practical application difficult. Leafy may face incomplete supplier data on labor practices and community impacts, fragmented lifecycle cost estimates and a lack of reference points for socio-economic improvements with novel biomaterials. Additionally, most available socioeconomic tools require expertise and resources beyond a startup's capacity, forcing reliance on assumptions and qualitative scoring that reduce assessment reliability. This underscores that while Step 5 is essential for a truly holistic SSbD evaluation, the absence of clear tools and guidelines makes it particularly challenging to operationalize in the early stages of sustainable innovation.

**Main Research Question: How can the Safe and Sustainable by Design (SSbD) framework be applied to arrive at a responsible green façade panel design?**

In answering the main question, this thesis concludes that the SSbD framework can be effectively operationalized for green façade panels through a tiered, multi-criteria assessment that combines hazard analysis, life cycle thinking and practical risk mitigation. A responsible design does not imply perfection across all metrics but rather requires minimum thresholds in both safety and sustainability dimensions, guided by the principles of precaution and transparency. For startups like Leafy, the SSbD process supports responsible innovation by enabling structured trade-offs, identifying critical risks and informing design and procurement strategies. Nevertheless, to fully realize its potential, the SSbD framework must evolve to accommodate biobased materials, digital risk tools and sector-specific adaptations that align with the dynamic needs of the construction industry.

# 7. Recommendations

## 7.1 Recommendation for Stakeholders and Organizations

These recommendations provide actionable insights for start-ups like Leafy, designers and policymakers involved in the development and implementation of biobased façade systems, guiding them toward more responsible and sustainable practices.

1. **Adopt a Hybrid Material Strategy**: Prioritise bio-based resin, bamboo fibre, jute cloth and stainless steel for exposed façade elements; restrict or phase out epoxy resin; limit thermoplastics (LDPE, PP, EPDM) to internal or replaceable parts.

2. **Integrate SSbD into Operational Processes**: Embed the SSbD framework into ongoing product development, risk documentation (e.g., RI&E) and compliance practices. Insights from SSbD steps can inform supplier audits, occupational risk assessments, material selection in installation protocols and end-of-life planning. This structured approach helps ensure continuous alignment with evolving EU regulatory frameworks.

3. **Leverage SSbD for Strategic Communication and Market Differentiation**: The SSbD assessment results, indicating a robust Level 2 for many materials, enable Leafy to credibly communicate its sustainability efforts to clients, certification bodies and investors. These outcomes can also support ESG reporting, green building certifications (e.g., BREEAM, LEED) and future funding proposals.

4. **Prioritize System-Level Evaluation**: Stakeholders emphasized the need to evaluate the safety and sustainability of the whole façade assembly, rather than just individual materials. This is particularly crucial for complex risks like fire, where interactions between the panel, air gap and vegetation are critical.

5. **Emphasize Maintenance and End-of-Life Planning**: Durable, low-maintenance design and clear end-of-life strategies (e.g., reuse, recyclability) must be explicitly addressed within SSbD to ensure long-term safety and sustainability.

6. **Bridge Sustainability with Market Viability**: For sustainability initiatives to succeed, designs must also be cost-effective and high-performing. SSbD should integrate socio-economic analysis and encourage value-driven design features, such as ease of installation and enhanced thermal performance, to gain market acceptance.

7. **Foster Transparency and External Validation**: Require third-party validation, such as EPD’s and fire tests, to substantiate product claims and build trust among stakeholders.

8. **Integrate SSbD Early in Design**: Apply SSbD principles from initial design stages to enable early risk mitigation.

9. **Advocate for Streamlined Regulatory Pathways**: Policymakers and industry players should collaborate to promote faster approval processes for novel biobased materials, including the standardization of test methods and the sharing of LCA data.

10. **Adapt SSbD for Startups**: Implement a tiered, phased SSbD model that aligns with a startup's growth stage. Early-stage R&D can use lightweight qualitative checks (e.g., SUNSHINE Tier 1), while later stages can employ more detailed quantitative tools like LCA and risk modeling, ideally with expert support. This flexibility helps integrate SSbD without overwhelming limited resources.

## 7.2 Recommendations for Future Research

These recommendations outline key areas for academic and industry research to further develop and refine the SSbD framework, particularly for its application in the built environment.

1. **Sector-Specific Calibration of SSbD Thresholds**: Future research should focus on refining the SSbD scoring systems and decision thresholds to better reflect the complexities of building material systems. Current criteria are often generic and their alignment with façade-specific concerns (e.g., weathering emissions, degradation products) requires additional interpretation.

2. **Collection of Longitudinal Environmental and Performance Data**: There is a critical need to collect real-life, long-term environmental and performance data for biobased façade panels. Monitoring emissions, material degradation and exposure pathways over extended periods would provide empirical evidence to validate or refine assumptions used in LCA and hazard scoring.

3. **Enhanced Socio-Economic Assessment in SSbD (Step 5)**: Research is needed to develop clearer, standardized guidelines and user-friendly tools for the optional Step 5. This step, which evaluates social and economic impacts using tools like Social LCA and Life Cycle Costing (LCC), currently lacks the clarity and resources needed for practical application by startups. This would help to fully integrate broader societal and economic responsibility into the SSbD framework.

4. **Improved Exposure Modeling at Application Phase**: Develop more refined models for user and environmental exposure, especially for outdoor materials subject to variable weather, UV radiation and microbial degradation. This includes quantifying specific on-site hazards like fine particulate dust generated during the cutting and drilling of façade panels and substructures during installation.

5. **Comparative SSbD Case Studies Across Building Typologies**: Conducting SSbD case studies across different building types (residential, commercial, industrial) could reveal how material selection and SSbD scoring vary by context, leading to the development of more adaptable SSbD guidelines.

6. **Integration of Digital Twins and AI-Based Predictive Models**: Explore how digital twins or AI-based predictive models can be integrated with SSbD evaluation tools to streamline decision-making, making the framework more accessible and efficient for small companies and non-expert stakeholders.

7. **Addressing Data Gaps for Novel Materials**: Future research should prioritize obtaining complete hazard and lifecycle data for emerging materials like bio-resins, coatings, additives and bio-composites. The current reliance on estimates or literature averages introduces significant uncertainty, especially for new or modified materials.

8. **Development of Harmonized Standards and Evaluation Tools**: Research is required to support the creation of PEFCR specifically for façade biocomposites and a harmonized regulatory framework for living or multifunctional façades incorporating biobased materials.

# 8. Limitations

While this study provided a structured and insightful evaluation of material safety and sustainability within the SSbD framework for biobased façade panels, several limitations inherent to the research context and methodology are acknowledged. These limitations affect the depth and generalizability of the findings:

1. **Reliance on incomplete and non-transparent material data:** Many critical materials used in biobased façade systems, such as bio-resins, coatings and additives, were often observed to lack complete hazard data or are based on proprietary formulations, which significantly limited the ability to identify and assess potential risks. In several cases, key data points were missing or estimated from similar materials, rather than based on direct testing. Safety Data Sheets (SDSs) are often incomplete, especially for small-batch or custom inputs. For startups like Leafy, which rely on external suppliers, gaining complete visibility into material composition is difficult. As a result, assessments often depend on estimates or literature averages, which introduces uncertainty, particularly for new or modified materials that have not been thoroughly tested.

2. **Challenges with Early-Stage Lifecycle and Exposure Data:** The study noted that conducting accurate LCA at the early stages of product development can be challenging, particularly when working with pilot-scale materials. In early-stage prototypes, emissions during application, like off-gassing or leaching, are rarely measured, leaving potential exposure risks unquantified. This also extends to specific on-site hazards such as fine particulate dust generated from drilling or cutting the facade panels and substructures during installation. While general material dust hazards are considered, comprehensive data on real-world occupational exposure levels during these specific installation activities often remains unquantified at early product development stages. Furthermore, defining exposure scenarios is challenging due to varying installation contexts and user proximity, which adds further uncertainty to environmental and health impact assessments. Although the Environmental Footprint (EF) method offers a comprehensive life cycle perspective, it currently omits direct biodiversity impacts and provides only limited resolution for marine and terrestrial ecotoxicity. They fail to capture specific impacts, such as the effects on biodiversity or the release of microplastics. Materials like Tricoya or modified bioplastics also raise issues because their altered chemistry is not fully reflected in standard LCA databases, skewing the results towards an optimistic bias.

3. **Constraints Posed by Startup Context:** While the case study with Leafy offered valuable real-world insights, the resource constraints typical for a startup limited the availability of certain data for the researcher. Conducting in vitro toxicology tests, applying New Approach Methodologies (NAMs), or running full LCA models often requires specialized expertise, financial resources and time that are beyond an early-stage company's capacity. This meant the study had to work with existing, sometimes less comprehensive, data.

4. **Impact of Unstable Prototypes and Evolving Processes:** The rapid design iterations common in startups like Leafy meant that finalizing a stable product version for consistent assessment was challenging. Small changes in resin use, curing conditions, or coatings could alter safety or environmental profiles, potentially impacting the reproducibility and reliability of the assessments.

5. **Gaps in Existing Standards and Evaluation Tools for Novel Materials:** Current tools, such as USEtox and ProScale, are not designed for novel biocomposites and often require input data that

is not available. Furthermore, the absence of PEFCR and the lack of a precise REACH classification for façade biocomposites make it difficult to benchmark their environmental and safety performance. This challenge is compounded by the fact that no harmonized regulatory framework currently exists for living or multifunctional façades that incorporate biobased materials, leaving developers without clear guidance or compliance pathways.

6. **Limited Scope for Real-World Performance Validation:** The durability of biobased façades under real-world conditions appeared to be largely untested, which limited the ability to comprehensively assess long-term safety. While durability and lifecycle safety are critical, their systematic integration into Step 1 of the SSbD framework is noted as a limitation of the framework itself, impacting the researcher's ability to evaluate long-term viability fully within this specific step

7. **Stringency of SSbD Criteria:** The SSbD Step 1, with its emphasis on intrinsic hazards without considering actual use conditions or risk mitigation, resulted in no material achieving Level 3, even those considered sustainable. This highlights a limitation in how the framework's strict criteria may penalize potentially sustainable materials or require more nuanced interpretation, affecting the researcher's ability to demonstrate full alignment based on the current scoring.

8. **Limited Sample Size for Stakeholder Interviews:** While semi-structured interviews were conducted with key stakeholders, the study interviewed only one individual from each stakeholder group (e.g., Leafy's founder, a single façade expert, one architect). This limited the breadth of perspectives captured and restricts the generalizability of qualitative insights regarding stakeholder concerns, trade-offs and perceptions of the SSbD framework. A broader, more extensive set of interviews would be needed to generalize these findings more widely.

9. **Gap between SSbD Goals and Market Realities**: In early-stage or budget-conscious markets, customers often prioritize cost, appearance, or basic performance over comprehensive SSbD compliance. Since there are no legal requirements for SSbD assessments, companies have little incentive to invest in the data and testing needed. Additionally, findings from one case, such as Leafy's panel, may not translate easily to other products or settings. While the results offer valuable internal guidance, the performance of materials may differ significantly under alternate applications, geographic conditions, or user profiles. For example, outdoor durability, fire exposure and moisture resistance may behave differently in tropical climates compared to European installations. These limitations underscore the importance of contextual validation, stakeholder engagement and continuous updates as new data and SSbD criteria evolve.

10. **Exclusion of Comprehensive Socio-Economic Assessment (Step 5):** While acknowledged as optional, the study noted that a robust socio-economic assessment (Step 5) posed significant challenges for Leafy, which in turn limited the researcher's ability to operationalize this crucial dimension fully. The lack of clear, standardized guidelines, fragmented supplier data on labor practices and the need for specialized expertise meant the study relied on assumptions and qualitative scoring, which reduced the reliability of this part of the assessment.

These limitations highlight the dynamic nature of researching novel biobased materials within an evolving regulatory and market landscape, emphasizing areas for future research and refinement of the SSbD framework.

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# Appendix A: Leafy Panel Photos

# Appendix B: Characteristic of Leafy Panel

| Theme | Category | Requirement | Description | MoSCoW | Validation method |
|---|---|---|---|---|---|
| Sustainability and environment | Sustaina bility | Minimum of 80% biobased or recycled materials | Reduces environmental impact and supports circular economy | Must | Material certification |
| Sustainability and environment | CO2 footprint | Must have a lower carbon footprint than conventional green facade systems | Supports climate goals and green building standards | Should | LCA |
| Sustainability and environment | Recyclabi lity | At least 70% of materials must be recyclable at end-of-life | Ensures sustainability beyond usage phase | Should | Material compositio n test |
| Sustainability and environment | No Harmful Chemical s | No toxic substances (REACH compliant) | Safe for people, plants and animals | Must | Material compliance check |
| Sustainability and environment | Sustaina bility | Compliance with BREEAM or LEED sustainability standards | Improves environmental impact and supports green building certifications | Should | Certificatio n application |
| Functionality & User-Friendliness | Modular Design | Panels must be interchangeable and expandable | Enables scalability and customization | Must | Assembly test |
| Functionality & User-Friendliness | Lightweig ht | Total system weight must not exceed 70 kg/m² | Ensures safe installation on various facade types | Should | Load test |
| Functionality & User-Friendliness | Lightweig ht | Total weight per assembly component must not exceed 10 kg | Ensures safe and easy installation on various facade types | Should | Load test |
| Functionality & User-Friendliness | Installatio n Time | Each panel should be installable in under 10 minutes | Reduces labor costs and complexity | Should | Installation test |
| Functionality & User-Friendliness | Maintena nce Frequenc y | Maximum of 1 maintenance intervention per year | Ensures long-term user-friendliness | Should | Maintenanc e simulation |
| Safety and certification | Fire Safety | The system must meet EN 13501-1 Class B-s1,d0 (or A2-s1,d0 for buildings above 13m) | Meets facade fire regulations, see if Class A2-s1,d0 is also possible. This is fo facades higher than 13 meters | Must | Fire resistance test |
| Safety and certification | Wind Load Resistan ce | Must withstand wind forces up to 1.6 kN/m2, EN 1991-1-4, EN 12210 | Ensures structural safety in storms | Must | Wind tunnel test |

| | | | | | |
|---|---|---|---|---|---|
| Safety and certification | Water Drainage | The system must prevent water penetration under simulated rain conditions of 60 mm/h for at least 24 hours, in accordance with EN 12467 | Ensures no water leakage onto the underlying façade. Prevents facade damage | Must | Water simulation test |
| Safety and certification | Impact Resistan ce | The panel must resist impact forces of 10 Joules, in accordance with EN 14019 | Withstands impacts from debris and weather | Must | Impact test (EN 14019) |
| Safety and certification | Structural Load | The mounting system must support a static load of at least 200 kg/m² without deformation, in accordance with EN 13364 | Secure attachment under all load conditions | Must | Load-bearing test |
| Safety and certification | Moisture Resistan ce | The material must withstand relative humidity of 95% without degradation, according to EN 12467 | Withstands exposure to rain and humidity | Must | Moisture resistance test |
| Safety and certification | Thermal Performa nce | The panel must have a thermal conductivity ≤ 0,1 W/mK, in accordance with EN 12667 | Ensures insulation & prevents thermal stress | Should | Thermal conductivit y test |
| Safety and certification | Acoustic Performa nce | Complies with EN ISO 10140-2 | Provides noise reduction benefits | Could | Acoustic test |
| Safety and certification | CE Certificati on | Complies with EN 14992 (if applicable) | Ensures regulatory compliance | Must | Certificatio n process |
| Weather Resistance & Durability | UV Resistan ce | The panel must resist discoloration and degradation for at least 10 years under UV exposure, tested according to ISO 4892-2 | Prevents aesthetic degradation | Should | UV exposure test |
| Weather Resistance & Durability | Frost Resistan ce | The system must withstand temperature cycles from -20°C to +50°C without cracking, in accordance with EN 12467 | Ensures year-round durability | Must | Thermal stress test |
| Weather Resistance & Durability | Waterpro ofing | Prevents water accumulation that could lead to mold or degradation of the materials | Maintains health of plants and structure | Must | Water exposure test |
| Aesthetics & Visual Impact | Base Panel Appearan ce | The panel must look visually attractive even without plants | Ensures facade remains aesthetically pleasing year-round | Should | Visual assessmen t & user feedback |
| Aesthetics & Visual Impact | Plant Integratio n | The panel should look integrated and natural when partially covered by plants | Ensures seamless transition between structure and greenery | Should | Visual integration test |
| Aesthetics & Visual Impact | Longevity | The panel's appearance must remain stable for at least 10 years | Prevents fading, cracking, or degradation | Must | Accelerate d aging test |
| Cost & Scalability | Productio n Cost | Must not exceed €250 per m² in mass production | Ensures affordability | Should | Cost analysis |

| | | | | | |
|---|---|---|---|---|---|
| Cost & Scalability | Scalable Production | System must be easy to mass-produce | Ensures affordability and availability | Should | Production feasibility test |
| Material and sustainability | Material | The panel and frame must be made of bamboo fiber composite, containing at least 80% biobased materials | Ensures sustainability and compliance with biobased goals | Must | Material certification |
| Material and sustainability | Material | The composite must be free from toxic additives and comply with REACH regulations | Ensures health and environmental safety | Must | Material compliance check |
| Strength and stability | Structural Strength | The mounting system and structural frame must support a static load of at least 200 kg/m² without deformation, in accordance with EN 13364 | Ensures that the mounting system and supporting frame can safely handle the combined weight of the panel, substrate and plants under all conditions | Must | Load-bearing test |
| Strength and stability | Impact Resistance | The panel must resist impact forces of at least 10 Joules, in accordance with EN 14019 | Ensures resistance against debris and accidental impacts | Must | Impact test |
| Strength and stability | Flexural Strength | The material must have a minimum flexural strength of X MPa, tested according to ISO 178 | Ensures bending resistance | Should | Mechanical testing |
| Assembly | Mounting | The panels must click or slide into place without visible screws from the front | Ensures clean aesthetics and easy installation | Should | Assembly test |
| Assembly | Connection | The frame must allow modular expansion and be compatible with multiple facade types | Supports scalability | Must | Installation test |
| Weather resistance | UV Resistance | The panel must resist UV degradation and discoloration for at least 10 years, in accordance with ISO 4892-2 | Prevents material aging | Should | UV exposure test |
| Weather resistance | Waterproofing | The material must not absorb more than X% water by weight, tested under EN 12467 | Ensures dimensional stability in wet conditions | Must | Water absorption test |
| Weather resistance | Thermal Expansion | The material must have a thermal expansion coefficient of ≤ X mm/m°C to prevent warping | Ensures stability under temperature changes | Should | Thermal stress test |
| Aesthetics | Base Panel Appearance | The panel must look aesthetically pleasing even without plants | Ensures a visually attractive facade year-round | Should | Visual assessment & user feedback |
| Aesthetics | Color Stability | The panel's color must remain stable for at least 10 years | Prevents visual degradation | Must | Accelerated aging test |

# Appendix C: Façade Material Details

## C1. Leafy Façade Material Mapping

| Component | Materials |
|---|---|
| Structural Mounting (Back-End) | Impregnated spruce battens (vuren latten)<br>SS hammer plugs<br>Facade anchors |
| Rear Panel (Substrate Holder) | NPSP bamboo fibre composite<br>Tricoya MDF<br>SS bolts, nuts, washers<br>Trespa screws |
| Side and Front Panels | Same as rear panels<br>Alternatives: MOSO Bamboo X-treme, Accoya wood |
| Substrate Composition (Soil-Free Growing Medium) | Coconut fibres<br>Crushed coconut chips<br>Biochar<br>Perlite<br>Compost<br>Wood fibres<br>Pumice stone |
| Irrigation Components | LDPE drip irrigation tubing<br>LDPE Tyleen hose<br>Polyethylene connectors<br>VDL pipe clamps |
| Root Barriers & Liners | Biobased: Jute root cloth (under testing)<br>Conventional: Polypropylene (PP) root cloths |

## C2. Assumed Composition for Substrate

| Component | Biobased | Function | SSbD Alignment |
|---|---|---|---|
| Coconut fibers (25%) | Yes | Aeration and water retention | Biobased, renewable and biodegradable |
| Crushed coconut chips | Yes | Drainage, anti-compaction | Biobased agricultural waste product |
| Biochar (10%) | Yes | Microbial habitat, carbon sequestration | Biobased, circular use of biomass waste, contributes to carbon sequestration |
| Compost (15%) | Yes | Nutrient source, supports microbial life | Biobased, supports healthy plant growth |
| Wood fibers | Yes | Nutrient retention and structure | Biobased, industrial wood waste reuse |
| Perlite (15%) | No | Aeration, compaction control | Inorganic but inert and essential for plant health and root aeration |
| Pumice stone (10%) | No | Moisture retention, physical support | Volcanic rock, inert, durable; necessary for physical performance |

## C3. Comparative Review for Four Reference Façade Materials

| Property | NPSP Bamboo Composite | Tricoya MDF | MOSO Bamboo X-treme | Accoya Modified Wood |
|---|---|---|---|---|
| Material Type | Natural Fiber Composite | Acetylated MDF | Thermo-Density Bamboo | Acetylated Solid Wood |
| Main Components | Bamboo fibers + Bio/unspecified resin | Acetylated wood fibers + Resin | Heat-treated bamboo strips | Radiata pine + Acetylation |
| Biobased Content (%) | ~70% (Assumed) | ~85% | >90% | >95% |
| Durability Class (EN 350) | Unknown / Under Testing | Class 1 (Very Durable) | Class 1 (Very Durable) | Class 1 (Very Durable) |
| Moisture Resistance | Moderate (depends on resin) | High (Low swelling) | Excellent | Excellent (Low moisture uptake) |
| Fungal/Rot Resistance | Depends on matrix | Excellent | Excellent (EN 113) | Excellent (EN 350) |
| Fire Resistance Class | Depends on formulation | Euroclass D (untreated) | Class Bfl-s1 (Fire-retardant) | Euroclass D (can be enhanced) |
| Dimensional Stability | Moderate | Very High | High (Density >1150 kg/m³) | Very High (Stable in all climates) |
| Warranties Offered | 10 years | 50 years above ground / 25 in ground | 25 years (residential facade) | 50 years above ground / 25 in ground |
| Certifications | Pending testing; likely REACH-registered | FSC, Cradle to Cradle™ Gold | FSC, EPD, Cradle to Cradle, EU CE | Cradle to Cradle Gold, FSC, EPD |
| SSbD Step 1 Compliance Potential | Depends on resin hazard class | Likely passes H1 & H2; low hazard resin used | Likely passes; treated bamboo, no SVHC used | Meets all H1–H3 criteria (low hazard profile) |
| Processing Requirements | Low-energy molding, thermoforming possible | Machinable like MDF, can be CNC cut | Requires thermal pressing, shaping | Standard woodworking tools |
| NotesA | Needs resin hazard validation; test results awaited | Ideal for moist interior/exterior applications | Best suited for façade cladding with high UV exposure | Best environmental profile with strong warranty |

## C4. Conventional vs Biobased Panel

| Design Characteristic | Relevance | Biobased Panel | Conventional Panel |
|---|---|---|---|
| Fire Safety (Reaction & Resistance) | Safety (Life Safety) | Often lower class without treatment (e.g., wood ≈ Class D, can be treated to B or A2). Fire resistance depends on adding fireproof layers. | Easily non-combustible (e.g., metal, fiber-cement Class A2 or A1). Can achieve EI 30/60 with proper system. |
| Structural Integrity (Wind & Load) | Safety (Structural) | Lightweight, but must account for wood creep and movement. Can meet wind loads (e.g., tested to >2000 Pa) if properly anchored. Weight ~10–20 kg/m² for wood systems. | Well-established systems for high wind (e.g., tested >2500 Pa). Dense materials (brick/stone) heavier (50–100 kg/m²) need strong anchors. Metal panels light (~5–15 kg/m²). |
| Moisture Control (Water Tightness & Ventilation) | Safety (Durability) & Health | Requires rainscreen cavity & coatings. Wood absorbs moisture (can be ~10–20% if exposed) so needs ventilation. Design includes 20–40 mm air gap and WRB. | Many are water-impervious (metal, plastic) so panel itself 0% absorb. Still use 20 mm cavity for drainage. Masonry absorbs but can dry. Generally more forgiving with moisture but still needs good detailing. |
| Thermal Performance (Insulation & Bridging) | Sustainability (Energy) | Often good due to low conductivity of material (wood λ~0.12 W/mK). Bio-insulation (wood fiber, etc.) achieves U ≤ 0.20 easily. Wood sub-framing reduces thermal bridging. | Requires thermal breaks for metal parts. Can use high-performance insulation (PIR, etc.) to reach low U. Panel itself often not insulating (metal/glass). Both types can meet passive standards with design. |
| Embodied Carbon (GWP) | Sustainability (Climate) | Very low or negative GWP (wood ~ –0.5 to +5 kg $CO_2$/m² for 1” board, storing biogenic carbon). High biobased content 80–100%. | Moderate to high GWP (e.g., aluminum ~20–30 kg $CO_2$/m², fiber-cement ~10–15 kg $CO_2$/m²). Mostly mineral/industrial content. Some can be offset with recycled content. |
| Recyclability & EoL (Circularity) | Sustainability (Waste) | Often biodegradable/compostable (wood, cork) or energy recoverable. Recyclability depends on purity (pure wood 100% reusable; wood-plastic composite harder). Typically no scrap value, but low toxin at EoL. | Metal panels ~100% recyclable (high scrap value). Inert panels (brick, concrete) downcyclable as aggregate. Composites (ACM, fiberglass) low recyclability. Some waste could be landfilled if not designed for disassembly. |
| Durability (Service Life) | Both (Long-term Safety & Sustainability) | With maintenance, can achieve 50-year life (e.g., treated wood cladding often 30–50 years). Without upkeep, risk of rot/decay in <20 years in wet climates. Vulnerable to UV (fading) unless coated. Needs periodic painting (5–10 yr interval) for best longevity. | Many panels designed for 50+ years life (metals, ceramics). Some like brick or stone can last 100+ years. Low maintenance for non-corroding materials (re-coating metal ~20 years if painted). Generally high durability, but metal can corrode if coating fails, etc. |
| Maintainability (Safe Access) | Safety (Worker) & Sustainability (Longevity) | Biobased panels often modular planks or boards that are relatively easy to replace piecewise. Lighter weight makes handling easier and safer. Need to ensure fixings accessible. Can integrate with typical rope access systems (anchors on roof). | Conventional panels vary: large glass panels need special equipment to replace. Many systems (e.g., curtain walls) designed with integrated maintenance access (e.g., monorails for BMU). Heavier panels require mechanical lifting (cranes) for replacement. Both systems must comply with Arbo rules for maintenance. |

# Appendix D: Interview Guide

**Section 1: Background & Expertise**

Q1. Can you briefly describe your experience with façade design and the types of materials you most commonly work with?

Q2. Have you previously worked on projects involving bio-based or sustainable façade materials (e.g., bamboo, jute, bio-resins)?

**Section 2: Safety Considerations**

Q3. What are the most critical safety considerations during installation and long-term performance of façades?

Q4. Are there specific materials you avoid due to safety or maintenance concerns? (e.g., flammability, degradation, sharp edges)

Q5. How do you typically address risks like façade failure, wind loads, or moisture ingress in your design and material choices?

**Section 3: Sustainability & Material Selection**

Q6. What role does environmental impact play in your façade material selection process?

Q7. Are life cycle assessments or environmental certifications (e.g., EPDs, Cradle-to-Cradle) used in your projects?

**Section 4: Regulations & Compliance**

Q8. How do you ensure compliance with building codes, regulations, or CE marking in façade design?

Q9. Have you encountered regulatory barriers when proposing or working with unconventional materials?

**Section 5: Practical Challenges & Tradeoffs**

Q10. Have you faced trade-offs between sustainability and technical performance (e.g., biobased vs non-biobased)? How did you navigate them?

Q11. Based on your experience, what are common limitations or concerns when using natural or bio-based façade materials? (e.g., weathering, fire safety, structural strength)

Q12. What kind of support (technical documentation, certifications, installation guidance) do you expect from suppliers of innovative façade systems?

**Section 6: Reflections on Leafy's Approach**

Q13. Based on your experience, what are your thoughts on Leafy's use of bamboo fibre, jute, bio-resins, and thermoplastics in façade applications?

Q14. What improvements or design modifications would you recommend for safer and more sustainable performance?

Q15. Would you feel confident specifying a system like Leafy’s in one of your projects? Why or why not?

**Section 7: Perceptions on SSbD Framework**

Q16. Are there any emerging trends or innovations in façade systems that you believe align well with SSbD principles?

Q17. Do you have any final advice for startups like Leafy working on sustainable façade technologies?

# Appendix E: Stakeholder Interview Coding

## E1. List of Safety Characteristics

| Safety | | | |
|---|---|---|---|
| **Stakeholder** | **Code** | **Quote** | **Insight** |
| Architect | Primary safety hazards | "…the main concern… is regarding the fire and the wind." | Fire safety and wind loads drive planning decisions |
| Architect | Fire safety measure | "…the green wall should start at least…" | Begin the green wall a few meters above ground (3m).<br>As a fire prevention measure |
| Architect | Safety access openings | "…we need to have openings in the facades…" | There are deliberate gaps or access zones (with no plants/panels) over the surface for emergency |
| Architect | Fire-stop at roof/parapet | "Then also separation from the parapet wall..." | The design includes a gap at the top (parapet) of the green façade acting as a fire-stop |
| Architect | Horizontal fire breaks | "…keep… between two floors… bands which are not planted." | Unplanted bands at each floor level acts as fire break |
| Architect | Lack of Fail-Safe | "No, not as far as..." | No fail-safe seen. Safety gap seen |
| Architect | Segmented panel design (modular safety) | "…it is similar to the norms of using cladding…" | Design modularly (in small patches/sections) limits the size of any potential falling piece |
| Architect | Pre-installation structural check | "While installation we have to check… if the facade… is crack free..." | 1. Underlying building facade must be inspected for structural integrity to safely carry new load.<br>2. Check for cracks and secure connections. |
| Architect | Structural load requirement | "… then there's also a norm… to consider the dead weight of the entire structure." | Regulations require accounting for the added weight of the green wall system. |
| Façade Expert | Safety by Design | "... structural stability , fire safety, moisture protection and general durability ..." | Wind, fire, water and wear is critical |
| Façade Expert | Safe-by-Design Concerns & Challenges | "...the main risks are design flaws, execution flaws, wrong material choices, harsh environment effects and lack of maintenance." | Failure factors are sloppy installation, unsuitable materials for climate, extreme weather exposure and neglected upkeep – mitigated by SbD |
| Leafy | Safety Requirements & Testing | "..difficult as a startup to put a hardware product in construction on the market". | Strict safety standards for façade products. |
| Leafy | Installation & Worker Safety | "We are confined with the law…" | Installation design focuses on safety and ease. Working at heights necessitates proper equipment (scaffolds, lifts) |
| Professor | Fire Safety Considerations | "Biobased material… means fire?…" | Fire performance is a critical safety factor. |
| Professor | No Safety–Sustainability Trade-off | "Sustainability is a given… but you cannot trade circularity with security." | Safety remains non-negotiable. |
| Professor | Design Integration | "The hexagon is really going to create a design problem..." | Hexagonal panel may pose practical integration challenges. |
| Supplier 1 | Chemical-Free Production Process | "...we fully mechanically extract the fibers.." | Purely mechanical process powered by renewable energy. |

| | | | |
|---|---|---|---|
| Supplier 1 | Chemical-Free Production Process | "...to get the fibers, we don't need any additive..." | Avoids adding chemicals to the bamboo fiber but performance increased by coatings |
| Supplier 1 | Occupational Safety – Dust Exposure & Inhalation | "During production, you indeed have quite some exposure to dust...might explode if you expose it to flame..." | Processing bamboo can generate fine dust which poses inhalation and explosion hazards. But well mitigated |
| Supplier 1 | Safety Requirements & Testing | "..difficult as a startup to put a hardware product in construction on the market". | Strict safety standards for façade products. |
| Supplier 1 | Installation & Worker Safety | "We are confined with the law…" | Installation design focuses on safety and ease Working at heights necessitates proper equipment (scaffolds, lifts) |
| Supplier 1 | Fire Safety – Material vs. System Design | "...but then the interesting shift that you see is whether you should qualify this on the material or on the whole facade..." | Fire safety cannot be evaluated on material properties alone; the configuration of the facade assembly is critical. Safe-by-design must consider interactions between components |

## E2. List of Sustainability Characteristics

| **Sustainability** | | | |
|---|---|---|---|
| **Stakeholder** | **Code** | **Quote** | **Insight** |
| Architect | Use of recyclable materials | "…if I want to use plastic, then I would see that OK, the plastic – if it is a recycled one…" | Prioritize materials that can be recycled or are from recycled sources. |
| Architect | Sustainability focus (after performance) | "I would just see that it is sustainable or not… once… has been approved then…" | Sustainability becomes the deciding factor once safety and technical performance are assured. |
| Architect | Avoiding future waste & hazards | "We wanted to use a polypropylene strip… joints become permeable… but we didn't use..." | Opting against a new product due to sustainability concerns. Sacrifice to avoid long-term env harm |
| Architect | Life-cycle considerations | "For me…firstly how it is produced (if it uses local resources)..." | Sustainability checklist for materials.<br>1. Production & sourcing – sustainably and with local resources<br>2. Interaction in use – is it compatible and safe within the system<br>3. End-of-life – can it be removed and reused or recycled instead of just disposed? |
| Architect | Emphasis on direct reuse | "Reusability also costs energy... if I take it out…" | Even Recycling or repurposing materials consumes energy. So panels must be reused. |
| Façade Expert | Sustainability by Design | "...truly sustainable design avoids toxic substances and minimizes any pollution or health risks..." | Renewable/recycled materials with transparency (EPDs) to validate environmental performance. |

| | | | |
|---|---|---|---|
| Leafy | Innovation Goals (Greening Cities) | "...Why don't we add green to that space that is not really used..." | Motivation is to increase urban greenery by utilizing building facades for living plants |
| Leafy | Sustainability & Industry Trends | "So you see that the larger contractors… are focusing now on building materials…". | A construction industry shift toward sustainable, biobased materials. |
| Leafy | Circularity & End-of-Life | "...we always wanna be a circular product, so we wanna close the loop". | Leafy intends to "close the loop" by recycling or reusing components: |
| Professor | Sustainability & Circularity Metrics | "You need to have a properly evaluated EPD …" | Rigor in assessing sustainability. |
| Professor | Composite Material Concerns | "… If it's epoxy or polyester as a binder, then it's a composite which is not (truly circular). That's a risk." | Unknown portion of the panel's material. Remaining synthetic content can "be a downer" for sustainability. |
| Supplier 1 | Chemical-Free Production Process | "...we fully mechanically extract the fibers.." | Purely mechanical process powered by renewable energy. |
| Supplier 2 | Chemical-Free Production Process | "...to get the fibers, we don't need any additive..." | Avoids adding chemicals to the bamboo fiber but performance increased by coatings |
| Supplier 3 | Resin Choice – $CO_2$ Footprint & Industry Reluctance | "...resin that the industry wants... usually the biggest impact of the $CO_2$ emissions..." | The binding resin in the composite is a major contributor to carbon footprint. |
| Supplier 4 | LCA and Carbon Footprint Data | "...We are in the process of making a new LCA... that will cover all facets again." | The company actively assesses and discloses the environmental impacts of its product. |
| Supplier 5 | Holistic Life-Cycle Considerations | "...you need to consider the whole cycle, so not only the material itself..." | A change that appears sustainable at the material level can have unintended negative consequences when viewed in the full product system or life cycle. |

## E3. List of Maintenance & Durability Characteristics

| **Maintenance & Durability** | | | |
|---|---|---|---|
| **Stakeholder** | **Code** | **Quote** | **Insight** |
| Architect | Maintenance as key concern | "…most of the questions are regarding the maintenance." | Maintenance is a dominant concern. |
| Architect | Regular upkeep requirement | "… has to do the timely maintenance. (For public buildings, this is in the tender)..." | Require consistent upkeep – you cannot "fit and forget" them. |
| Architect | Design Principles | "… I think it is quite good as far as the maintenance aspect ..." | Having separate layers/modules makes maintenance easier. |
| Architect | Corrosion Resistance | "… this material should be rust free..." | Durability concern: all metal components (frames, fasteners, etc.) must be rust-resistant. |
| Façade Expert | Safe-by-Design Concerns & Challenges | "One challenge is timeline and cost… Another challenge is the knowledge required – you might need diverse expertise..." | Implementing SSbD can be resource-intensive |
| Façade Expert | Maintenance & Lifecycle | "...what happens after installation...who waters them or replaces dead plants? | Long-term performance was stressed as part of design responsibility. |
| Leafy | Maintenance & Modularity | "...you always see those concrete walls where there's a lot of (algae) on there…" | The façade system is designed for low maintenance. Certain heavy materials (like concrete) are avoided because they complicate maintenance |
| Professor | Durability & Warranty (Longevity) | "How long is this going to last? … If it's a three-year, I'm not interested..." | Long-term durability/warranty is crucial for safety and feasibility. |
| Professor | Maintenance & Operational Needs | "...how many gardener hours do I need to pay to secure that this facade works?" | Green façades require ongoing care. |
| Supplier | End-of-Life and Recycling Challenges | "...I'd say recycling is definitely a challenge...we just grind them and then reuse them as a filler..." | Thermoplastics vs thermoset. "Sustainable by design" must account for disposal. |
| Supplier | Natural Fiber Facade Concerns & Mitigation | "So there are three or four main aspects to consider..." | Flammability, moisture sensitivity, long-term strength and weathering/aging (UV stability and resistance to biological growth). Safe-by-Design approach by adding resin to composite |

## E4. List of Regulation mentions

| Regulations | | | |
|---|---|---|---|
| **Stakeholder** | **Code** | **Quote** | **Insight** |
| Architect | Certification requirement | "… So the product must be qualified for that… Otherwise we cannot use it." | Regulations require that any green wall system meet established standards. |
| Architect | Fire safety priority in codes | "…fire safety which is one of the biggest concerns of the product." | Fire safety is top concern. |
| Architect | Regulations dictate choices | "...any of the products… I had to either use it or discard it because of the regulations." | Regulations have the final say in material choice. |
| Architect | Performance-based code guidelines | "…the norms… (don't) say 'I want a steel of XYZ quality'… it will just give the guidelines…." | Regulations are often performance-based: they specify the required outcome rather than prescribing exact materials. (e.g., corrosion resistance in this case). |
| Architect | Height limit regulations | "…in Germany… I have seen up to 22 meters… maybe 30 meters is doable..." | Height limits for green façades. |
| Façade Expert | Regulatory Norms & Standards | "...The EU's SSbD initiative itself isn't a law, but it signals a direction... Don't treat as a bureaucratic hurdle but as a design input..." | Innovators must ensure new façade materials meet building code mandates. |
| Leafy | Regulatory Compliance (Policy) | "the MPG… by law you had to have a score of 0.8 when I started… it changed to 0.6… ambitions to 0.4..." | Evolving regulations that mandate sustainability (e.g., the Dutch MPG score requiring lower environmental impact). |
| Leafy | Material Selection & Future-Proofing | "Because legislation is going so fast… you will not have a likelihood of surviving …" | Deliberate choice of biobased materials to ensure the product remains relevant under future sustainability norms and laws. |
| Professor | Regulatory Compliance for New Materials | "Uncertainties with new materials...Is it an approved material?" | Concern with biobased is whether they meet building codes and certification standards. |
| Supplier | Regulatory Compliance & Clean Factory | "...some companies have some kind of safety regulations... only thing they want is a clean factory..." | The material is benign and stakeholder concerns center on housekeeping (cleanliness) rather than chemical safety. |

## E5. List of Stakeholder Concerns

| Stakeholder Concerns | | | |
|---|---|---|---|
| **Stakeholder** | **Code** | **Quote** | **Insight** |
| Architect | Design adaptability & cost priorities | "…what is important for me is the flexibility of the material.…And then secondly, the cost." | Product must adapt to the design needs (flexibility) and be cost-effective. |
| Architect | Collaboration with manufacturer | "…you always have a person from the product side who guides us…" | Close collaboration between the architect and the product supplier. |
| Architect | Liability distribution | "…if the facade got… burning from one end to the other (no breaks)…" | Design failure: architect<br>Installation/Product failure: supplier |
| Architect | Contractual risk management | "…in (the tender), I would write… execution according to the specifications of the manufacturer…" | To manage risk, the architect includes clauses in contracts/tenders that installation must follow the manufacturer's specifications. |
| Architect | Market/regulatory acceptance barrier | "…if you want to… sell it in different European countries, every country has its own norms, especially…" | Challenge for innovation diffusion: building regulations and market acceptance vary by country. Need to navigate regulatory landscapes |
| Façade Expert | Stakeholder Perspectives | "The building industry can be conservative..." | Stakeholder tend to be cautious with new façade system (performance tests, certifications) |
| Façade Expert | Prototyping & Testing | "...It's much better to have a prototype fail in a controlled test than a product fail on a building." | This approach yields proof (e.g., "it didn't leak under X rain conditions") that can be shown to investors, clients and regulators. |
| Façade Expert | Interdisciplinary Collaboration | "...Façades intersect with structural engineering, fire engineering, building physics, biology… The more voices and eyes on the design, the fewer blind spots you'll have." | Developing safe & sustainable façades requires input from multiple domains. |
| Leafy | Stakeholder Engagement & Partnerships | "...we need partners that provide us for example with a gasket and a panel or..." | A collaborative business model involving multiple stakeholders. |
| Professor | Client Priorities vs. Regulatory Needs | "you're pleasing the one who pays you... Then...regulatory aspects." | Client's requirements drive facade design. |
| Professor | Material Selection Criteria | "Money and technical performance (come first)… then in the second step availability in systems..." | Key factors for choosing facade materials are cost and performance, followed by r ease of integration. |

| | | | |
|---|---|---|---|
| Professor | Early Validation & Benchmarking | "They need to analyze the competing systems which exist and show where they are better..." | Startup should validate their design early by benchmarking against existing facade solutions. |
| Supplier | Need for Real-Life Proof & Longevity Data | "...the supply chain needs to mature, but... you actually have to have some proof in the market..." | Buyers in the construction sector are highly risk-averse. Pilots and accumulating in-service performance data is critical. |
| Supplier | Importance of Data and Demonstration (Startup Advice) | "...you really have to show the benefits of the material...sales is the biggest problem..." | Need for evidence and real-world validation. |

## E6. List of Trade-offs

| **Trade-offs** | | | |
|---|---|---|---|
| **Stakeholder** | **Code** | **Quote** | **Insight** |
| Architect | Navigating performance vs. sustainability | "… if the material has been approved then… performance is not a question…" | Only use certified (authorized) products. Performance is a given; sustainability becomes the differentiator. |
| Architect | Compliance over innovation | "… So that is one of the limitations… of getting innovative here..." | Trade-off between strict safety compliance and innovation. Novel or bio-based materials often lack such certification. |
| Architect | Performance vs. material purity | "...use bio-based resin which is sustainable, but the epoxy resin is not obviously..." | Epoxy resin is used for performance. safety considerations outweigh the desire for 100% sustainability. |
| Architect | Accepting necessary non-green elements | "… Some things you cannot really get away with without totally converting them." | Conscious trade-off: striving for maximum sustainability while acknowledging some conventional materials must be used for now. |
| Architect | Sustainable material vs. local feasibility | "…bamboo is definitely not a material which is… common in this part of Europe…" | There's a trade-off between using an eco-material and the carbon footprint/cost of transporting or importing it to where the project is – a nuance in sustainable design decisions. |
| Façade Expert | Balancing Safety & Sustainability | "...structurally sound, fire-resistant and weather-proof and sustainable by design..." | Finding an optimal trade-off where both objectives are satisfied. |

| | | | |
|---|---|---|---|
| Leafy | Biobased Material Challenges | "...more expensive, less durable, there's not a lot of quantity, so you cannot get them that fast…". | Higher cost, lower durability, limited supply and less technical maturity compared to traditional materials. |
| Leafy | Economic Feasibility (Cost) | "I always hate to say it but money (is crucial)… the construction industry has small percentages…". | Profit margins are slim (~4%),expensive components risk being cut from projects |
| Leafy | Trade-offs: Safety vs Sustainability | "...not on… safety and sustainability. At least in my experience I never had that". | No trade-off between safety vs sustainability. |
| Supplier 1 | Market Barriers: Performance, Cost & Carbon Economics | "I think from safety point of view, sometimes it (biobased) can be better... but typically it's the same chemical composition..." | Switching to a bio-based resin does not automatically make the product safer. |
| Supplier 1 | Sustainability as Insufficient Selling Point | "...So whenever sustainability is the only reason for using it, they don't want to pay..." | Although clients express interest in sustainability, they ultimately prioritize performance and cost. |
| Supplier 1 | Natural Fiber Facade Concerns & Mitigation | "So there are three or four main aspects to consider..." | Flammability, moisture sensitivity, long-term strength and weathering/aging (UV stability and resistance to biological growth). Safe-by-Design approach by adding resin to composite |
| Supplier 1 | Market Barriers: Performance, Cost & Carbon Economics | "...people always come from the $CO_2$ reduction perspective to you…but people are not only going to do this for $CO_2$, right?" | The current economic and technical context makes it difficult for sustainable materials to gain traction. Need stronger carbon pricing or clear performance advantages |
| Supplier 1 | End-of-Life and Recycling Challenges | "...I'd say recycling is definitely a challenge...we just grind them and then reuse them as a filler..." | Thermoplastics vs thermoset. "Sustainable by design" must account for disposal. |

## E7. List of SSbD Related answers

| SSbD Relevance | | | |
|---|---|---|---|
| **Stakeholder** | **Code** | **Quote** | **Insight** |
| Architect | SSbD | "... I think for me it is extremely important to check if it is, if it is us, if it is produced sustainably..." | Important for me to have a check it. |
| Façade Expert | SSbD Framework Application | "I think applying SSbD in façade innovation will lead to better products. It ensures you're not just chasing one metric..." | SSbD cultivates an innovation culture of "foresight and responsibility" in product design which is likely to become a hallmark of successful facade technologies. |
| Leafy | SSbD Framework Practicality (Bio-Based Context) | "... the steps are basically in the wrong order..." | For bio-based materials, this sequence should be adjusted: LCA, safety and then other aspects. |
| Leafy | SSbD | "… you should always focus on these things… even if it's like 0.1% (chance), you should still have an answer". | Employing the SSbD framework is seen as prudent – identifying potential issues (even if unlikely) early and addressing them as part of the design process. |

# Appendix F: Step 1 Scoring

This appendix outlines the sources and rationale used to classify materials in terms of physical, environmental and human health hazards, based on regulatory databases, safety data sheets and scientific reports.

## F1. Human Health Hazard Classification

| Hazard Group | Hazard Category | Epoxy Resin | Bio-Based Resin | Bamboo Fibre | LDPE | PP | EPDM | SS | Tricoya | Jute Cloth |
|---|---|---|---|---|---|---|---|---|---|---|
| H1 | Respiratory Sensitisation | Cat 1 | NC | Cat 1 (dust) | NC | NC | NC | NC | NC | Cat 1 (dust) |
| H2 | Skin Sensitisation | Cat 1 | NC | NC | NC | NC | NC | NC | NC | NC |
| H3 | Skin Corrosion/Irritation | NC | NC | NC | NC | NC | NC | NC | Cat 2 (adhesive) | NC |
| H3 | Eye Damage/Irritation | NC | NC | Cat 1 | NC | NC | NC | NC | Cat 2 | Cat 1 |
| H3 | Acute Toxicity Inhalation | NC | NC | NC | NC | NC | NC | NC | Cat 4 | NC |
| H1/H2 | STOT-RE | Cat 2 | NC | NC | NC | NC | NC | NC | NC | NC |
| H1/H2 | Carcinogenicity | Cat 2 | NC | NC | NC | NC | NC | NC | NC | NC |
| H1/H2 | Reproductive Toxicity | Cat 2 | NC | NC | NC | NC | NC | NC | NC | NC |
| H1/H2 | Endocrine Disruption (Human) | MISS | NC | NC | NC | NC | NC | NC | NC | NC |
| H3 | Acute Toxicity Dermal | NC | NC | NC | NC | NC | NC | NC | NC | NC |
| H3 | Acute Toxicity Oral | NC | NC | NC | NC | NC | NC | NC | NC | NC |
| H3 | Aspiration Hazard | NC | NC | NC | NC | NC | NC | NC | NC | NC |
| H1/H2/H3 | STOT-SE (Single exposure) | Cat 3 | NC | NC | NC | NC | NC | NC | NC | NC |

NC=not classified according to CLP
MISS=data missing
PBT= Persistent Bioaccumulative and Toxic
vPvB= very persistent and very bioaccumulative

POS=confirmed SVHC
NEG=no SVHC
PMT= Persistent Mobile and Toxic
vPvM= very persistent and very mobile

| Material | Hazard Classification(s) | Justification |
|---|---|---|
| Epoxy Resin (Conventional) | Respiratory & Skin Sensitisation, Carcinogenicity, STOT-RE | ECHA CLP DB, Araldite SDS. Strong evidence of chronic toxicity and irritation. |
| Bamboo Fibre, Jute Cloth | Respiratory Sensitisation, Eye/Skin Irritation, Dust Toxicity | ILO/NIOSH dust exposure studies. Sensitisation from airborne particles during machining; interview |
| Tricoya | Eye/Skin Irritation, Dust Inhalation | Tricoya SDS – or acelated MDF (Accsys); resin ahesives may irritate skin/eyes. Dust classed as nuisance dust. |
| LDPE, PP, EPDM | NC in GHS, fume hazard on heating | Polymer Hazard Reports (TURI); polymers are non-toxic in bulk but produce hazardous fumes on burning. |
| Bio-Based Resin | NC (data gap) | Assumed low hazard based on design intent. Data gaps exist; treated as precautionary. |
| SS | NC (bulk form); hazards if welded | ECHA; inert in use but may release metal dusts or fumes during machining, not included in base classification. |

## F2. Environmental Hazard Classification

| Hazard Category | Epoxy Resin | Bio-Based Resin | Bamboo Fibre | LDPE | PP | EPDM | SS | Tricoya | Jute Cloth |
|---|---|---|---|---|---|---|---|---|---|
| PBT/vPvB | POS | MISS | NC | POS | POS | POS | NC | MISS | NC |
| PMT/vPvM | MISS | MISS | NC | MISS | MISS | MISS | NC | MISS | NC |
| ED (environment) | POS | MISS | NC | MISS | MISS | MISS | NC | MISS | NC |
| Ozone Depletion | MISS | NC | NC | NC | NC | NC | NC | NC | NC |
| Chronic Aquatic Toxicity | POS | NC | NC | POS | POS | POS | NC | NC | NC |
| Acute Aquatic Toxicity | MISS | NC | NC | MISS | MISS | MISS | NC | NC | NC |
| SVHC Classification | POS | MISS | NEG | POS | POS | MISS | NEG | MISS | NEG |

| Material | Hazard Classification(s) | Source |
|---|---|---|
| Epoxy Resin (Conventional) | PBT/vPvB, Chronic Aquatic Toxicity, SVHC (POS) | ECHA Candidate List substances; epoxy oligomers like DGEBA are persistent, bioaccumulative and toxic. |
| Bio-Based Resin | NC / MISS | Not yet harmonised under REACH; assumed safer but flagged due to lack of full hazard characterization. |
| Bamboo Fibre, Jute Cloth | NC / NEG | Naturally degradable materials; low environmental persistence. Supported by IUCN biodegradation literature; interview |

| | | |
|---|---|---|
| LDPE, PP, EPDM | PBT/vPvB (POS), Aquatic Toxicity (POS) | REACH evaluations and polymer hazard reports (TURI). Known microplastic persistence in aquatic systems. |
| Tricoya | Environmental Hazard (MISS) | Accsys Tricoya SDS, No REACH registration; potential toxicity from resins remains unverified. |
| SS | NEG | ECHA: Non-hazardous alloy classification, Not bioaccumulative; stable in environmental conditions. Classified as non-hazardous under EU CLP for bulk alloy. |

## F3. Physical Hazard Classification

| Hazard Category | Epoxy Resin | Bio-Based Resin | Bamboo Fibre | LDPE | PP | EPDM | SS | Tricoya | Jute Cloth |
|---|---|---|---|---|---|---|---|---|---|
| Explosive | NC | NC | NC | NC | NC | NC | NC | NC | NC |
| Flammable | MISS | MISS | NC | Yes | Yes | Yes | NC | Yes | MISS |
| Aerosols | NC | NC | NC | NC | NC | NC | NC | NC | NC |
| Oxidising | NC | NC | NC | NC | NC | NC | NC | NC | NC |
| Gases under pressure | NC | NC | NC | MISS | MISS | MISS | NC | NC | NC |
| Self-reactive | MISS | NC | NC | NC | NC | NC | NC | NC | NC |
| Pyrophoric liquids | NC | NC | NC | NC | NC | NC | NC | NC | NC |
| Pyrophoric solids | NC | NC | NC | NC | NC | NC | NC | NC | NC |
| Self-heating | MISS | NC | NC | NC | NC | MISS | NC | NC | NC |
| Emits flammable gas | NC | NC | NC | NC | NC | NC | NC | NC | NC |
| Organic peroxides | MISS | NC | NC | NC | NC | NC | NC | NC | NC |
| Corrosivity | MISS | NC | NC | NC | NC | NC | NC | NC | NC |
| Desensitized explosives | MISS | MISS | NC | NC | NC | NC | NC | NC | NC |

| Material | Hazard Classification(s) | Source |
| --- | --- | --- |
| Epoxy Resin (Conventional) | Flammable, Self-reactive, Organic peroxides (MISS) | ECHA DGEBA-type resins; Araldite SDS. Epoxy monomers are known to release flammable vapors and can be exothermic. |
| Bio-Based Resin (Safer Alt) | Flammable (MISS), Desensitized Explosives (MISS) | Classification inferred from renewable thermosets; no ECHA listing. Risk assumed due to polymeric flammability unless proven otherwise. |
| Bamboo Fibre | Flammable, Dust Explosion Risk | ILO plant fibre guidelines; OSHA combustible dust directive. Dust from bamboo machining poses inhalation and fire risks. |
| LDPE, PP, EPDM | Flammable Solids | EU Risk Assessment Reports; NIOSH Pocket Guide; TURI polymer hazard summaries. These polymers combust under high heat, releasing toxic fumes. |
| Tricoya | Flammable Dust, Irritant | Accsys SDS for Tricoya; risks stem from acetylated wood + adhesive resins. |
| SS | Not Classified | ECHA REACH dossiers for metal alloys. Inert in bulk form; dust/fume generation during cutting is a process hazard, not intrinsic. |
| Jute Cloth | Flammable, Dust Hazard | ILO working paper on jute mill hazards; natural fibres pose combustion and dust inhalation risks. |

**Abbreviations Used:**

- PBT/vPvB:Persistent, Bioaccumulative Toxic / very Persistent and very Bioaccumulative
- SVHC: Substance of Very High Concern
- STOT-RE / STOT-SE: Specific Target Organ Toxicity – Repeated / Single Exposure
- MISS: Data Missing or Inconclusive
- NC: Not Classified
- NEG: Not Expected to be Hazardous

## F4. List of Criteria

| Criteria | Description | Observations |
| --- | --- | --- |
| H1: Most Harmful Substances (SVHCs) | Identifies whether any material contains substances of very high concern (SVHCs) under REACH Article 57. This is a cut-off criterion failure here may disqualify a material from SSbD unless justified. | - Bamboo  resin needs hazard class verification.<br>- No confirmed SVHCs yet but tests for formaldehyde, phthalates, halogens are needed.<br>- If SVHCs are present, substitute or redesign required. |
| H2:  Substances of Concern (CSS-listed hazard categories) | Materials classified under CSS as hazardous (but not SVHCs) are assessed here. A safety score may be applied depending on severity. | - Resin or coatings with flammability, sensitization, or ecotoxicity potential fall under H2.<br>- If hazard is moderate, proceed with risk-managed use and tracking. |
| H3: Other Hazard Classes | Covers all remaining hazard classes (e.g., persistent, bioaccumulative, endocrine disruptors) not captured in H1 or H2. | - Materials like bio-based fire retardants must be reviewed for additional chronic risks.<br>- Materials flagged under H3 require lifecycle monitoring or substitution if alternatives emerge. |

# Appendix G: Step 2 Scoring

This appendix provides justification for the Occupational Safety and Health (OSH) scoring of materials used in the Leafy Green Façade system, as presented in the Step 2 SSbD evaluation. Each score is based on available chemical safety data, occupational exposure profiles, physical handling characteristics and the effectiveness of risk management measures (RMMs).

## G1. Scoring Justification

| Material | Source | Reference Sources |
|---|---|---|
| Bamboo Fibre Composite | Moderate chemical hazard due to respiratory and skin sensitisation (Cat 1). Medium exposure frequency during cutting/sanding. Dusty physical properties. Open processing. Basic PPE and ventilation assumed. | ILO Fibre Dust Exposure Report, NIOSH Dust Hazard Guidelines |
| Tricoya | Chemical hazard from acetylated wood and adhesives (irritation). Moderate exposure during handling. Some dustiness. Indoor processing with localized ventilation. Moderate RMMs. | Accsys Tricoya SDS |
| Epoxy Resin (Conventional) | High hazard due to skin sensitisation, STOT-RE and carcinogenicity. Exposure likely during preparation and curing. Requires strict RMMs. Medium physical hazard due to fumes. | ECHA Epoxy Dossier, Araldite SDS |
| Biobased Resin | Low toxicity design but limited hazard data. Moderate exposure during application. Closed processes expected. Moderate dustiness and controlled RMMs. | Bio-based Thermoset Review, DOI:10.1016/j.indcrop.2019.111553 |
| LDPE | Very low chemical hazard. Occasional exposure during handling. Stable thermoplastic. Often processed in closed systems. Basic RMMs sufficient. | NIOSH LDPE Guide, TURI Polymer Reports |
| SS | No intrinsic hazard in bulk form. Minimal exposure unless machined. Inert, dust-free. Typically closed handling. No RMMs required. | ECHA Metals Alloy Database |
| PP | Inert thermoplastic. Very low exposure and stable physical properties. Typically safe under normal processing. Low flammability risk. | TURI Polymer Reports |
| EPDM | Chemically stable elastomer. Non-hazardous under typical conditions. Minimal exposure, closed processes. Non-reactive, non-volatile. | ECHA EPDM dossier, NIOSH Database |
| Jute Cloth | Moderate hazard from fibre dust. Frequent exposure during handling. Dusty. Some manual open processing. PPE and dust control are needed. | ILO Jute Hazard Report, NIOSH Fibre Studies |

## G2. List of Criteria

| Criteria | Description | Key Considerations |
|---|---|---|
| Chemical/Material Hazard | Based on GHS/CLP classifications | Carcinogenicity, mutagenicity, reproductive toxicity, sensitisation, STOT, etc. |
| Exposure Frequency & Duration | How often and how long workers are exposed to the material | One-time vs. repeated or continuous exposure during handling, processing, or maintenance |
| Physical & Chemical Properties | Characteristics influencing exposure risk | Volatility, dustiness, particle size, fugacity, reactivity, etc. |
| Process Conditions | Working environment and process configuration | Open vs. closed systems, indoor vs. outdoor, high-temperature processes, ventilation |
| Amount Handled | Typical mass or volume handled per operation | Small-scale lab handling vs. large-volume industrial mixing or extrusion |
| Risk Management Measures (RMMs) | Degree of control implemented to reduce worker exposure | Use of LEV (Local Exhaust Ventilation), PPE, automation, containment systems |
| Potential Exposure Routes | Pathways by which workers might be exposed | Inhalation (dust, vapours), dermal contact (splashes), ingestion (cross-contamination, hand-to-mouth) |

# Appendix H: Step 3 Scoring

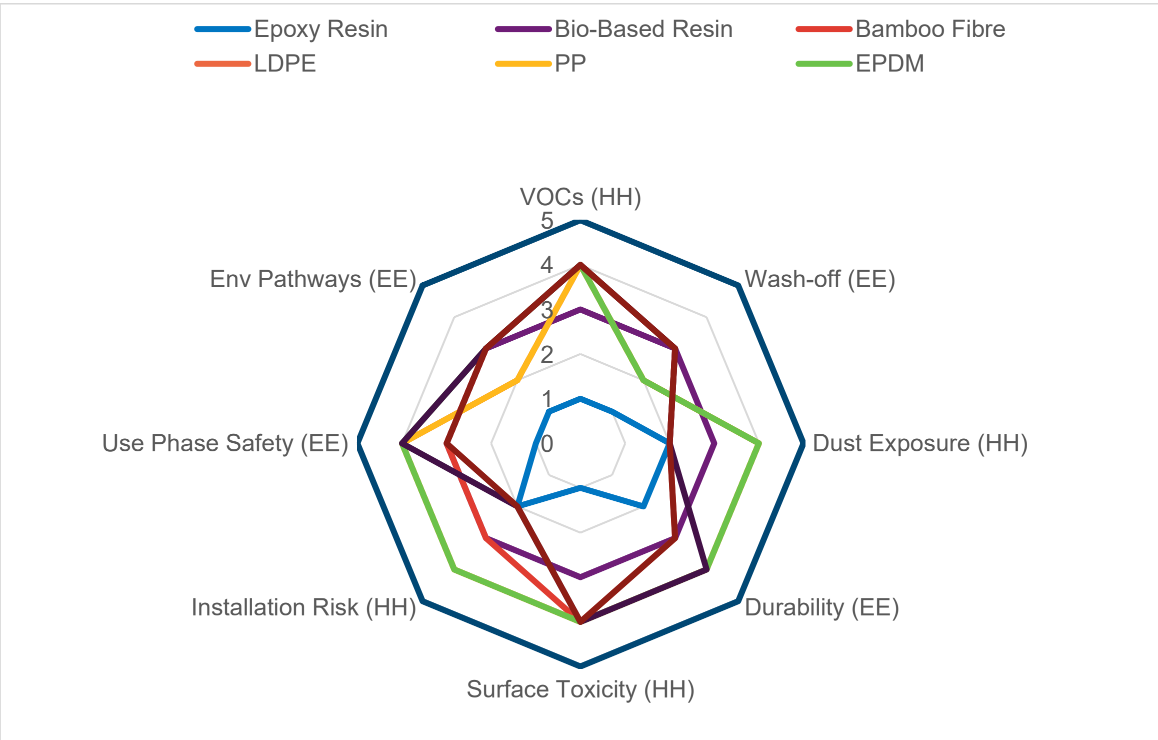
This appendix provides justifications and supporting references for the scoring assigned to each material under the Step 3 Application Phase Risk Assessment. Scores were based on known material properties, scientific literature, safety datasheets and environmental databases.

| Criteria | Epoxy Resin | Bio-Based Resin | Bamboo Fibre | LDPE | PP | EPDM | SS | Tricoya | Jute Cloth |
|---|---|---|---|---|---|---|---|---|---|
| VOCs (HH) | 0 | 2 | 3 | 3 | 3 | 3 | 3 | 2 | 3 |
| Wash-off (EE) | 0 | 2 | 2 | 1 | 1 | 1 | 3 | 2 | 2 |
| Dust Exposure (HH) | 1 | 2 | 3 | 3 | 3 | 3 | 3 | 2 | 2 |
| Durability (EE) | 1 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 2 |
| Surface Toxicity (HH) | 0 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| Installation Risk (HH) | 1 | 2 | 2 | 3 | 3 | 3 | 3 | 1 | 2 |
| Use Phase Safety (EE) | 1 | 2 | 3 | 3 | 3 | 3 | 3 | 1 | 2 |
| Env Pathways (EE) | 0 | 2 | 2 | 1 | 1 | 1 | 3 | 2 | 2 |

## H1. Scoring Justification

| Material | Criterion | Score Justification | Reference Source |
|---|---|---|---|
| Epoxy Resin | VOCs (HH) | High VOC emissions during mixing and curing. | ECHA Substance Info, Araldite SDS |
| | Wash-off (EE) | Degradation products can leach into water. | REACH Dossier, Huntsman Literature |
| | Installation Risk (HH) | Requires gloves, mask and proper ventilation. | Huntsman SDS |
| Bio-Based Resin | Use Phase Safety (EE) | Formulation-dependent; generally low off-gassing. | DOI:10.1016/j.indcrop.2019.111553 |
| | Env Pathways (EE) | Biodegradable with limited environmental persistence. | Green Chemistry Journal |
| Bamboo Fibre | Dust Exposure (HH) | Sawdust and fine particles can pose inhalation risk. | ILO Bamboo Sector Safety Guide |
| LDPE | Durability (EE) | Highly weather-resistant and chemically stable. | NIOSH Material Guide |

| | | | |
|---|---|---|---|
| | Env Pathways (EE) | Can degrade into microplastics under mechanical stress. | UNEP Plastics Report 2021 |
| PP | Surface Toxicity (HH) | Non-toxic, widely used in food-safe applications. | TURI Polymer Hazard Evaluation |
| EPDM | Use Phase Safety (EE) | Low emissions and excellent UV/weather resistance. | RAC Opinion Document on EPDM |
| SS | All Criteria | Inert, no emissions, no dust, no degradation products. | ECHA Metal Alloys Risk Assessment |
| Tricoya | VOCs (HH) | Low VOC profile due to acetylation process. | Accsys Tricoya SDS |
| | Dust Exposure (HH) | Fine dust during sawing may require extraction. | Manufacturer Handling Guide |
| Jute Cloth | Wash-off Potential (EE) | Naturally biodegradable, minor runoff possible. | ILO Jute Fibre Report |
| | Installation Risk (HH) | Fibres may cause mild respiratory irritation during install. | FAO Natural Fibre Study |



# Appendix I: Step 4 Scoring

This appendix explains critical impact categories and the justification for it.

| Material | Toxicity | Climate (GWP) | Pollution | Resource | Overall | Critical |
|---|---|---|---|---|---|---|
| Epoxy resin | 1 (toxic monomers) | 1 (5–9 $kgCO_2/kg$) | 1 (solvent/VOC emissions) | 0 (fossil feedstock) | 0 | Resource & toxicity (BPA) |
| Bamboo fiber | 3 (natural) | 3 (net negative) | 3 (minor fuel use) | 3 (renewable) | 4 | Climate (biogenic storage) |
| LDPE | 2 (polymer) | 2 (1.93 $kgCO_2/kg$) | 2 (fuel/aux) | 1 (fossil) | 2 | Climate & resource (fossil fuel) |
| PP | 2 (polymer) | 2 (1.55 $kgCO_2/kg$) | 2 (fuel/aux) | 1 (fossil) | 2 | Climate & resource |
| EPDM | 2 (inert rubber) | 1 (≈7 $kgCO_2/m^2$) | 2 (fuel use) | 1 (petro) | 2 | Climate (fossil processing) |
| SS | 2 (manufact. emissions) | 1 (≈54 $kgCO_2/m^2$) | 1 (high SOx/NOx) | 0 (energy-intensive) | 0–1 | Resource use & pollution |
| Tricoya wood | 2 (MDI resin) | 2 (wood+process) | 2 (manufacturing) | 2 (part-wood) | 3 | Resource use (MDI, acetic acid) |
| Jute cloth | 3 (natural) | 3 (low/neutral) | 3 (minimal runoff) | 3 (renewable) | 4 | N/A (overall very low impact) |

# Appendix J: Arbo: Risk Inventory & Evaluation Plan (RI&E)

| Category | Requirement / Guideline |
|---|---|
| PPE (Personal Protective Equipment) | Must be provided free by employer; Must be CE-marked and suitable for identified risks; Proper training and maintenance required |
| Manual Handling – General Limits | Max 23 kg under optimal conditions; >12 lifts/day: max 12 kg; Use MAC/NIOSH tool for 3–25 kg repetitive lifts |
| Façade Panel Handling Limits | Max 50 kg per person manually; Panels >100 kg require mechanical lifting; Over 50 kg: redesign for crane/hoist installation |
| Fall Protection (work >2.5 m) | Mandatory use of: Guardrails, Scaffolding (certified), Fall arrest systems (EN 361 harness, lifelines, anchors) |
| Aerial Work Platforms (AWP) | Must have CE mark and recent inspection; Cannot drive extended or under wind >6 Beaufort; No internal floor risers or standing on railings |
| Edge Protection | Guardrails, edge barriers, or safety nets required where fall risk exists |
| Lifting Aids | Use trolleys, forklifts, cranes, or tail lifts for anything approaching weight limits; Must be pre-inspected and operated by trained personnel |
| PPE – Required Types | Safety boots (steel toe); High-vis vest; Hard hat; Eye protection; Gloves; Fall-arrest gear; FFP2 dust mask for fibers |
| Workplace Ergonomics | Keep loads at hip height; Rotate panels with 2 people; Schedule rest breaks; Mandatory training on lifting technique |
| Risk Inventory & Evaluation (RI&E) | Must cover: Lifting risks, Height work, Ergonomic strain, Chemical/fiber exposure |
| V&G-Plan (Construction Safety Plan) | Mandatory for façade works on construction sites; Must outline work phases, risks, protective measures |
| Working Hours Act (Arbeidstijdenwet) | Rest breaks and work-hour limits must be enforced for physical work |
| ATEX (Explosion Risk) | Evaluate if vapors/dusts from coatings or adhesives present risk; Zone classification and mitigation if required |

By completing the questionnaire, a Risk Inventory is made. Based on this, a Plan of Action is drawn. This Plan of Action can be discussed annually on progress and this can be written down. Topics have been dealt with and new topics may be added. When discussing progress, also include the possible causes of accidents and the possible causes of absenteeism. You may want to give these causes priority and they influence the topics you will tackle in the coming year. It is useful to have the drawing up of a Plan of Action or the discussion on progress coincide with the drawing up of the annual budget. By combining topics from the Plan of Action with investments, these can often be resolved without additional money.

# Plan of approach

## 2 Screen work

### 2.4 Employees are aware of the risks of working with a screen.

*This risk is not present, but since it is a top-5 risk, it is included here.*
*This is a high risk category.*

Employees who work with a screen must be familiar with how to do this safely, including setting up the workplace correctly and what to do if there is a suspicion that physical complaints in the neck, back, arms or wrists are caused by the work. For more information, seeeducation about healthy behavior in the workplace.

### 2.5 A screen worker is not entitled to an eye examination.

*This risk exists.*
*This is a low risk category.*

An employee who is going to work with a screen for the first time is entitled to an eye examination. This eye examination must be repeated at regular intervals. This examination may show that screen glasses are necessary. The employer is obliged, after a positive recommendation from the company doctor, to reimburse these screen glasses.

## 3 Work pressure, working atmosphere, working hours

### 3.9 The employees have received information about measures against work pressure and undesirable behavior.

*This risk is not present, but since it is a top-5 risk, it is included here.*
*This is a high risk category.*

It is necessary that employees are aware of how to deal with work pressure, the rules to prevent undesirable behavior and the agreements on working and rest times. For more information, seeemployee information, work pressure and undesirable conductmen

## 4 Physical strain

### 4.3 Heavy lifting, pushing or pulling occurs.

*This risk exists.*
*This is a high risk category.*

The maximum limit for lifting is 23 kg. It may be that a smaller weight is already too heavy, for example if it is a large package that has to be moved or if someone has to carry light items all day long. The maximum weight is also lower if an employee has to bend over or turn the body while lifting.

There are no legally established standards for pushing and pulling loads. There are guidelines, for more information see theKIM guideline.

### 4.6 Activities are not free from vibrations and shocks.

*This risk exists.*
*This is a high risk category.*

Vibrations or shocks can come from vibrating or bumping tools or machines such as forklifts. This can lead to back pain or motion sickness, among other things.

### 4.7 The employees have received information about the measures

**against heavy physical work.**

*This risk is not present, but since it is a top-5 risk, it is included here.*
*This is a high risk category.*

Employees who perform physical work must be familiar with how to do this safely and how to use the necessary tools. For more information, seethe Arboportaal.

## 5 Noise

### 5.1 We have taken measures to work without noise or with less noise.

*This risk is not present, but since it is a top-5 risk, it is included here.*
*This is a high risk category.*

An employer can take various measures to reduce noise in the workplace, for example:

- purchase and use of quieter machines
- developing quieter production methods
- placing machines in soundproof cabinets
- have staff work in soundproof booths
- good maintenance of equipment
- limit exposure time as much as possible

### 5.2 Hearing protection is used.

*This risk is not present, but since it is a top-5 risk, it is included here.*
*This is a high risk category.*

If despite measures the noise is still louder than 80 dB(A), then hearing protection must be available to employees. If the noise is louder than 85 dB(A), then employees must wear thehearing protectionlegally required to wear.

### 5.3 The employees have received information about the measures to be taken against noise.

*This risk is not present, but since it is a top-5 risk, it is included here.*
*This is a high risk category.*

Employees exposed to noise are familiar with the effects of noise and know what personal hearing protection to use.

## 6 Hazardous substances

### 6.5 We always leave hazardous substances in their original packaging and the packaging is clearly labelled.

*This risk is not present, but since it is a top-5 risk, it is included here.*
*This is a high risk category.*

It is important to easily recognize a hazardous substance. You can see this on the original packaging of your products. Products that contain hazardous substances have a so-called Safety Information Sheet that describes how to work with them safely.

### 6.6 The hazardous substances present are stored in a safe manner.

*This is a high risk category.*

Make use of the guidelinePublication series Dangerous Substances 15 (PGS-15)if you have stored more than 25 litres or kilos of hazardous substances in packaging (cans, barrels, tins, etc.) in your company, for example flammable substances. This PGS-15 may be mandatory prescribed in the

*This is a high risk category.*

A device has a safety device for a reason. Its use is mandatory. Not using a safety device can easily lead to accidents.

The machine is shielded from rotating parts and from very high or very low temperatures to prevent injury.

### 7.4 Machines are equipped with an emergency stop and the emergency stop is within easy reach.

*This risk is not present, but since it is a top-5 risk, it is included here.*
*This is a high risk category.*

Machines and equipment must be easy to switch off in an emergency.

### 7.5 The employees are sufficiently instructed in how to use machines and tools.

*This risk is not present, but since it is a top-5 risk, it is included here.*
*This is a high risk category.*

Instructions and safe behavior are necessary to avoid accidents with machines and devices as much as possible. For more information, seeWorking safely with machines.Before we start work, we check that the equipment does not pose any danger and that the electrical connection is not defective.

## 8 Falling, slipping and suffocating

### 8.1 Working at heights is carried out safely.

*This risk is not present, but since it is a top-5 risk, it is included here.*
*This is a high risk category.*

There are safe stairs or ladders. There is no danger of falling from a height such as roofs, floor openings or landings without fencing. Measures have been taken to prevent falls. Measures are legally required for a height difference of 2.5 m or more. More information aboutworking at height.

### 8.4 Before entering confined spaces, pits or trenches, we are certain that it is safe and that we have taken all necessary precautions.

*This risk is not present, but since it is a top-5 risk, it is included here.*
*This is a high risk category.*

There must be sufficient oxygen in a room and there must be no chance of an explosive gas mixture forming. More information aboutan explosive atmosphereand aboutchoking hazard.

### 8.5 Dangerous work is carried out by two persons.

*This risk is not present, but since it is a top-5 risk, it is included here.*
*This is a high risk category.*

Should anything happen, there is always someone present who can offer or call for help. More information aboutworking alone.

### 8.6 The employees have received information about measures against specific risks.

*This risk is not present, but since it is a top-5 risk, it is included here.*
*This is a high risk category.*

Employees must be familiar with solutions for working at heights and working in confined spaces.

# 9 Tidy workplace and assistance

## 9.7 The employees have been informed about company emergency response.

*This risk is not present, but since it is a top-5 risk, it is included here.*
*This is a high risk category.*

There must be clear rules on how to act in case of fire or accident. Everyone is well informed about the escape routes so that the building can be left quickly. The employees must be familiar with the rules on what to do in case of fire, evacuation and life-saving actions.

# 11 Occupational health and safety

## 11.1 You do not seek assistance by means of a so-called basic contract from a BIG registered company doctor/certified expert or a certified occupational health and safety service.

*This risk exists.*
*This is a low risk category.*

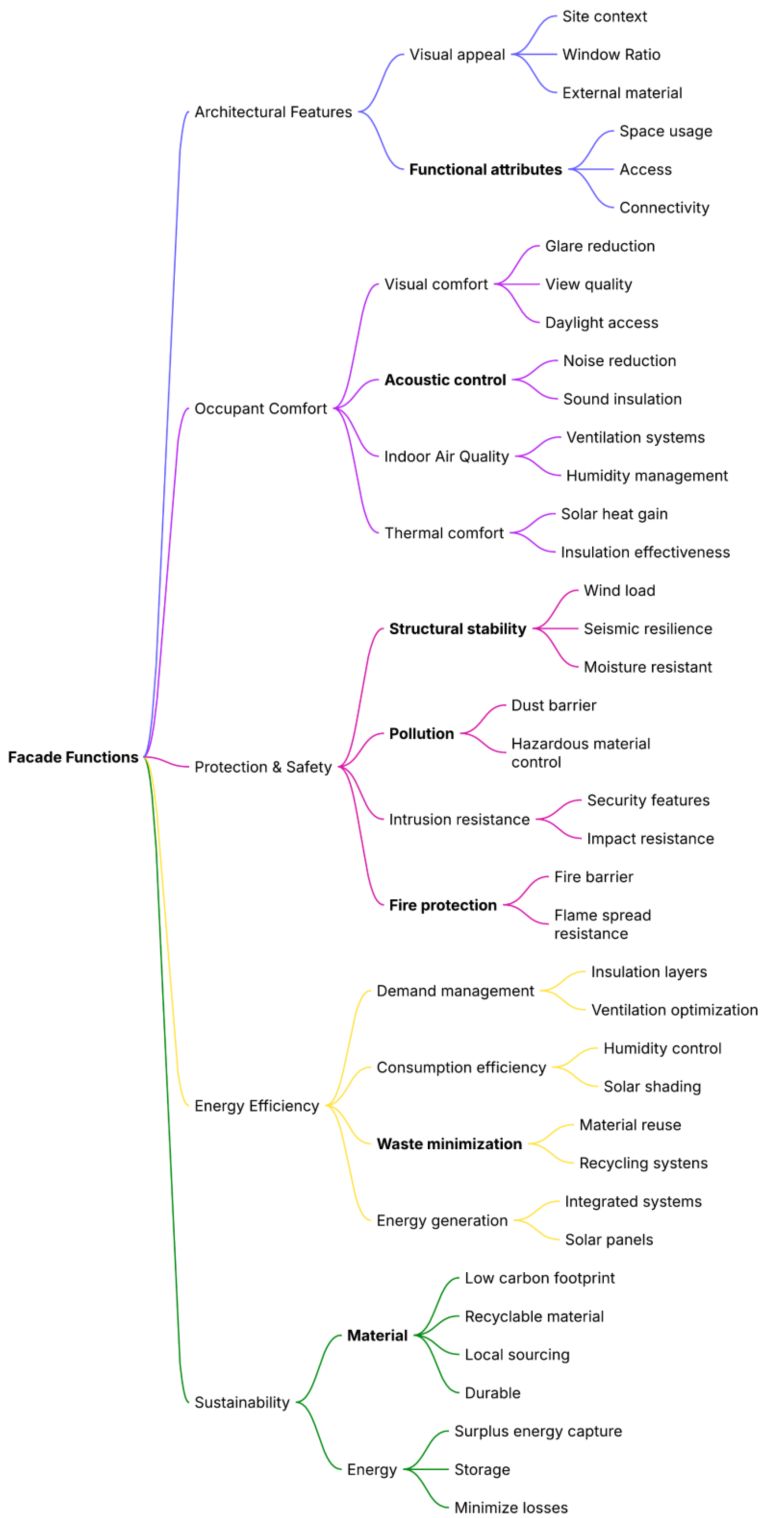
According to the Working Conditions Act, you are required to seek expert support for your occupational health and safety and absenteeism policy. Companies can opt for a contract with an occupational health and safety service (the so-called safety net scheme) or for the use of an occupational health and safety expert (a customised scheme). With the customised scheme, the employer determines how and with whom he arranges the prevention and guidance of absenteeism due to illness. However, the company must have a contractual agreement with at least one BIG-registered company doctor and must continue to adhere to the statutory guidelines for prevention and absenteeism.

**NB!**You can only opt for a customised scheme if you agree with your employees. For example, via a written agreement in the collective labour agreement, with the Works Council or the Employee Representation (PVT). If you do not agree, you will automatically enter the safety net scheme and keep the existing contract with the occupational health and safety service. With both the customised and the safety net scheme, you must always seek support for:

- assessment of the Risk Inventory and Evaluation (RI&E) including the action plan;
- sickness absence management;
- periodic occupational health examination (PAGO);
- appointment examinations
- occupational health and safety consultation hours.

For more information about the basic contract, see:the Arboportaal.

# Appendix K: Functional Components and Key Performance Aspects of the Building Envelope



# Appendix L: Façade Installation

## L1. Installation Stages

| Step | Action |
|---|---|
| 1. Pre-Installation | • Review drawings and ensure permits under Omgevingswet are approved.<br>• Conduct risk inventory (RI&E): working at height, chemical safety (adhesives), lifting risk. |
| 2. Material Preparation | • Inspect battens and panels for deformation or damage, use only CE marked parts.<br>• Pre-drill battens and panels if required.<br>• Leafy's click-on/click-off mounting system enables adhesive-free, easy installation and replacement, supporting rapid assembly and circularity. |
| 3. On-site Work | • Set up scaffolding or aerial platform with valid CE and annual inspection.<br>• Fall protection for height >2.5 m.<br>• Mark safe access paths and lifting zones. |
| 4. Panel Installation | • Install impregnated battens vertically with RVS hammer plugs or substrate-specific anchors.<br>• Mount Leafy's rear panel with SS screws, 2 mm expansion gap.<br>• Check level and spacing every 3–5 panels.<br>• Fix side/front panels with same system or approved Trespa screws. |
| 5. Post-Installation | • Attach irrigation and drainage lines using LDPE pipe clamps<br>• Install EPDM seals on perimeter, check for leaks.<br>• Perform torque check on fixings.<br>• Submit photo documentation and safety inspection log. |

## L2. Wooden vs Metal Substructure

| Aspect | Wooden Battens | Metal Battens |
|---|---|---|
| Permit/Substrate | Use pressure-treated, pre-dried wood, suitable for exterior (Use Class 3.2) | CE-marked metal brackets and rails; CE-approved anchors to supporting walls |
| Durability & Corrosion | Susceptible to rot unless properly treated | High durability; resistant to corrosion and ideal for masonry/concrete mounting |
| Fire Performance | Timber must meet fire-safety requirements; may need additional fire barriers in buildings >13 m | Often required above 13 m building height to achieve Euroclass B-s1,d0 façades |
| Maximum Height | Typically, suitable up to mid-rise buildings; above 13 m, metal preferred for fire compliance | Suitable for façades of any height, especially above 13 m, due to steel's load-bearing and fire properties |
| Design Configurations | Single or double battens for ventilated rainscreen façades; spacing 16–24″ (400–600 mm) | Similar spacing supported; supports heavier panels and higher wind loads |
| Venting & Drainage | Wood should have 15° slope and ≥¾″ (20 mm) ventilation cavity | Gaps and slopes are similarly required; membranes should be UV-resistant |

## L3. Façade Panel Installation By Wall Type

| Wall | Anchoring Method | Load Considerations | Thermal Performance | Moisture Management | Design Notes |
|---|---|---|---|---|---|
| Brick | Expansion bolts or chemical anchors into brick/mortar joints; sub-frame distributes loads | Can support significant weight; ensure proper spacing and embedment to avoid cracking | Risk of thermal bridging through anchors; use thermally broken ties or low-conductivity anchors | Ventilated air gap prevents moisture buildup; flashing and weep holes critical | Efflorescence and freeze-thaw damage risks; rainscreen design preferred |
| Timber-Frame | Screws or bolts through cladding into studs or sheathing; use washers/plates to distribute load | Limited load-bearing; use lightweight panels and align fasteners with structural members | Improved with added insulation; avoid thermal bridging through studs using furring strips | Critical to protect wood from rot; use WRB, ventilated gap and allow movement in attachments | Use slotted holes for movement; furring strips and WRB enhance durability |
| Concrete | Expansion anchors, undercut anchors, or concrete screws; can support heavy cladding | High load capacity; dense and rigid structure handles heavy panels well | Good thermal inertia; maintain performance using thermally broken brackets and continuous insulation | Less sensitive to moisture; ventilated cavity and sealing around anchors protect from long-term damage | Sealants and gaskets at penetrations; pressure-equalized rainscreen ideal |
| Asbestos | Anchoring not recommended due to health risks; avoid mechanical disturbance | Generally unsuitable for added loads; material is brittle and hazardous when disturbed | Historically used for thermal insulation but now obsolete; no further enhancements recommended | May resist moisture but degradation and safety risks outweigh benefits | Facade panel installation not advised; asbestos should be professionally removed or encapsulated |

# Appendix M: Relative Toxicity Ranking

| Substance | Relative Hazard Rank | Key Health Risks | Environmental Concerns | Regulatory Notes (EU/Intl) | Relevance to Building Materials |
|---|---|---|---|---|---|
| Cyanide | 1 (Highest) | Extremely high acute toxicity (GHS Cat. 1); fatal via ingestion, inhalation, skin contact | Highly toxic to aquatic life at microgram levels; not persistent | Strictly controlled under EU REACH; severe use restrictions | Rarely used; potential in some metal surface treatments, but avoided in modern façade materials |
| PFAS | 2 | Chronic toxicity; some carcinogenic (IARC Group 1); reproductive toxins (H360) | Extreme persistence ("forever chemicals"); bioaccumulative; global distribution | Increasing EU restrictions; proposed phase-out under REACH | Used in surface coatings, sealants and weatherproofing treatments; potential substitution challenge for water/oil repellency |
| Furan Compounds | 3 | Moderate acute toxicity (GHS Cat. 3 inhalation); suspected carcinogens (IARC Group 2B) | Limited persistence; localised contamination risk | Occupational exposure limits; regulated in resin production | Found in some biobased resins (furfuryl alcohol-based) for composites; potential in sustainable panels but with worker safety considerations |
| Epoxy Resin | 4 (Lowest) | Irritant, skin sensitizer; toxic to aquatic life; cured form not carcinogenic; precursors (e.g., epichlorohydrin) probable carcinogens (IARC 2A) | Moderate persistence; mainly local aquatic toxicity | REACH classification for precursors; safe handling protocols required | Widely used in adhesives, coatings and composites for high durability; common in façade panels for structural integrity |