Research Article/ Review Article/ Perspective Article (Remove where relevant)

Digital Landscape Information Management (DLIM): Integrating BIM and Nature-Based Solutions for Net-Zero, Smart and Sustainable Urban Greenscapes

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Abstract

The push toward net-zero carbon cities has placed unprecedented demands on the performance of green infrastructure. Yet, landscape architects continue to work with fragmented datasets and coordination methods that haven't fundamentally changed in decades. BIM revolutionised how we design buildings, but where is the equivalent transformation for landscapes? This research examines Digital Landscape Information Management (DLIM) as a landscape-centric evolution of BIM principles, specifically tailored to integrate Nature-Based Solutions into the planning and management of urban greenscapes. A convergent mixed-methods approach has been employed to understand this gap. First, literature spanning 1996-2025 revealed persistent disconnects between BIM capabilities and landscape needs. Eight UK practitioners then provided candid insights through semi-structured interviews about the realities of current practice, whilst 45 professionals (evenly split between architects and landscape/BIM specialists) completed an online survey. When triangulated, these datasets pointed toward clear patterns in both opportunities and obstacles. The findings were striking: 82% of practitioners identified environmental performance as their primary design driver, yet most admitted lacking the tools to properly quantify it. Interviewees repeatedly stressed that interoperability remains "the elephant in the room," alongside concerns about deskilling younger designers. Our proposed DLIM framework addresses these tensions through four integrated stages: context capture, parametric authoring, performance analytics, and lifecycle handover. Crucially, this sits atop a standards-compliant landscape database that finally bridges vegetation, soil, and hydrological data with IFC-compatible geometries. DLIM represents more than technical advancement; it's about giving landscape architects the digital vocabulary to participate equally in tomorrow's smart cities. [Abstract, Keywords Aptos, 9]

Keywords: keyword 1; keyword 2; keyword 3 (Provide a minimum of 4 and up to 8 keywords that encapsulate the main topics of the manuscript.)

Highlights

- Cities seeking to achieve net-zero carbon by 2050 increasingly depend on high-performance green infrastructure; however, digital support for landscape design still lags behind building practice. Building Information Modelling (BIM) dominates architecture and engineering, but its landscape counterpart, Digital Landscape Information Management (DLIM), remains in its embryonic stage. This study, therefore, asks: How can DLIM, conceived as a landscape-specific evolution of BIM and aligned with Nature-Based Solutions (NBS), enhance the design, delivery and long-term performance of sustainable urban greenscapes?

1 Section 1- Introduction

Urban greenscapes, including parks, gardens, street plantings, and other vegetated open spaces, play a pivotal role in sustainable and resilient cities. They provide ecosystem services, including carbon sequestration, urban heat mitigation, biodiversity habitats, and improved public health and well-being (Liu, Zhang and Wang, 2025). Indeed, urban green spaces are seen as vital assets for climate change mitigation, capable of absorbing atmospheric CO_2 and contributing to cities' net-zero carbon goals. Concurrently, the rise of smart city initiatives has spurred interest in smart green spaces that leverage digital technologies (sensors, IoT, data analytics) to enhance management efficiency, user experience, and climate resilience in parks and landscapes. These trends underscore the need for advanced digital frameworks to plan, design, and manage urban greenscapes in line with sustainability and smart city objectives.

Human history has consistently drawn inspiration from nature's biodiversity, ecosystems, and landscapes, influencing art, culture, and scientific progress. Well-designed urban green spaces, featuring trees, offer tranquillity, educational value, and aesthetic appeal, potentially enhancing overall health and well-being (Scholz, 2016). Creating sustainable communities requires planners to focus on preserving the landscape's structure and functions, safeguarding environmental processes, and maintaining productivity for future generations, with additional attention to ecological integrity over economic gains (Grant, Manuel, and Joudrey, 1996).

One such innovation is Building Information Modelling (BIM) which is a digital process for collaborative design, construction, and operation that is widely adopted in architecture and engineering. BIM creates detailed 3D models enriched with information, establishing a shared knowledge resource that supports a facility throughout its life cycle (Saputra, Lai and Nafeed, 2024). This approach has enabled improved stakeholder collaboration and real-time data exchange, leading to smoother design processes and better project outcomes. As a result, BIM has become a de facto standard for efficient building and infrastructure delivery. However, Although BIM was not initially developed for landscape architecture, it has made landscape and infrastructure projects more interconnected through tools like Autodesk Revit and Industry Foundation Classes (IFC), enabling the creation and sharing of BIM models for both building and diverse landscape elements (Fritsch, Clemen, and Kaden, 2019).

The insufficient focus on landscape design within existing BIM advancements and integrated design-construction approaches results in challenges, such as the difficulty in managing landscape information in BIM, inefficient operations, and expensive knowledge development and exchange, indicating the requirement for more developed standards and platforms supporting Landscape Information Modelling (LIM) in BIM (Abdirad and Lin, 2015) As shown in the Figure 1, LIM is an evolving technology in the field of BIM, that provides benefits like standardised landscape design knowledge and improved information exchange among various fields in the project; however, its full potential is not yet widely embraced by landscape designers and land development sectors (Borkowski and Wyszomirski, 2021).

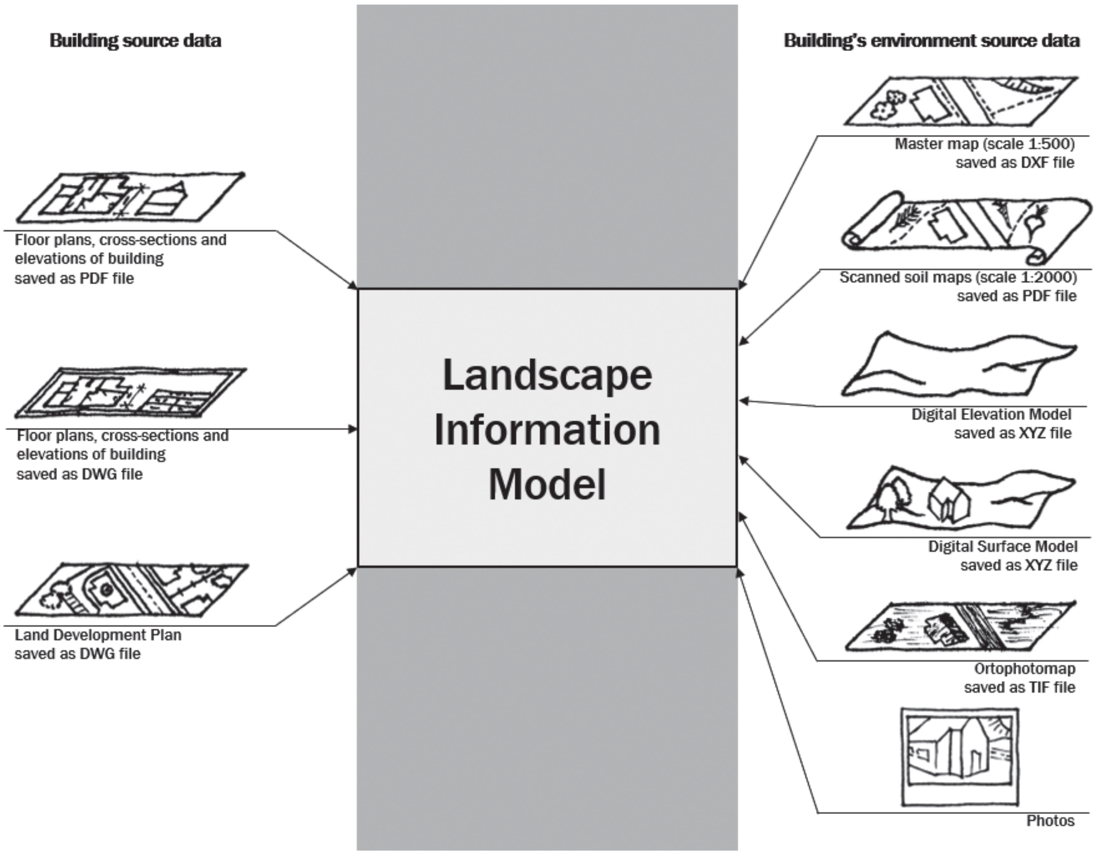

Figure 1: Diagram illustrating the input data for the LIM (Borkowski and Wyszomirski, 2021).

The integration of LIM within BIM enhances the understanding of planned projects and introduces new opportunities for landscape simulations (Fritsch, Clemen,and Kaden, 2019). The availability of an information model for landscape would facilitate seamless integration between landscape, architecture and urban design by enabling the exchange of information models, which is beneficial when considering the inherent connection of landscape design to various aspects of urban structures (Zajíčková and Achten, 2013).

Aim and Scope: In response to the above gaps, this paper aims to explore and establish Digital Landscape Information Management (DLIM) modelling as a framework for smart and sustainable urban greenscapes. We aim to explore how BIM-related digital practices can be applied to landscape architecture to support Nature-based Solutions (NBS) implementation and achieve holistic sustainability goals. The study develops a four-stage DLIM framework that integrates data on landscape ecology and sustainability into BIM processes, enabling enhanced simulation, collaboration, and information management for urban green infrastructure. By aligning landscape design with BIM, the framework addresses the need for a coordinated approach where buildings and site interventions are planned in unison to maximise environmental benefits. The research is grounded in an extensive review of past work and insights from professionals, ensuring both theoretical foundation and practical relevance. In the following sections, the research methodology will be outlined, presenting key findings on the current state and needs of digital landscape practice, proposing the DLIM framework, and discussing its implications for the smart, sustainable built environment.

2 Literature review

This section explores the intersection of landscape architecture's digitalisation and BIM, examining transformative digital technologies in the Architecture, Engineering, and Construction (AEC) industry. It focuses on BIM's role in as-built modelling, knowledge capture, and integration with parametric modelling in LIM. The review addresses digital landscape sustainability, data management tools, and evolving visualisation techniques while highlighting challenges and opportunities in bridging BIM and landscape architecture.

AEC's focus on sustainability arises from environmental concerns, aiming to fulfil present requirements without compromising the well-being of future generations (Yates and Castro-Lacouture, 2018). The growth in landscape sustainability research from the early 2000s incorporates landscape ecology, ecological economics, and sustainability science, focusing not only on ecological and practical aspects but also social, cultural, and theoretical dimensions, with key concepts like ''sustainable landscape'' and ''landscape sustainability'' (Figure 2), demanding a clear sustainability perspective, scale consideration, and a transdisciplinary approach to address unsustainability issues (Zhou, Wu and Anderies, 2019). [Text (Body)-ABC2, Aptos, 11]

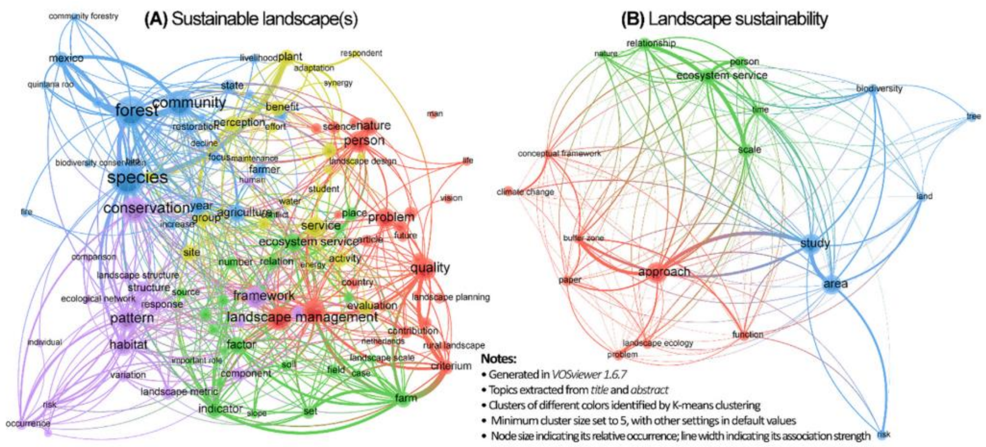

Figure 1: The different key elements of (A) Sustainable Landscape & and (B) Landscape Sustainability (Zhou, Wu and Anderies, 2019).

Advancing sustainable landscape design requires deeper engagement with digital tools, like BIM offering a promising avenue for assessing eco-friendly criteria, even though needing improved connections to analysis software, and the refurbishing of spaces for social sustainability demands innovative procurement strategies, emphasising the crucial role of embracing digital tools at every stage to unlock their full potential in landscape and urban design for sustainability (Borkowski and Łuczkiewicz, 2023). BIM enhances scientific planning and design, facilitating efficient collaboration among designers, constructors, and managers in sustainable landscape planning, with a primary focus on ecological protection (Han et al., 2023). The Sustainable Sites rating system encourages environmentally friendly design through credits earned for responsible decisions in water usage, soil conservation, and construction practices. LIM enhances this process by automatically adjusting these credits throughout the design evolution, facilitating compliance with the Sustainable Sites initiative (Nessel, 2013). Globally, incorporating BIM into landscape and environmental planning faces significant challenges, given the variations in methods and professional regulations worldwide; however, BIM plays a vital role in improving sustainability aspects throughout the entire lifecycle, demanding necessary digital responsibilities for Geographic Information System (GIS) and interdisciplinary cooperation (Gnädinger, 2023).

2.1 Digitalisation in AEC

The AEC industry is undergoing a profound transformation through digitalisation, with BIM emerging as a central tool for enhancing project lifecycle efficiency and collaboration. However, its application in Landscape Architecture is still limited. The implementation of digitalisation in the AEC industry involves automated regulatory compliance checking, applicable in construction, health and safety, and landscape quality assessment, with the utilisation of autonomous mobile scanning systems for building digitalisation and demanding considerable investments for its implementation (Reis et al., 2020) (Fernández-Alvarado and Fernández-Rodríguez, 2022). Throughout the BIM life cycle, various aspects, including open spaces, landscape, building, and construction operations, can be focused on, covering the incorporation of innovative digital technologies and planning tools across the entire BIM process chain, as shown in Figure 3 (Brückner, Haverland, and Halbrügge, 2022).

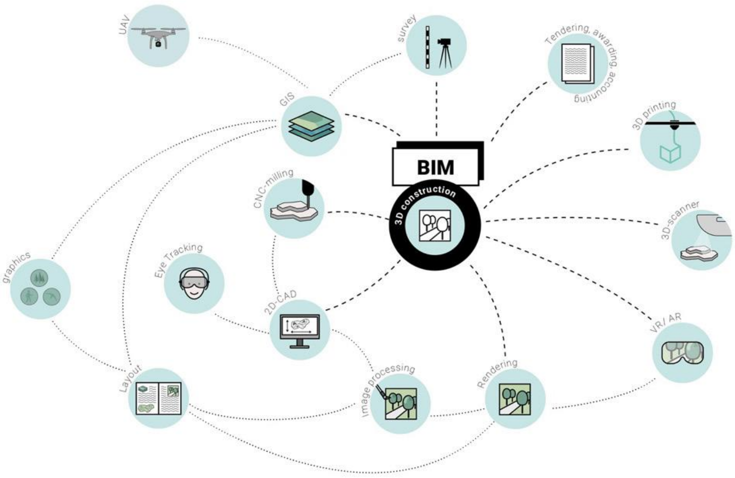

Figure 2: BIM process chain - Digital technologies and planning tools (Brückner, Haverland and Halbrügge, 2022)(Brückner, Haverland and Halbrügge, 2022)

Currently, BIM tools are gaining more acceptance in the AEC sector, facilitating comprehensive modelling of both structures and processes. Architects use them to simulate indoor environment quality factors, and engineers use them to analyse the performance of various infrastructure components under simulated conditions (Nessel, 2013). BIM incorporates project data throughout the entire AEC project lifecycle, providing standardised and dynamically updated 3D models, which result in advantages such as asset management, collaborative work, and diverse applications extending beyond design to link workload calculations and construction simulation (Xian and Zhang, 2021). Moreover, BIM models, as object-based and data-rich representations of a project, function as a centralised storehouse for design and construction information, serving as effective platforms to capture, store, and disseminate knowledge throughout the project lifecycle, thus preventing data loss due to time constraints (Deshpande, Azhar and Amireddy, 2014).

Furthermore, the AEC industry is being revolutionised by BIM and Virtual Design and Construction (VDC), which are enhancing project performance by improving communication, early detection of clashes, simulating construction sequences, and better coordination with stakeholders (Deshpande, Azhar and Amireddy, 2014).

2.2 Landscape and Digitalisation

While landscape architecture has a long-standing relationship with digital technologies, the integration of advanced tools, such as parametric modelling, virtual reality, and BIM, into landscape workflows is still evolving. Landscape architecture, with a historical connection to digital technologies since the 1960s, faces an imbalance between the potential capabilities of tools and their practical implementation, characterised by 3D parametric modelling of a seamless digital workflow with the influence of Big Data and advancement in the digital fabrication process (Walliss and Rahmann, 2016) Some researchers have categorised seven specific forms of Digital Landscape (DL), including digital maps, virtual reality (VR) and augmented reality (AR) landscapes, computer-generated landscapes, and hybrid landscapes blending the physical and digital domains (Wik et al., 2018). As a result, it is essential to encourage collaborative efforts among professionals from various disciplines, such as climate science, geology, hydrology, ecology, and perception, for the study and design of DL. However, existing BIM software cannot effectively handle environmental data, requiring a specialised object library to store standard landscape elements and adapt to individual project requirements. Parametric modelling serves as a solution, enabling designers to customise objects based on specific parameters (Semeraro et al., 2019).

2.3 Data and Digital Tools in the Digital Landscape

Effective digital landscape design hinges on robust data management and specialised tools. Yet, current practices face challenges in standardisation and the integration of ecological data, underscoring the need for a dedicated landscape information modelling approach. Leveraging digitalisation, landscape architects can create objective and rigorous design logic, boosting problem-solving skills and creativity, which can result in landscape design solutions that integrate art and science, promoting both aesthetics and environmental sustainability (Li and Wu, 2013). Various advanced tools contribute to DL as shown in Figure 4, including ArcGIS for data manipulation and spatial analysis, Landsat-8 remote sensing for surface feature analysis, FRAGSTATS for spatial pattern analysis in landscape ecology, VR technology for immersive virtual environments, LIM for modelling landscape information, and additional tools such as BIM, Google Earth Engine, laser scanning, Grasshopper, and others (Fernández-Alvarado and Fernández-Rodríguez, 2022).

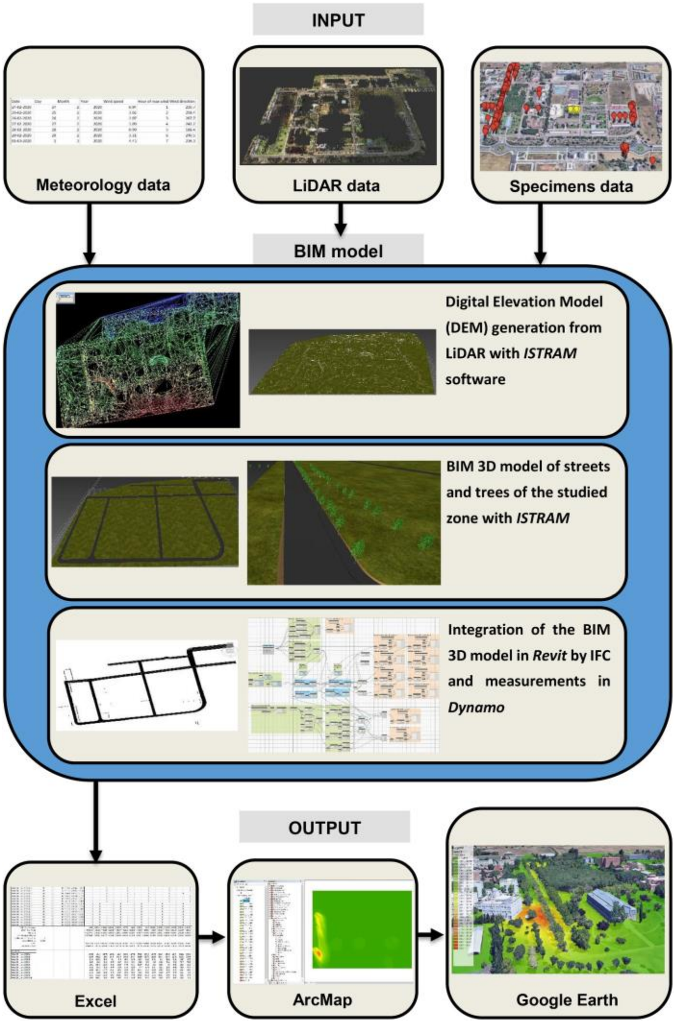

Figure 3: Flowchart – 3D BIM model with urban environmental consideration (Fernández-Alvarado and Fernández-Rodríguez, 2022).

During the design and construction process accurately locating diverse plant models in the landscape can be challenging due to their variety, which is addressed through the utilisation of CAD, Excel, Revit, and Dynamo tools with parameterisation, resulting in an efficient program that ensures precise model location and collaborative plant management methods via BIM and mixed reality (MR) devices (Zhao, 2022).

Moreover, tree models compliant with BIM incorporate nature's designs into the digital realm, capturing crown and root shapes for clash detection, performance analysis, and detailed visualisation. At the same time, consistent classification facilitates automatic scheduling, age representation, and species-specific growth patterns, ensuring accurate digital representation of real-world trees through data exchange (Figure 5 & Figure 6) (Luka and Guo, 2021).

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Flora
Product Data Template

Template Category	Flora			
Template Version	v6.1			
Category Description	Plant species grown for the purpose of planting out in a landscape.			
Classification System				
Classification	Value			
Suitability for Use				
Template Custodian	Landscape Institute			
Information Category	Parameter Name	Value	Units	Notes
Manufacturer Data				
Specifications	Supplier		Text	
Specifications	Supplier Website		URL	
Specifications	Product Range		Text	
Specifications	Product Model Number		Text	Or Code
Specifications	CE Approval		Text	Number, Yes, No
Specifications	Product Literature Webpage		URL	
Specifications	Product Features		Text	Free text to describe product
Naming Data				
Specifications	Product Code		Text	
Specifications	Botanical Name		Text	
Specifications	Alternative Botanical Name		Text	Or Names
Specifications	Common Name		Text	Or Names
Specifications	Category or Class		List	Or Type. Select from list
Specifications	Sub-Category or Sub-Class		List	Select from list or type to define new value

Figure 4: An example layout for the ‘’Flora’’ scheduling spreadsheet by Landscape Institute 2016 (Peters and Thon, 2019).

OBJECT SPREADSHEET Tree	Programfase (LOD 000) programming	Skisseprosjekt (LOD 100) sketch proposal	Forprosjekt (LOD 200) preliminary project	Detaljprosjekt (LOD 300) detail project	Byggefase (LOD 400) construction	FDVU (LOD 500) operations and maintenance
	0	1	2	3	4	5
Parameter name						
Type Tree		x	x	x	x	x
Height				x	x	
Spread				x	x	
Girth				x	x	
Clear stem height				x	x	
Root protection and condition				x	x	
Form specified				x	x	
planting distance			x	x	x	x
planting system			x	x	x	x
Origin		x	x	x	x	x
Stakeout data					x	
Ultimate height		x	x	x		x

Figure 5: Spreadsheet for the tree object, indicating the phases for parameter implementation and specifying corresponding values (Wik et al., 2018).

As current BIM software cannot handle environmental data, it is necessary to integrate mitigate efforts into BIM presents a new challenge for landscape, architecture and urban planning; addressing this requires a specialised object library that can store standard landscape elements and adapt to project-specific needs, highlighting the effectiveness of parametric modelling in customising object concerning the project requirement (Semeraro et al., 2019). Utilising a BIM vegetation library within BIM models facilitates time-saving. It minimises human errors in landscape data collection, yet challenges arise in exporting IFC files across diverse platforms. Certain processes need to overlook the age of trees, which affects their potential for greening over time (Lin et al., 2022). IFC-format models, designed for exchange purposes, are exported to coordination software for overlapping and clash detection, followed by exporting to visualisation. Visualisation in various styles is facilitated by tools like Lumion and Enscape, with potential for VR glasses viewing. An example of the workflow from sketch to visualisation using digital tools is shown in Figure 7 (Brückner, Haverland,and Halbrügge, 2022).

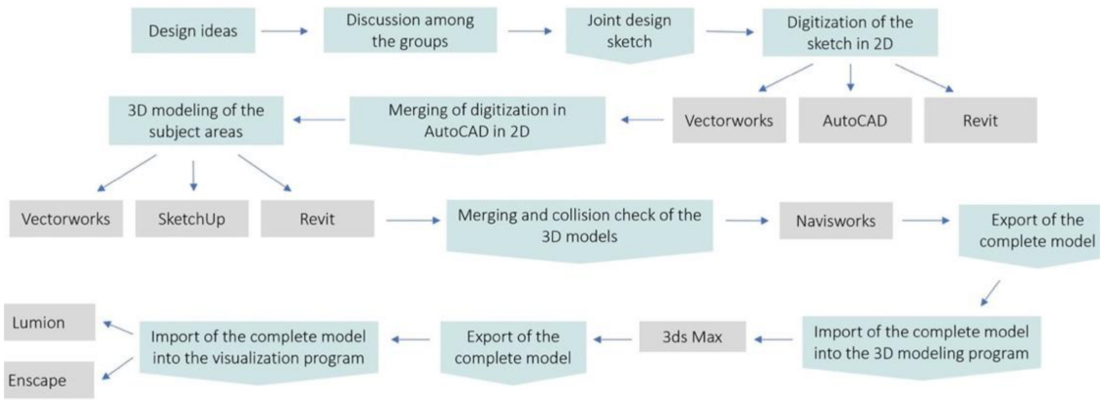


Figure 6: Project development workflow (Brückner, Haverland and Halbrügge, 2022).

The Green Plot Ratio (GnPR) in landscape design measures the greenery on the site by determining the ratio of the total leaf area of all the plants to the overall area (Ong, 2003). Table 1 compares the timing taken for calculating GnPR through various methods. Lin et al. (2022) state that within BIM software calculating GnPR is feasible without a dedicated BIM vegetation library, but this approach may result in inaccuracies and to get more accurate GnPR support in assessing vegetative materials, light, water, and soil needs, with a workflow synchronising plant data on BIM platforms for streamlined project design and construction, eliminating the dependence on separate libraries.

Table 1: Comparison of GnPR calculation methods (Lin et al.*, 2022).*

GnPR	Time Taken (Manual Tabulation)	Time Taken (Manual Checking)	Time Taken (Manual - Total)	Time Taken (IFC Workflow)
1.296	20 mins	1 hr 40 mins	2 hrs	15 mins
1.459	30 mins	2 hrs 30 mins	3 hrs	5 mins
1.923	1 hr	5 hrs	6 hrs	15 mins
3.052	30 mins	3 hrs	3.5 hrs	6 mins

The call for public institutions to establish regulations for landscape digitisation underscores the necessity for tools specified to conduct accurate landscape analysis, advocating for streamlined information reuse to optimise analysis and contextual studies, ultimately reducing delays (Semeraro et al., 2019). Post-construction analysis can be conducted on a live, interactive BIM platform, where interactions among various landscape elements and their supporting sources can be inspected. This holistic approach can incorporate a data feed system into a digital dashboard to evaluate the impact of green architecture and strengthen connections between architecture and landscape for biodiversity analysis Briscoe, 2020).

2.4 Proposed Conceptual Model [1.1 Heading, Aptos, 14, Bold]

In this section, these insights are taken and have been translated into a proposed DLIM framework, detailing the stages and components needed to realise a BIM-aligned, nature-based approach to landscape design. Key figures and tables are highlighted to illustrate the framework and summarise the supporting findings.

2.4.1. DLIM Framework Proposal

Based on the converged findings, we propose a four-stage Digital Landscape Information Management (DLIM) Modelling framework that integrates landscape sustainability considerations into the digital project delivery process. Figure illustrates this proposed DLIM framework, which is designed to align with typical BIM workflows while adding dedicated steps for landscape data and nature-based solutions. The framework's stages are described below, followed by a concrete example of its application (focused on a vegetation workflow, shown in Figure). The goal is to provide a clear, practitioner-friendly roadmap for implementing DLIM in urban greenscape projects, ensuring that essential environmental data and feedback loops are incorporated.

2.4.2. Stage 1: Landscape Data Collection and Setup

The process begins with assembling a comprehensive digital database of landscape information relevant to the project. This corresponds to the pre-design or early design phase. Here, various essential elements (identified in this research as critical for sustainability) are collected and stored as structured digital data. These elements include, for example, site topography and soil data, climate metrics (such as sun, wind, and rainfall statistics), existing vegetation and biodiversity data, water resources, and any relevant socio-cultural site information. In addition, standard NBS design parameters, such as species characteristics and carbon sequestration rates, as well as runoff coefficients for green infrastructure, are input into the database. The database can be a BIM common data environment or a cloud library, and it serves as the single source of truth for landscape factors. By front-loading the process with data, Stage 1 ensures that designers have the necessary information to make sustainability-driven decisions. The findings strongly support this stage: participants emphasised centralising landscape data for reuse and consistency across projects. It is envisioned that this database will be continually expanded and updated (e.g., as new plant performance data become available), and one of our recommendations is that industry bodies consider maintaining open landscape data libraries analogous to BIM object libraries.

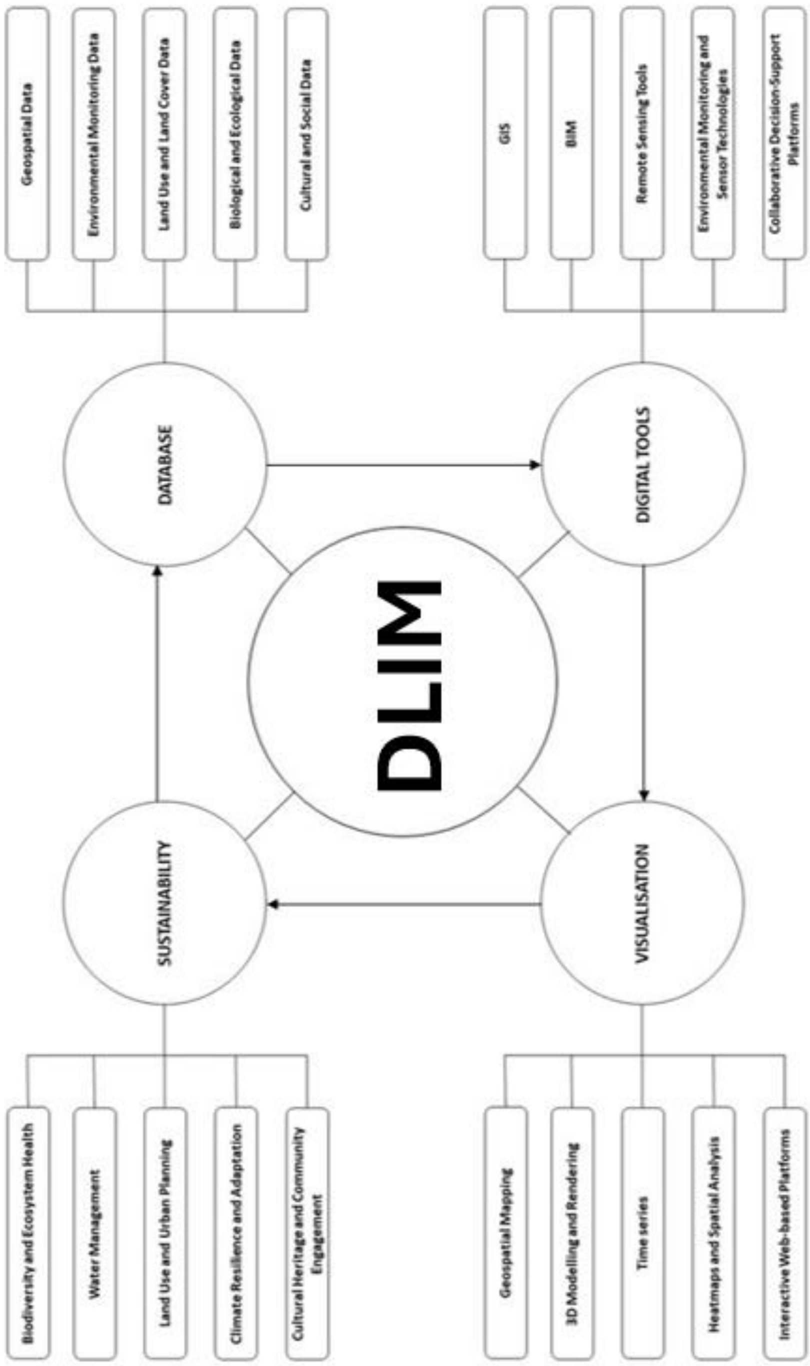


Figure 8: Proposed DLIM framework (Author's own)

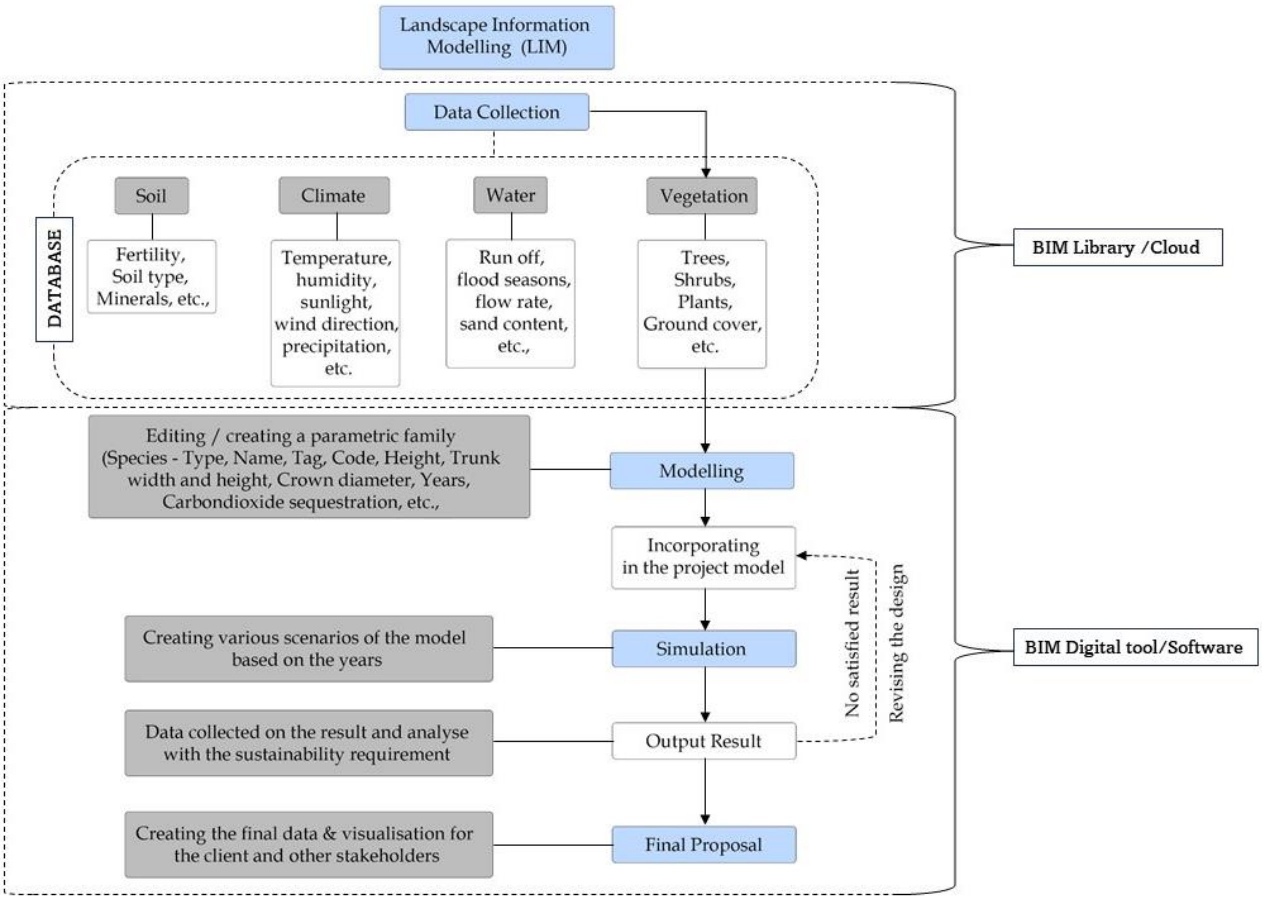


Figure 9: DLIM workflow process - Vegetation (Author's own)

2.4.3. Stage 2: Digital Landscape Modelling and Integration

In Stage 2, the landscape data is utilised to create the landscape model within a BIM or DLIM authoring tool. Essentially, this is the design and modelling phase, where the traditional landscape design workflow is augmented with parametric and data-driven components. Using the Stage 1 database, landscape architects develop digital models of proposed landscape interventions: terrain models, planting schemes, water features, pavements, etc., complete with their attached data (from Stage 1). This may occur in software such as Autodesk Revit (with landscape plug-ins), Vectorworks Landmark, or other BIM-compatible landscape design tools. The framework emphasises integration, which means the landscape model is not isolated but rather integrated with the building/infrastructure BIM models. By linking to the architectural BIM, the combined model can reflect relationships (e.g. how a building's shadow affects plant growth, or how landscape grading interfaces with structural foundations). In practice, this could be achieved through a shared coordination model or by utilising open standards (e.g., IFC for site, once matured). Figure conceptually illustrates that various digital tools contribute to this modelling stage. These include CAD/GIS for base mapping, generative design tools for layout optimisation, and BIM tools for detailed modelling. The output of Stage 2 is a rich landscape information model that embeds the sustainability data (from Stage 1) in the design elements. For example, each tree in the model can carry attributes such as species, carbon uptake, and water needs; each porous pavement area has data on its infiltration capacity. Having these attributes enables the next stage of evaluation. Our interviewees indicated that this stage mirrors their ideal workflow: *"Designing with data in hand," so that every design decision (such as* choosing a plant palette or contouring the land) is informed by real performance metrics.

2.4.4. Stage 3: Simulation and Analysis (Visualisation & Feedback)

Once the initial landscape model is built, Stage 3 involves simulating and visualising the landscape performance using various analysis tools. This is analogous to running analyses on a building model (like energy simulation or clash detection), but here focused on landscape/NBS outcomes. Within the framework, the landscape model from Stage 2 is fed into visualisation and simulation tools, such as computational fluid dynamics for wind flow, solar analysis for shade and heat mapping, hydrologic models for stormwater behaviour, or even agent-based models for pedestrian use of space. Modern tools, such as Unity 3D and Unreal Engine (for real-time landscape visualisation), or GIS-based simulators, can be linked at this stage. The aim is to check whether the proposal has attained the required sustainability targets. The framework encourages iterative testing. If simulations reveal shortfalls, designers revisit and adjust the model (Stage 2), which constitutes the feedback loop. Notably, any data outputs from the simulation (performance results, metrics) are recorded and fed back into the Stage 1 database for future reference. For instance, if a certain planting arrangement failed to meet biodiversity targets, that insight (and the data) is saved so that future projects can learn from it. This builds a knowledge base over time, enhancing predictive capabilities. Our participants highlighted this as a time-saving aspect: *"A big plus of going digital is you don't start from scratch each time, so basically you can reuse past project data,"* which the framework facilitates by capturing results. Through Stage 3, the DLIM process leverages the power of digital twins or prototypes of the landscape. In fact, this resonates with the emerging concept of a *"digital landscape twin"*, which is essentially what Stage 1–3 accomplish: a virtual counterpart of the physical landscape, used to test interventions before implementation.

2.4.5. Stage 4: Implementation and Knowledge Management

The final stage involves applying the insights and managing the information as the project progresses to implementation (and even post-construction). After simulation, once the design is optimised to meet sustainability criteria, the project proceeds to construction documentation, implementation on site, and maintenance. The DLIM framework ensures that the validated model and data from Stage 3 inform these subsequent steps. In practice, this could mean the model is handed over to contractors and facility managers via BIM tools, ensuring landscape specifications and data (planting schedules, soil volumes, performance benchmarks) are clear. Importantly, the framework calls for updating the central landscape database with as-built information and monitoring data over time. For example, if sensors on the built project report actual water usage or growth rates, these can be compared to the model's predictions, and the database can be refined accordingly. This learning loop aligns with the concept of continuous improvement, making future designs more intelligent. The database in Stage 1 thus evolves with each project, increasing in value over time. Stage 4 also includes any necessary workflow adjustments; Figure (an example workflow for *vegetation design*) demonstrates how a specific subset of data (vegetation parameters) goes through iterative modelling and simulation until the desired output is achieved. In that figure, the process for a *vegetation library element* is detailed. For example, data about a plant species is stored in the cloud library, and the plant model is brought into the BIM design, where its parameters (height, canopy, etc.) are edited for the project. Growth or visualisation simulations are run, and the model is tweaked repeatedly until performance (like shading or aesthetic) is satisfactory. This micro-level workflow exemplifies Stage 4's ethos of refining design through feedback loops as many times as needed to meet goals. By the end of Stage 4, the project has a well-documented digital landscape model and a trove of data for post-occupancy evaluation and future use.

3 Methodology [1 Heading, Aptos, 16, Bold]

To investigate DLIM and develop the framework, a mixed-methods research design has been adopted. This approach combined a broad and comprehensive literature review with field data from expert interviews and industry surveys, allowing for the triangulation of findings and robust conclusions.

- Literature Review (LR): LR has been conducted to map existing knowledge at the intersection of BIM, landscape architecture, sustainability, and digital tools. A comprehensive search (1996–2025) was performed using databases such as Scopus. Keywords included "BIM", "landscape design", "nature-based solutions", "green infrastructure", "digital landscape", "LIM (Landscape Information Modelling)", and "Virtual Design and Construction (VDC)". The literature review established the current state-of-the-art, including BIM applications in landscape design, the concept of LIM in research, digital visualisation techniques, and known challenges (e.g., the lack of standards for landscape data exchange). It provided context and informed the design of our empirical instruments.
- Expert Interviews: We gathered qualitative insights via semi-structured interviews with eight experts in the field. These interviewees were experienced professionals spanning roles such as head landscape architects, senior architects, BIM managers, and environmental consultants (with 9 to 24 years' experience) in both the public and private sectors. Interviews were conducted one-on-one and were open-ended, guided by themes from the literature (e.g., current digital practices in landscape, perceived barriers, data needs, and sustainability considerations). The expert interviews enabled us to probe the practical challenges and opportunities for integrating BIM and landscape in depth, from software limitations to organisational and workflow issues. Conversations were recorded, transcribed, and thematically analysed to extract common patterns.
- Practitioner Survey: In parallel, we conducted a questionnaire survey targeting a broader set of practitioners to gain a quantitative perspective on key issues. The survey was distributed online (via Qualtrics) to landscape architects, architects, urban designers, BIM specialists, and other stakeholders familiar with digital tools in design and construction. We received 45 complete

responses (out of 65 distributed surveys – the remainder incomplete). Respondents' profiles were roughly 50% architects and 50% landscape or related professionals, including BIM coordinators and engineers, from various firm sizes. The survey included both Likert-scale and ranking questions on topics such as familiarity with sustainability and NBS, current use of software/tools, data needs for landscape modelling, expected benefits and concerns regarding LIM, and perceived impact on collaboration. The quantitative data were analysed to produce summary statistics and rankings.

All three data sources were ultimately triangulated. The literature has been used to frame the issues, the interviews to explain the why behind current practices, and the survey to gauge the extent of trends and consensus among practitioners. This mixed-methods strategy enhanced the validity of the findings, as insights that converged across the literature, expert opinion, and survey data were considered robust evidence to inform the design of the DLIM framework. The next section summarises the key results and findings from the research, which then lead into the proposed framework.

1. Results- Key Findings Current Practices and Gaps in Digital Landscape Design

1.1.1. Emphasis on Sustainability and NBS

Nearly all participants (95%) recognised sustainability's centrality to contemporary practice, with over half identifying climate change and biodiversity loss as primary design drivers. This aligns with Musacch's (2011) Six E's framework, which encompasses environment, economics, equity, experience, aesthetics, and ethics, as illustrated in Figure 7. This framework provides a holistic perspective on landscape sustainability.

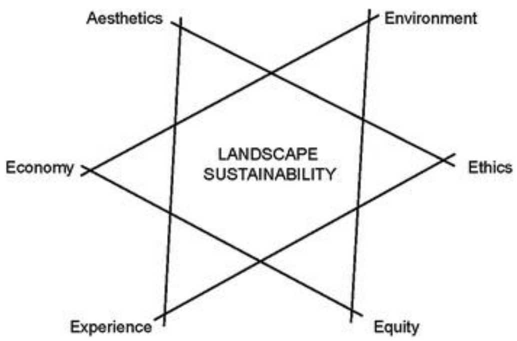


Figure 7: The six Es of landscape sustainability (Musacchio, 2010).

1.1.2. Practitioners stressed practical applications

Green roofs, carbon sequestration, water management, and native plantings. Yet tensions emerged between aspirations and reality. As one interviewee noted, "*Clients want sustainability until they see the price tag.*" This echoes broader industry challenges where, despite BIM's potential for ecological assessment, implementation remains fragmented (Cao, Zhang and Luo, 2021). The disconnect between available tools and actual practice suggests sustainability remains more rhetorical than operational for many firms. When the question **(Q10 – Table 2)** about the role of data and technology in attaining the sustainability goals in digital landscape design was put forth in the survey the participants prioritised enhancing stakeholder engagement and communication during the sustainability process are most important, followed by other approaches like optimising resource use and energy efficiency, developing predictive models to check the effects of climate changes and other environmental impacts and to provide real-time data on environmental conditions.

Table 2: Role of data and technology on sustainability goals

Q10 - How could data and technology better support sustainability goals in digital landscape design?

Field	Min	Max	Mean	Median	Standard Deviation	Variance	Sum
Provide real-time data on environmental conditions.	1.00	4.00	2.07	2.00	1.06	1.13	93.00
Develop predictive models for climate change and other environmental impacts.	1.00	4.00	2.09	2.00	0.96	0.93	94.00
Optimise resource use and energy efficiency.	1.00	4.00	2.42	2.00	1.00	1.00	109.00
Enhance stakeholder engagement and communication.	1.00	4.00	3.42	4.00	0.86	0.73	154.00

According to the interview participants, the sustainability approach considers air quality, temperature, carbon sequestration, and acoustics. They also mention that landscape architecture is integral to broader BIM principles for sustainability, offering education and guidance in adapting prototypes to address the global climate crisis. When it comes to key sustainability elements throughout the digital landscape design process, they were prioritised through the use of sustainable materials and construction practices, water conservation and management, energy efficiency and renewable energy, and native planting and wildlife habitat restoration, respectively. These data and technologies can support better sustainability goals through digital landscape design by providing real-time data on environmental conditions, developing predictive models for various environmental impacts, optimising resource usage and energy efficiency, and enhancing stakeholder engagement and communication.

Figure 8 shows the vital factors of sustainability from the interviewees' perspective. According to the interview data, sustainability challenges encompass balancing costs and maintaining features, addressing urban restrictions, and tackling environmental issues in urban areas. Striking a balance between compliance and human experience presents challenges that involve commercial factors, cost implications, and delays in landscape information model development. Proper site development, local ecosystem adaptation, and effective management of carbon and water are integral considerations.

Client budgets impact sustainability decisions, with some clients prioritising it only if it is affordable. A proactive approach seeks to integrate sustainability despite budget constraints, viewing it as a learning opportunity and emphasising its importance. Other challenges include convincing stakeholders of the value of investing in sustainable landscape design, while others consistently focus on sustainability regardless of budget constraints, yielding varying perspectives. With sustainability, the focus is on achieving net zero, implementing BIM principles, and conducting detailed digital analysis for improved project development and stakeholder coordination.

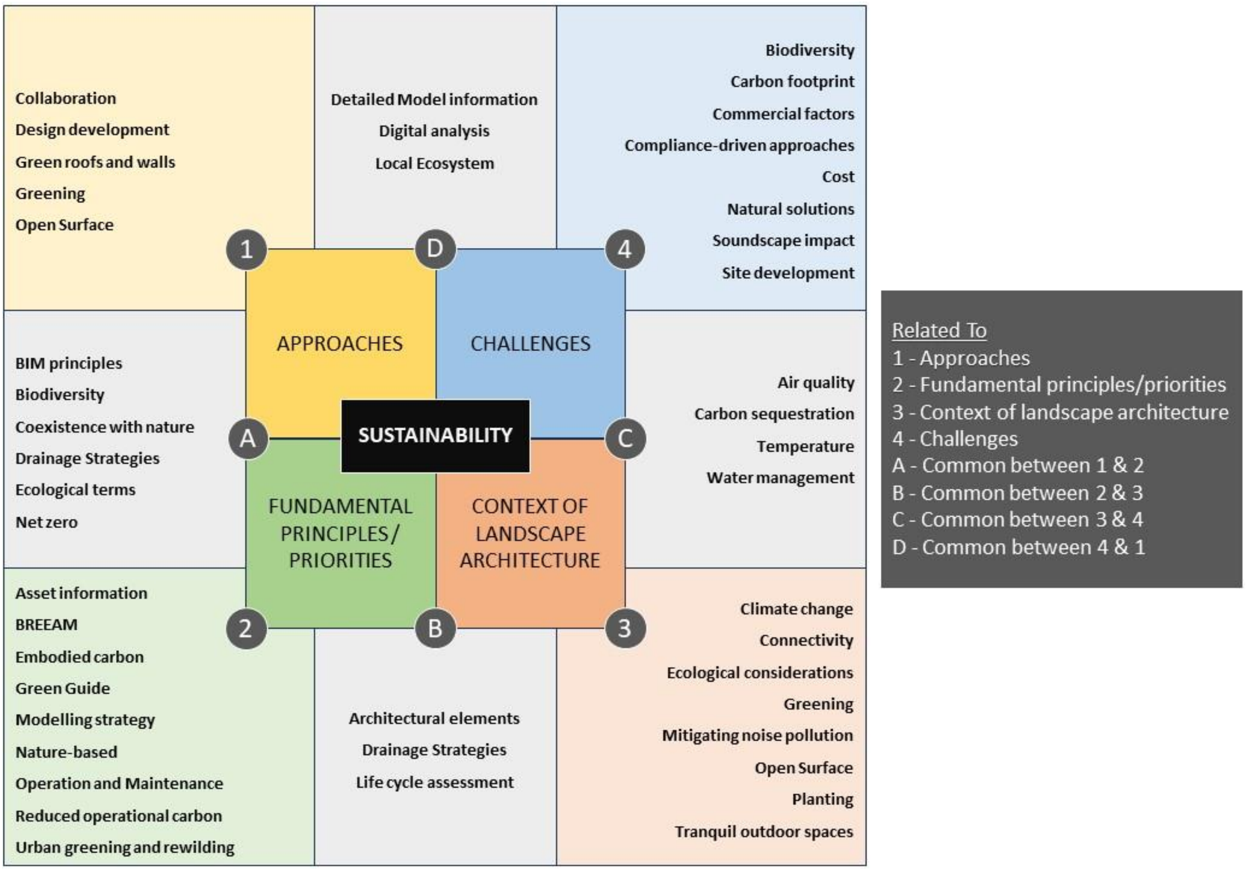


Figure 8: Sustainability – Qualitative data chart (Author's own)

1.1.3. Use of Digital Tools

The research found that digital tool adoption in landscape architecture is growing but fragmented. According to the survey, practitioners are very familiar with general CAD and modelling software (over 80% use AutoCAD and SketchUp, and many use BIM tools like Revit and cloud platforms like BIM 360) (Figure 9).

Nonetheless, software specifically tailored to landscape design shows lower uptake; for example, only a minority of respondents had experience with GIS-integrated landscape BIM tools, such as Vectorworks Landmark or Autodesk Civil 3D. Interviews confirmed this pattern: most firms use a mix of standard architectural BIM (Revit) and visualisation software (Twinmotion, Lumion) for landscape projects, leveraging BIM for documentation and coordination. *"We follow BIM Level 2 standards for big projects,"* noted one landscape architect, *"but Revit doesn't handle planting or topography analysis well, so we still export to other tools."* Indeed, Revit's limitations for detailed landscape modelling (such as grading, plant databases, or soil analysis) were a recurring challenge cited. Some specialised tasks, such as acoustic modelling in landscapes or microclimate analysis, are handled with niche tools (e.g., SoundPLAN for noise, or Rhino/Grasshopper for complex forms). This siloed tool usage leads to data exchange issues, as one expert described, *"there's no single source of truth for landscape data; we end up manually stitching together outputs."* The literature review reinforces this finding; prior studies have highlighted that current BIM standards (e.g. IFC) do not natively support many landscape elements, forcing workarounds that hinder interoperability (Wei, 2024). The need for a unified landscape information database and better tool integration emerged as a critical factor.

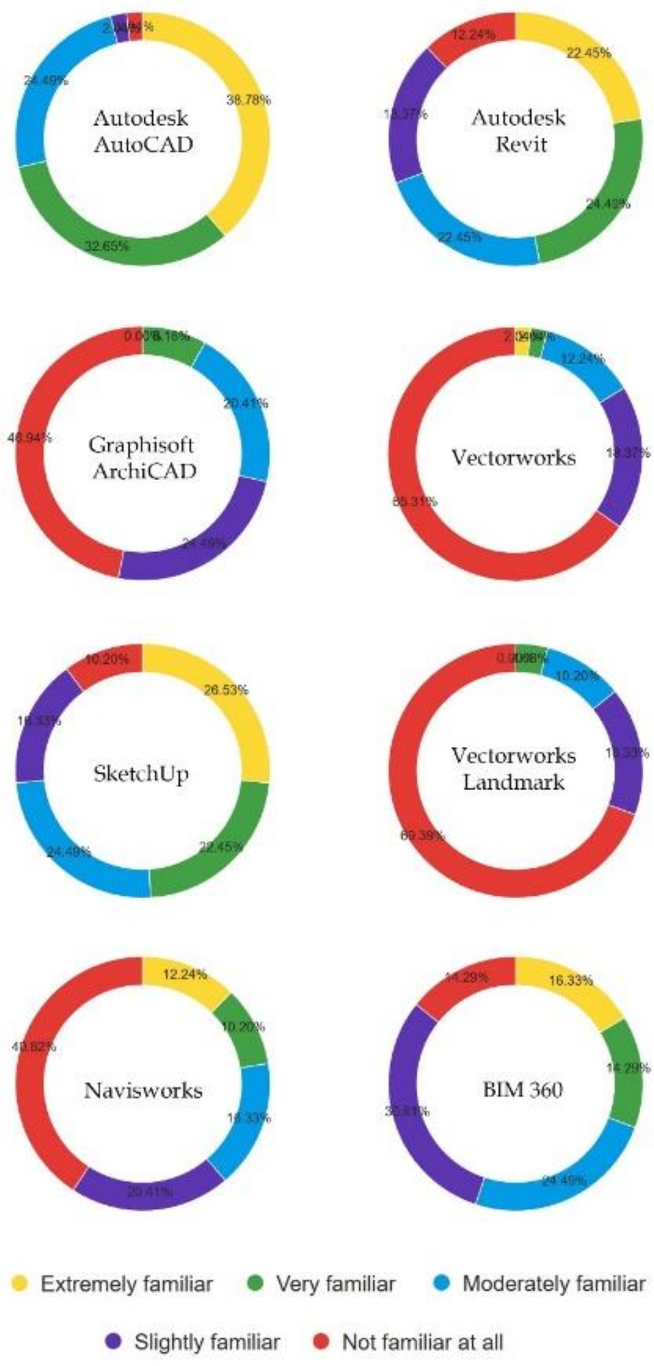
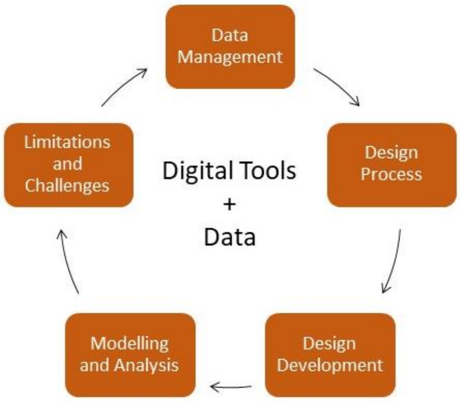


Figure 9: Participant's familiarity level with various software – Quantitative data (Author's own)

Figure 10 shows the process of digital tools and data and the list of essential factors that are to be considered when it comes to using digital tools and data in the digital landscape process.



Priority list based on Quantitative analysis

BIM 360 & Federated Models	Clash Detection	Carbon Emission Data
Cost	Design Options	Water Management
Collaboration & Coordination	Design - Process, Sequencing & Value	Holistic approach
Databases & Libraries	Site Development & Management	Reducing Misconception
Landscape and Sustainability Analysis		

Figure 10: Digital tools and data – Qualitative data chart (Author's own)

Digital tools, including BIM 3D modelling, are crucial for accurate documentation, clash detection, and coordination in landscape design. They inform decisions on materials and plant species, aiding a holistic approach. As an Information Manager, involvement in setting up data environments and aligning information models with project requirements is pivotal. Embracing advancing technology, the user considers data as crucial, emphasising collaboration, site management, energy analysis, and stakeholder coordination in their design process. The use of VDC is prevalent in government projects, where BIM 360 and Federated models are employed for coordination and walkthroughs. Limited familiarity with VDC is evident among landscape architects, who primarily use 2D drawings in Revit. Challenges include bidirectional links between models and integrating tools like Revit with acoustic modelling. VDC is primarily applied in the construction phase for design sequencing, simulations, and visualisations, and focuses on benefits such as improved client understanding, enhanced coordination, real-time site development, stakeholder engagement, and operational maintenance.

Despite the lack of BIM libraries and limitations in BIM applications, parametric components for landscape mitigation work can be created using standard objects and visual scripts. This approach offers advantages in design, data management, and customisation for landscape architects (Semeraro *et al.*, 2019). Challenges in digital tools include software limitations, such as Revit's limitations for detailed landscape analysis, and a lack of detailed carbon emission data for materials. Issues include handling multiple options, time-consuming data discovery, and a shortage of specialised tools and sustainable material libraries. Gaps exist between monitoring and modelling/consulting aspects, facing challenges in commercial factors, cost implications, and lagging landscape information model development. Improved workflow understanding and embedded standards can enhance efficiency; however, challenges persist in accessing real-time updates on weather, vegetation, energy analysis, and asset information for effective maintenance.

1.1.4. Data Requirements

A major insight from the findings is the emphasis on data and information management for digital landscapes. Both experts and survey respondents believe that compiling comprehensive, up-to-date data on landscape elements is foundational to effective modelling. Participants strongly supported creating a centralised *"landscape database"* analogous to an architectural BIM library. Such a database would include a wide range of information, e.g., plant species attributes, soil and hydrology data, topography, climate statistics, and maintenance records, which should be stored in a digital form that can be reused across projects. *"If we had a shared landscape object library like architects have for doors and windows,"* one interviewee noted, *"it would save us enormous time. We're constantly redrawing or re-researching the same things."* This aligns with recent research by Lin et al. (2022)who envision a BIM-integrated vegetation library that landscape architects worldwide could tap into. Our survey asked practitioners to rate the importance of various data types for a digital landscape model. The top priorities were data on the economic value of landscape features, pollution control metrics, carbon sequestration, air quality improvements, and water management, followed by a robust database of softscape (plant) features. These results (see Table 3) indicate that users want DLIM tools to handle not just geometric information, but also quantitative environmental data to inform sustainable design decisions. The DLIM framework responds to this by making data collection and management the first step of the process (with a dedicated database of sustainability factors).

Table 3: Essential data sources

Q11 - Which data sources are essential in the digital landscape design process?

Field	Min	Max	Mean	Median	Standard Deviation	Variance	Sum
Trees and Plants databases	1.00	6.00	2.44	2.00	1.71	2.91	110.00
Water management	1.00	6.00	2.38	2.00	1.16	1.35	107.00
Air Quality	1.00	6.00	3.18	3.00	1.18	1.39	143.00
Carbon dioxide sequestration	1.00	6.00	4.07	4.00	1.36	1.84	183.00
Pollution Control data	1.00	6.00	4.11	5.00	1.54	2.37	185.00
Economic Value	1.00	6.00	4.82	6.00	1.65	2.72	217.00

1.2. Perceived Benefits and Challenges of DLIM Adoption:

1.2.1. Anticipated Benefits

The study's findings suggest that practitioners see great value in adopting DLIM if certain capabilities are met. In the survey, the respondents ranked potential benefits of integrating DLIM into their workflow. The results, summarised in Table 4, show a clear trend: the highest-ranked benefit is improved data-driven decision-making in landscape projects. Users expect that having a digital model of the landscape (with rich data) would enable more evidence-based choices; for instance, selecting materials or plantings based on performance data rather than solely aesthetics. The second major benefit is enhanced collaboration and communication among stakeholders. A DLIM model could act as a shared platform where landscape architects, architects, engineers, and clients can all view and comment on the same integrated model of the site, thereby reducing misunderstandings. Other notable benefits ranked highly include a *better understanding of site conditions and impacts* (through simulations of scenarios such as flooding, shading, and vegetation growth), as well as improved design quality and efficiency, for example, by automating routine calculations or flagging clashes early. These anticipated benefits correspond well with findings in the literature; prior studies have noted that a landscape BIM approach can facilitate visualising and integrating data for informed decision-making and support site-specific sustainability analyses (Chen, 2024; Liu *et al.*, 2024; Yu, Zhang and Gong, 2022). Interview participants who had some digital landscape design experience (e.g. using Civil 3D or GIS integrations) attested to time savings and better stakeholder buy-in when 3D landscape visuals and data were presented: *"Clients understood the design much better when we showed the 3D landscape model, it sped up approvals."* Overall, the results suggest that if technical and workflow hurdles can be overcome, practitioners believe DLIM will enhance project sustainability, efficiency, and interdisciplinary teamwork.

Table 4: Benefits of LIM adaptation

Q15 - What specific benefits can you see in adopting Landscape Information Modell...

Field	Min	Max	Mean	Median	Standard Deviation	Variance	Sum
Improved design quality and efficiency	1.00	4.00	1.82	1.00	1.02	1.04	82.00
Enhanced collaboration and communication	1.00	4.00	2.69	3.00	0.96	0.93	121.00
Increased data-driven decision-making	1.00	4.00	2.91	3.00	0.91	0.84	131.00
Greater understanding of site conditions and impacts	1.00	4.00	2.58	3.00	1.24	1.53	116.00

1.2.2. Challenges and Concerns

On the other hand, the research also identified several key challenges that have inhibited DLIM adoption to date. We specifically queried concerns in the survey (see Table 5). The top-ranked concern was a potential *negative impact on designers' creativity*. Some respondents fear that an over-reliance on standardised digital processes might constrain the creative, iterative nature of landscape design; *"Will young landscape architects still learn to sketch freely, or will they be boxed in by what the software can do?"* was a representative worry. The next major concern was the time and resource investment required. Small landscape firms, in particular, are wary of the learning curve and the cost of adopting BIM-based tools. Unlike architecture, landscape practices tend to be smaller, and dedicating staff to manage a BIM library or provide training can be burdensome. *Data security and privacy* issues were also noted, as DLIM would involve extensive site data (potentially including sensitive environmental or client information), ensuring secure data management is essential. Finally, *integration with existing software/hardware* is a practical hurdle. Many landscape firms already use a patchwork of software; they worry whether a new DLIM system would play nicely with their CAD, GIS, or rendering tools, or require an overhaul of their IT infrastructure.

Table 5: Concerns on LIM adaptation

Q16 - What specific concerns will you have about adopting LIM?

Field	Min	Max	Mean	Median	Standard Deviation	Variance	Sum
Data security and privacy	1.00	4.00	2.22	2.00	1.19	1.42	100.00
Integration with existing software and hardware	1.00	4.00	2.11	2.00	0.99	0.99	95.00
Time and resource requirements	1.00	4.00	2.64	3.00	0.87	0.76	119.00
Impact on design creativity	1.00	4.00	3.02	3.00	1.14	1.31	136.00

Beyond these survey-elicited concerns, our expert interviews shed light on broader implementation challenges. A recurring theme was the *lack of standards and guidance* specific to landscape information management and modelling. Unlike building projects, which benefit from well-defined BIM standards (e.g. ISO 19650) and object libraries, landscape projects suffer from a dearth of standardised object classifications, parametric components, and metadata schemas for natural elements. This is slowly changing; for instance, buildingSMART's IFC extensions for site and landscape are in development to enable exchange of landscape objects (Wei, 2024). Still, in practice, interviewees noted that current BIM exchanges often omit or simplify landscape data. Another challenge is software fragmentation; different stages of landscape work (planning, design, analysis, maintenance) might each use different tools, leading to interoperability problems. *"Interdisciplinary planning in a BIM-oriented* *manner"* can be hindered by these toolchain gaps, as noted by Our participants called for greater software interoperability and simpler interfaces, as well as more comprehensive content libraries for landscape (plants, terrains, etc.) to truly make DLIM feasible. Additionally, training and cultural factors play a role, many landscape professionals haven't been formally trained in BIM, and there can be resistance to change. Some interviewees advocated for industry bodies and education to introduce DLIM concepts (e.g. training modules, pilot projects) to build confidence.

In summary, while there is enthusiasm for the benefits of DLIM, addressing these challenges —such as preserving creativity, managing costs, developing standards, and improving tools —will be crucial. These findings inform the layout of our DLIM framework, which seeks to maximise advantages while providing a clear process that can mitigate certain issues (for example, by emphasising flexibility and feedback in the workflow). Moreover, when we asked how DLIM would affect different project stakeholders (Table 6), the answer was clear: better communication topped the list. A shared digital model allows everyone, from clients to the public, to visualise proposed projects instead of relying on technical drawings. This not only improves communication but also reduces errors, saves costs through better coordination, and enables the visual representation of sustainability impacts. Imagine demonstrating how a green corridor reduces urban heat or how bioswales protect neighbourhoods from flooding, with actual numbers. One municipal official put it bluntly: "*Having hard data on carbon sequestration and runoff reduction makes it much easier to sell projects to decision-makers.*" This highlights DLIM's real value, as it's not just another design tool, but a platform for evidence-based conversations about urban development.

Table 6: DLIM's impact on stakeholders

Q17 - Which impacts of LIM matter most to stakeholders in landscape projects?

Field	Min	Max	Mean	Median	Standard Deviation	Variance	Sum
Improved decision-making due to better information	1.00	4.00	1.84	2.00	0.87	0.75	83.00
Increased project efficiency and cost savings	1.00	4.00	2.20	2.00	0.98	0.96	99.00
Enhanced communication and collaboration among stakeholders	1.00	4.00	3.20	3.00	0.86	0.74	144.00
Greater understanding of project impacts and benefits	1.00	4.00	2.76	3.00	1.21	1.47	124.00

4 Discussion [1 Heading, Aptos, 16, Bold]

The digital landscape transformation isn't merely technical but fundamentally cultural. Success requires reimagining landscape architecture's relationship with data, standardisation, and creativity. Rather than viewing DLIM as a constraint on creativity, practitioners might embrace it as a liberation, freeing designers from the burden of technical documentation to focus on ecological innovation. The profession stands at an inflexion point. Climate imperatives demand quantifiable performance, clients expect digital delivery, and younger professionals arrive digitally native. DLIM offers the framework to bridge these demands, but only if the profession moves beyond defensive posturing to proactive engagement with digital possibilities.

When it comes to the digital landscape, there are a few recommendations that need to be addressed first before moving further into technological advancement: creation of a centralised landscape database, updating the models in the database regularly, upgrading the software that can incorporate the DLIM process, and conducting more research on LIM to make it as feasible as BIM.

5 Conclusions

In summary, the four stages of the DLIM framework: (1) Data Collection, (2) Digital Modelling, (3) Simulation & Feedback, and (4) Implementation & Knowledge Management, create a closed-loop system for integrating sustainability in landscape design. Figure 8 concisely visualises these steps and their interactions. The framework's strength lies in making landscape architecture a data-rich, iterative process analogous to BIM for buildings, thereby elevating the role of landscape in achieving smart city goals. Figure 9 should also be included as a valuable illustration of how one can drill down into a specific process (vegetation modelling) within the overall framework. Together, these figures translate the conceptual framework into a tangible depiction that practitioners and researchers can understand at a glance. [Text (Body)-ABC2, Aptos, 11]

[Text (Body)-ABC2, Aptos, 11]

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The authors declare no conflict of interest.

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