

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

**SMART SUSTAINABLE BUILDING-CITY INTEGRATION EVALUATION
MODEL (SSB-CIEM)**



Ph.D. THESIS

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Department of Architecture

Project and Construction Management Programme

JULY 2025

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

**AKILLI SÜRDÜRÜLEBİLİR BİNA-ŞEHİR BÜTÜNLEŞMESİ
DEĞERLENDİRME MODELİ (ASB-ŞBDM)**

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To my family,



FOREWORD

This doctoral thesis signifies more than an academic pursuit; it encapsulates a significant life lesson grounded in patience, sacrifice, hope, and devotion. The successful completion of this thesis, which has transcended various challenges, stands as a testament to my intrinsic motivation, the invaluable mentorship of my advisor, and the steadfast support of my family.

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July 2025

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ABBREVIATIONS

AR	: Augmented Reality
AVE	: Average Variance Extracted
BIM	: Building Information Modeling
CB-SEM	: Covariance Based Structural Equation Modeling
CityGML	: City Geography Markup Language
GIS	: Geographical Information System
HTMT	: Heterotrait-Monotrait
IFC	: Industry Foundation Classes
IoT	: Internet of Things
KML	: Keyhole Markup Language
LEED	: Leadership in Energy and Environmental Design
LIDAR	: Light Detection and Ranging
SSB-CIEM	: Smart Sustainable Building-City Integration Evaluation Model
SSR	: Smart Sustainable Resilience
SSE	: Smart Sustainable Environment
SSMo	: Smart Sustainable Mobility
SSA	: Smart Sustainable Aesthetics
SSMa	: Smart Sustainable Management
SSWW	: Smart Sustainable Welfare-Wellbeing
RFID	: Radio-Frequency Identification
UAVs	: Unmanned Aerial Vehicles
VR	: Virtual Reality
PLS-SEM	: Partial Least Square Structural Equation Modeling



SYMBOLS

ρ_A	: Rho_a/composite reliability
ρ_C	: Rho_c/composite reliability
R^2	: Coefficient of determination
f^2	: Effect size
Q^2	: Predictive relevance





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SMART AND SUSTAINABLE BUILDING-CITY INTEGRATION EVALUATION MODEL (SSB-CIEM)

SUMMARY

The urban landscape is undergoing a significant transformation, with cities currently housing 55% of the world's population, a figure projected to reach 68% by 2050. This increase is driven by individuals seeking enhanced opportunities in both work and education. However, this rapid urbanization has led to the depletion of natural resources, primarily due to the construction sector's high resource consumption and unsustainable growth patterns. Since the 1970s, there has been a growing emphasis among policymakers on sustainable development. International collaboration has been critical in developing policies and research that promote smart and sustainable building and urban practices. Such initiatives are crucial for mitigating the impacts of global warming and enhancing the quality of urban life. The terms "smart" and "sustainable" are intrinsically linked, representing two facets of a comprehensive approach to urban and building development. "Smartness" plays a vital role in enhancing the effectiveness of sustainability initiatives through innovative methods and technologies. Despite the potential advantages of an integrated approach to smart sustainable building and urban development, these benefits are often underappreciated. Achieving either "smart" or "sustainable" design in isolation fails to unlock the full potential of these concepts. Therefore, it is imperative that smart and sustainable features of buildings and cities synergize, supported by advanced digital technologies in construction. This thesis proposes a systematic evaluation framework for integrating smart sustainable building-city concepts. Such an integration evaluation involves assessing the current state of digital technology usage to identify opportunities. Through a comprehensive literature review and frequency analysis, the proposed model encompasses thirty-six indicators categorized under six areas. Following this, an expert panel convened by the Ministry of Environment, Urbanization, and Climate Change validated these areas. The identified areas are: 1. Smart Sustainable Resilience (SSR), 2. Smart Sustainable Environment (SSE), 3. Smart Sustainable Management (SSMa), 4. Smart Sustainable Aesthetics (SSA), 5. Smart Sustainable Mobility (SSMo), 6. Smart Sustainable Welfare and Well-Being (SSWW). Indicators are derived from prevalent tools within the literature related to smart and sustainable evaluation, specifically focusing on their applicability throughout the building lifecycle, which includes planning, construction, operation, and demolition. The strength of these indicators lies in their relevance at the intersection of building and urban development, facilitating a more integrated approach to smart sustainability.

In the digital age, achieving smart and sustainable integration in construction can be accomplished through the use of Building Information Modeling (BIM) and Geographic Information Systems (GIS). BIM is a tool used in the construction sector to create digital representations of building designs and streamline project delivery processes. In contrast, GIS is a technology that processes geographical data, allowing for the capture, storage, integration, processing, analysis, and display of spatially

referenced information. Integrating BIM and GIS combines the physical and geographic information of buildings (microscale) with urban systems (macroscale) to provide an advanced methodology for a comprehensive management approach to smart sustainable cities. This doctoral thesis aims to evaluate the maturity of construction professionals in Türkiye regarding the integration of smart sustainable building and city concepts using BIM and GIS throughout the building life cycle. It is expected that these professionals will evaluate the integration of Smart Sustainable Building-City based on the availability of both physical and digital infrastructure within their city and projects. To evaluate the indicators of this integration, five levels of questions have been prepared: 1. Data is not utilized, 2. Either BIM data or GIS data is utilized, 3. BIM data and GIS data are used separately, 4. BIM data and GIS data are used in a partially integrated manner, 5. BIM data and GIS data are fully integrated.

An online survey was conducted using Google Forms to provide the necessary data for testing SSB-CIEM. The survey was meticulously designed and consisted of three chapters. The first chapter included demographic questions and BIM/GIS familiarity, the second chapter measured the maturity level about SSB-CIEM areas (SSR, SSE, SSMa, SSMo, SSA, SSWW), and the third chapter measured the SSB-CIEM indicators (36 indicators). The collected data were initially analyzed using SPSS. As it was assumed that the data were not normally distributed, non-parametric tests were employed to ensure the highest level of accuracy. A reliability test (Cronbach's Alpha) was conducted on the cleaned dataset.

Firstly, a comparison test was performed for the entire sample through the Nonparametric One-Sample Wilcoxon Signed Rank Test. While the hypothetical median across all areas and indicators was set at 4, the observed median was significantly lower: recorded at 2 for the indicator SSMa2 (indicating the utilization of either BIM or GIS data) and 1 for all other areas and indicators, suggesting a lack of data utilization. Nonparametric tests, including the Kruskal-Wallis One-Way ANOVA and the Mann-Whitney U Test, were used to compare the means of sectors regarding the use of BIM and GIS technologies in integrated smart sustainable building-city. Significant findings revealed that despite small differences in mean rankings, public sector professionals consistently reported higher mean rankings for all indicators assessed. Although some of the indicators did not show any significant difference in the evaluation results, it was concluded that there was a significant difference between the public and private sectors for some indicators. However, according to the evaluation results of the six main areas (maturity), there was no significant difference between the public and private sectors regarding the use of BIM-GIS data.

In this doctoral thesis, a robust framework is established to assess the reliability and validity of the Smart Sustainable Building-City Integration Model (SSB-CIEM) through a conceptual Structural Equation Modeling (SEM). This initial model consists of seven latent variables: Smart Sustainable Resilience (SSR), Smart Sustainable Environment (SSE), Smart Sustainable Aesthetics (SSA), Smart Sustainable Management (SSMa), Smart Sustainable Mobility (SSMo), Smart Sustainable Welfare and Wellbeing (SSWW), and Smart Sustainable Maturity (SSMaturity), accompanied by 42 observed variables. The SSMa and SSMaturity serve as dependent variables, while SSR, SSE, SSMo, SSA, and SSWW act as independent variables. This framework leads to the formulation of six hypotheses, suggesting that the implementation of BIM and GIS among Turkish construction professionals has a positive influence on the integration of smart, sustainable buildings and cities, particularly in management contexts. To validate these hypotheses, Partial Least

Squares Structural Equation Modeling (PLS-SEM) was employed, utilizing SmartPLS software. PLS-SEM is particularly advantageous in exploratory research because it accommodates smaller sample sizes, allows for the analysis of single-question scales, does not impose stringent model fit criteria, and does not necessitate the assumption of normality in the data. Furthermore, it adeptly captures relationships between latent and manifest variables in both reflective and formative manners.

The PLS-SEM structure using data collected for SSB-CIEM, along with rigorous reliability and validity assessments, elucidates the interrelationships among the model's components. The adapted PLS-SEM, revised to fit the threshold values based on the results of Cronbach's Alpha, Composite Reliability, Discriminant Validity, and Multicollinearity tests, ultimately comprises the latent variables SSR, SSE, a combined variable of SSWW, SSMo, and SSA, along with 24 observed variables. Thus, the six hypotheses prepared according to the draft model are revised and reduced to four hypotheses. The PLS-SEM analysis indicate that all four hypotheses have been accepted. This reveals a positive effect of integrating BIM and GIS technologies in evaluating the integration of smart sustainable buildings and cities among Turkish construction professionals through management maturity (SSMa). In particular, it was found that the combined effect of Smart Sustainable Welfare-Wellbeig (SSWW), Smart Sustainable Mobility (SSMo), and Smart Sustainable Aesthetics (SSA) had the most significant impact on Smart Sustainable Management (SSMa). It emphasizes the importance of prioritizing user well-being, inclusive mobility, and environmental aesthetics during the digital transformation of urban areas. On the other hand, while there is a significant effect of integrated BIM/GIS management maturity (SSMa) on the overall perception of maturity (SSMaturity), its explanatory power is relatively low. This finding may arise from the differences between perceived maturity levels (six main areas) and the actual maturity levels observed (indicator level). Ongoing efforts are being made to establish standardized and holistic integrated smart sustainable building-city practices alongside the use of BIM/GIS in Türkiye.

The outcomes from the PLS-SEM analysis primarily indicate the positive effect of the integrated application of BIM and GIS technologies on the dependent variable SSMa, which serves to assess the maturity of smart sustainable building and city integration among Turkish construction professionals. Notably, it identifies that the combined effect of SSWW, SSMo, and SSA exerts the most significant influence on SSMa. Conversely, while the integration of BIM/GIS within the SSMa area exhibits low explanatory power, it demonstrates a considerable effect on maturity. The findings emphasize the importance of developing ICT infrastructure and enhancing the use of integrated BIM and GIS to improve the integration of smart sustainable buildings and cities. To achieve this, steps that can be taken include creating educational programs at universities, establishing standards to promote smart sustainable technologies and applications, and implementing financial incentives. Additionally, the SSB-CIEM initiative aims to enhance urban development and improve city service programs by exploring the potential for integrating buildings with city infrastructure. This initiative is expected to serve as a roadmap for investments in infrastructure and superstructure projects directed by the Ministry of Environment, Urbanization, and Climate Change. The ministry can formulate strategies for metropolitan and district municipalities involved in city management. SSB-CIEM can support investment decisions in infrastructure for integrated smart sustainable building-cities. Additionally, it may inspire innovative projects through collaboration among the public, private, and academic sector.



AKILLI SÜRDÜRÜLEBİLİR BİNA-ŞEHİR BÜTÜNLEŞMESİ DEĞERLENDİRME MODELİ

ÖZET

Şehirler dünya nüfusunun %55'inin yaşadığı yerler olsa da, iş ve eğitim gibi alanlarda daha iyi fırsatlar bulmak için bu rakamın 2050 yılına kadar %68'e çıkması bekleniyor. Şehirlerdeki bu hızlı ve kontrolsüz nüfus artışı, doğal kaynakların tükenmesini hızlandırmıştır. Bu durumun oluşmasında en önemli faktörlerden biri, şehirlerdeki inşaat faaliyetlerinin hızlanması ve buna bağlı olarak göz ardı edilemez doğal kaynak tüketimidir. Kentleşme ve tüketim oranlarındaki bu önemli artış, 1970'lerden itibaren uluslararası politikaları zorunlu kıldı ve politika yapıcılar sürdürülebilir kalkınma kavramından bahsetmeye başladılar. Ülkeler, iş birliği içerisinde uluslararası politikaları ve araştırmaları desteklerken, küresel ısınmanın ortadan kaldırılması ya da etkilerinin en aza indirilebilmesi için, akıllı ve/veya sürdürülebilir bina-şehir pratiklerinin gerekliliğine inandılar. “Bina” ve “şehir” için “akıllı” ve “sürdürülebilir” kavramları bir madalyonun iki yüzü gibi birbirinden ayrılmaz parçalardır ve “akıllılık”, yöntem ve teknolojilerle “sürdürülebilir hedeflere” ulaşmada etkinliği sağlayabilir. Ancak bir şehrin ya da binalarının ayrı ayrı akıllı ya da sürdürülebilir olması, tam manasıyla akıllılık ya da sürdürülebilirliği sağlayamaz. Bina ve şehirlerin akıllı ve sürdürülebilir kapasitelerinin inşaatta kullanılan en son dijital teknolojiler yardımı ile birlikte çalışabilirliği, akıllı sürdürülebilir bina-şehir bütünleşmesini sağlamanın bir yoludur.

Mevcut şehir yönetim sistemleri, bütünleşik akıllı sürdürülebilir bina-şehir konseptinin sistematik olarak ele alınmasının sürdürülebilirliğe sağlayacağı potansiyel faydaları göz ardı eder. Binalar ve şehirlerin akıllı sürdürülebilirliği ayrı araçlar ile değerlendirilir. Bu nedenle bu doktora tezi, bütünsel ve sistematik bir Akıllı Sürdürülebilir Bina-Şehir Bütünleşmesi Değerlendirme Modeli (ASB-ŞBDM) kurmayı amaçlar. İlk olarak, kalitatif ve kantitatif (bibliyometrik analiz) araştırma yöntemlerinin her ikisini birden içeren ayrıntılı ve güncel sistematik literatür taraması yapılmıştır. Bu kapsamlı literatür taramasının birinci bölümü ile, akıllı sürdürülebilir bina-şehir arakesitindeki alanlar ve göstergelerin belirlenmesi için, akıllı sürdürülebilir bina ve şehir değerlendirme araçları derinlemesine analiz edilmiş ve kavramsal bir ASB-ŞBDM çerçevesi çizilmiştir. Sistematik literatür taramasının ikinci bölümünde ise, inşaatta yararlanılan bütünleşik YBM (yapı bilgi modellemesi), CBS (coğrafi bilgi sistemi) ve birlikte çalışan dijital teknolojiler derinlemesine araştırılmış; ASB-ŞBDM alan ve göstergelerinde kullanımları analiz edilmiştir. Literatür taramasını takiben sıklık analizi yapılarak, taslak Akıllı Sürdürülebilir Bina-Şehir Bütünleşmesi Değerlendirme Modeli hazırlanmıştır. Modelde altı ana alan altında gruplandırılmış 36 alt başlık (gösterge) vardır. Bu alanlar: akıllı sürdürülebilir dayanıklılık, akıllı sürdürülebilir çevre, akıllı sürdürülebilir yönetim, akıllı sürdürülebilir estetik, akıllı sürdürülebilir hareketlilik ve akıllı sürdürülebilir sağlık-refah (ASD, ASÇ, ASE, ASY, ASH ve ASSR)'tır. Göstergeler, literatürdeki akıllı veya sürdürülebilir bina-şehir değerlendirme modellerinde/araçlarında yaygın olarak yer alan göstergelerden, bir

binanın yaşam döngüsü boyunca (planlama, inşaat, işletme ve yıkım) “bina-şehir bütünleşmesi potansiyeli taşıyanlardan” seçilmiştir. Göstergelerin temsil gücü, binaların şehir ile ilişkili göstergelerinden diğer bir deyişle bina-şehir kesişimindeki alanlardaki uygulamalardan gelir.

ASB-ŞBDM bütünleşme değerlendirme ölçeği, literatürde binalar ve şehirlerin yönetim sistemlerinde öne çıkan iki temel teknolojiye; YBM (yapı bilgi modellemesi) ve CBS (coğrafi bilgi sistemi) odaklanmıştır. YBM, inşaat sektöründe yapıların temsilini ve proje teslim süreçlerini dijitalleştirmede kullanılan bir araçtır. CBS, coğrafi verileri işleyerek, mekansal referanslı verileri yakalayan, depolayan, bütünleştiren, işleyen, analiz eden ve görüntüleyen bir bilgi sistemi teknolojisidir. Binaların (mikro ölçekli) fiziksel-coğrafi bilgilerini kentsel sistemlerle (makro ölçekli) birleştirmek için YBM verileri ve CBS verilerini bütünleştirmek, akıllı sürdürülebilir şehirlere bütünsel yönetim yaklaşımı için gelişmiş bir metodoloji sunar. Bu kabulle, akıllı sürdürülebilir bina-şehir bütünleşmesi alanlarına ait göstergeleri değerlendirmek üzere hazırlanan beş seviyeli bütünleşme değerlendirme ölçeği şöyledir: 1. Veri kullanılmamaktadır, 2. YBM verisi veya CBS verisinden biri kullanılmaktadır, 3. YBM verisi ve CBS verisi ayrı ayrı kullanılmaktadır, 4. YBM verisi ve CBS verisi kısmen bütünleşik bir şekilde kullanılmaktadır, 5. YBM verisi ve CBS verisi tamamen bütünleşik bir şekilde kullanılmaktadır. ASB-ŞBDM, Çevre, Şehircilik ve İklim Değişikliği Bakanlığı, Akıllı Şehirler Dairesi Başkanlığı personellerinden oluşan bir uzman paneli tarafından değerlendirilerek, tüm alan ve göstergelerin modelde kullanılmasına karar verilmiştir.

Taslak ASB-ŞBDM'nin geçerlilik ve güvenilirlik testlerinin yapılabilmesi için, modelin bir anket ile mimar, mühendis ve şehir plancılarını kapsayan Türkiye'deki inşaat sektörü profesyonellerince değerlendirilmesi planlanmıştır. Profesyonellerden, hazırlanan ASB-ŞBDM'nin içerdiği alan ve göstergeleri, projelerinde YBM/CBS kullanım durumlarına göre değerlendirmeleri beklenmiştir. ASB-ŞBDM'yi test etmek için, veri toplama aracı olarak Google Formlar kullanılarak çevrimiçi bir anket yürütüldü. Anket titizlikle tasarlandı ve üç bölümden oluşturuldu. İlk bölümde demografik sorular ve YBM/CBS aşinalığı yer alırken, ikinci bölümde Türkiye'deki inşaat sektörü profesyonellerinin projelerinde, ASB-ŞBDM alanlarındaki (ASD, ASÇ, ASE, ASY, ASH ve ASSR) olgunluk düzeyi ölçüldü. Üçüncü bölümde ASB-ŞBDM göstergelerinin (36 gösterge) bütünleşme ölçeğine göre değerlendirilmesi beklendi. Bu bölümler ASB-ŞBDM'yi test etmek için gerekli verileri sağlamıştır. Toplanan veriler başlangıçta SPSS kullanılarak analiz edildi. Verilerin normal dağılım göstermediği varsayıldığından, en yüksek doğruluk düzeyini sağlamak için parametrik olmayan testler kullanıldı. Toplanan ve düzenlenen veri kümesinde bir güvenilirlik testi (Cronbach'ın Alpha katsayısı) gerçekleştirildi.

Daha sonra tüm örneklem için nonparametrik tek örneklemli Wilcoxon İşaretli Sıra Testi ile bir karşılaştırma testi gerçekleştirildi. Tüm alanlar ve göstergeler için varsayımsal medyan 4 olarak belirlenirken, gözlenen medyan önemli ölçüde daha düşüktü: SSMA2 göstergesi için (YBM veya CBS verilerinin kullanımını gösterir) 2 olarak kaydedilirken, diğer tüm alanlar ve göstergeler için 1 olarak kaydedildi ve bu sonuçlar veri kullanımının eksikliğini gösterdi. Kruskal-Wallis tek yönlü ANOVA ve Mann-Whitney U Testi de dahil olmak üzere nonparametrik testler, bütünleşik akıllı sürdürülebilir bina-şehirde, YBM ve CBS teknolojilerinin kullanımına ilişkin sektörlerin cevaplarının ortalamalarını karşılaştırmak için kullanıldı. Önemli bulgular, ortalama sıralamalarındaki küçük farklılıklara rağmen, kamu sektörü profesyonellerinin değerlendirilen tüm göstergeler için sürekli olarak daha yüksek ortalamaya sahip

olduğunu ortaya koydu. Değerlendirme sonuçlarında bazı göstergeler önemli bir fark göstermese de, bazı göstergeler için kamu ve özel sektör arasında önemli bir fark olduğu sonucuna varıldı. Ancak altı ana alanın (olgunluk) değerlendirme sonuçlarına göre, YBM-CBS verilerinin kullanımı açısından kamu ve özel sektör arasında anlamlı bir fark bulunmamıştır.

Bu doktora tezinde, ASB-ŞBDM'nin güvenilirliği ve geçerliliğini test etmek için kavramsal bir yapısal eşitlik modeli (YEM) hazırlanmıştır. Bu başlangıç modeli, yedi gizli değişken ve 42 gözlemlenen değişkenden oluşmaktadır. Gizli değişkenler: Akıllı Sürdürülebilir Dayanıklılık (ASD), Akıllı Sürdürülebilir Çevre (ASÇ), Akıllı Sürdürülebilir Estetik (ASE), Akıllı Sürdürülebilir Yönetim (ASY), Akıllı Sürdürülebilir Hareketlilik (ASH), Akıllı Sürdürülebilir Sağlık-Refah (ASSR) ve Akıllı Sürdürülebilir Olgunluk (ASO)'dir. ASY ve ASO ekzojen bağımlı değişkenlerken; ASD, ASÇ, ASH, ASE ve ASSR endojen bağımsız değişkenlerdir.

Kavramsal yapısal eşitlik modeline uygun olarak toplam altı hipotez geliştirildi. Bu hipotezler, Türk inşaat sektörü profesyonelleri arasında akıllı sürdürülebilir bina-şehir bütünleşmesi alanlarında (ASD, ASÇ, ASE, ASY, ASH ve ASSR), YBM-CBS teknolojilerinin kullanımının akıllı sürdürülebilir binaların ve şehirlerin yönetim bütünleşmesine ve bütünleşme olgunluğuna etkisini test etmek üzere kurulmuştur. Hipotezleri test etmek için SmartPLS programından yararlanılarak, KEKK-YEM-Kısmi En Küçük Kareler Yapısal Eşitlik Modellemesi (Partial Least Square Structural Equation Modeling-PLS-SEM) hazırlanmıştır. KEKK-YEM yeni geliştirilen keşfedici çalışmalarda daha çok tercih edilir. Bunun yanı sıra, düşük örneklem ile çalışabilir, tek sorulu ölçeklerle analiz yapabilir, standartlaşmış genel kabul gören model uyum ölçütleri yoktur ve toplanan verilerin normal dağılımını zorunlu tutmaz. Dahası gizli ve gözlenen değişkenler arasındaki ilişkiyi yansıtıcı ve biçimlendirici yollar ile sunabilir. KEKK-YEM'in ASB-ŞBDM için toplanan verinin özelliklerine uyması, güvenilirlik ve geçerlilik testleri ile modelde yer alan yapılar arasındaki ilişkileri açıklamadaki güçlü yönleri, ASB-ŞBDM 'nin yansıtıcı ölçüm modellerini ve yapısal modelini test etmek için uygun bir tercih olduğunu gösterir.

ASB-ŞBDM için toplanan veriler kullanılarak KEKK-YEM'in oluşturulması, titiz güvenilirlik ve geçerlilik değerlendirmeleriyle birlikte, modelin bileşenleri arasındaki karşılıklı ilişkileri açıklığa kavuşturur. Cronbach'ın Alfa'sı, bileşik güvenilirlik, ayırt edici geçerlilik ve çoklu doğrusallık testlerinin sonuçları doğrultusunda, literatürde yer alan eşik değerleri sağlamak üzere revize edilir. Uyarlanmış KEKK-YEM, son durumda 24 gözlenen değişkenle birlikte, bir birleşik yapı olan "ASSR-ASH-ASE", ve dört diğer yapı "ASD, ASÇ, ASY, ASO" olmak üzere beş gizli değişkenden oluşur. ASB-ŞBDM'in analizi için hazırlanan KEKK-YEM'in modifiye edilmesi, kurulan altı hipotezin de basit değişiklik içeren yeniden düzenlenmesini gerektirmiştir. ASB-ŞBDM için hazırlanan model son durumda dört hipotez üzerine kurulmuştur. Bu hipotezler, ASSR-ASH-ASE, ASD ve ASÇ'nin ASY üzerine olumlu etkisi ve ASY'nin ASO üzerine olumlu etkisi olduğunu savunur.

Bu doktora tezi güvenilirlik ve geçerlik testlerinden başarı ile geçmiş; KEKK-YEM analizinden elde edilen sonuçlar kurulan dört hipotezi de desteklemiştir. Bulgular, Türk inşaat profesyonellerinin akıllı sürdürülebilir bina ve şehir bütünleşme alanlarında kullanılan bütünleşik YBM/CBS teknolojilerinin, ASY üzerinde açıklayıcı gücünü ve etkisinin olumlu olduğunu göstermektedir. Özellikle, Akıllı Sürdürülebilir Sağlık-Refah (ASSR), Akıllı Sürdürülebilir Hareketlilik (ASH) ve Akıllı Sürdürülebilir Estetik'in (ASE) birleşik etkisinin Akıllı Sürdürülebilir Yönetim (ASY)

üzerinde en önemli olumlu etkiye sahip olduğu bulunmuştur (Hipotez 3 desteklendi). ASSR, ASH ve ASE boyutlarının entegrasyonu, yönetim uygulamalarını şekillendirmede temeldir. Kentsel alanların dijital dönüşümü sırasında kullanıcı refahını, kapsayıcı hareketliliği ve çevresel estetiği önceliklendirmenin önemini vurgular. Hipotez 1 ve hipotez 2'nin test sonuçları, ASR'nin ve ASE'nin de ASY üzerinde olumlu etkisinin olduğunu gösterir (Hipotez 1 ve hipotez 2 desteklendi). Öte yandan, bütünleşik YBM ve CBS yönetim olgunluğunun (ASY) genel olgunluk algısı (ASO) üzerinde olumlu bir etkisi olmasına rağmen (Hipotez 4 desteklendi), açıklayıcı gücü nispeten düşüktür. Bu bulgu, algılanan olgunluk seviyeleri (altı ana alan) ile gözlemlenen gerçek olgunluk seviyeleri (gösterge seviyesi) arasındaki farklardan kaynaklanıyor olabilir. Bu sonuçlar, Türkiye'de bakanlıkların YBM ve CBS kullanımı ile ilgili çalışmalarının hali hazırda devam ettiği göz önünde bulundurularak değerlendirilmiştir. Diğer taraftan yine bakanlıkların standartlaştırılmış ve bütünsel bütünleşik akıllı sürdürülebilir bina-şehir uygulamaları oluşturmak için çalışmalarının da devam ettiği bilinmektedir.

Bu doktora tezinin bulguları, akıllı sürdürülebilir binaların ve şehirlerin bütünleşmesini iyileştirmek için bilgi teknolojileri/dijital teknoloji altyapısının geliştirilmesinin ve bütünleşik YBM ve CBS kullanımının artırılmasının önemini altını çizmektedir. Bunu başarmak için atılabilecek adımlar arasında üniversitelerde eğitim programları oluşturmak, akıllı sürdürülebilir teknolojileri ve uygulamaları teşvik etmek için standartlar belirlemek ve finansal teşvikler uygulamak yer almaktadır. Ek olarak, ASB-ŞBDM girişimi, binaları şehir altyapısıyla bütünleştirme potansiyelini araştırarak kentsel gelişimi artırmayı ve şehir hizmet programlarını iyileştirmeyi amaçlamaktadır. Bu girişimin, Çevre, Şehircilik ve İklim Değişikliği Bakanlığı tarafından yönetilen altyapı ve üstyapı projelerine yapılan yatırımlar için bir yol haritası görevi görmesi bekleniyor. Bakanlık, bu modelden faydalanarak, şehir yönetiminde söz sahibi olan büyükşehir ve ilçe belediyeleri için stratejiler formüle edebilir. ASB-ŞBDM, bütünleşik akıllı sürdürülebilir bina şehirler için altyapıya yatırım kararlarını destekleyebilir. Ayrıca, kamu, özel ve akademi arasında iş birliği yoluyla yenilikçi projelere ilham verebilir.

1. INTRODUCTION

1.1 Purpose of Thesis

Integration between smart and sustainable buildings and their urban context has become increasingly vital in the face of rapid urbanization and technological advancement. Although numerous tools exist to evaluate either smart or sustainable features of buildings, the literature reveals a distinct lack of comprehensive models that assess their combined integration within the urban fabric. This gap highlights the need for a unified evaluation framework that captures both smart and sustainable dimensions across building and city scales.

The objective of this thesis is to create an evaluation model that facilitates the integration of smart sustainable buildings with smart sustainable urban frameworks. This study involves testing a model that leverages the Geographic Information System (GIS) platform to assess the level of integration within a smart sustainable city, utilizing the Building Information Modeling (BIM) platform throughout a smart sustainable building's life cycle, which includes phases of planning, construction, operation and maintenance, and demolition.

The SSB-CIEM, developed through meticulous literature analysis and expert panel evaluation, aims to evaluate the impact of various areas and indicators on the managerial maturity of smart sustainable building-city integration. Hypotheses were formulated to evaluate the effects of the integrated application of BIM and GIS technologies within designated areas and indicators on the smart sustainability management and the overall maturity of smart sustainable building-city integration. This doctoral thesis explores how the convergence of these technologies can enhance decision-making processes, optimize resource management, and promote sustainable practices across various domains.

This doctoral thesis seeks to compare the readiness for smart sustainable building-city integration among construction sector employees, distinguishing between public, private, and university sectors professionals; architects, engineers, and city planners.

The model serves as a visionary framework, with the thesis findings poised to enhance the evaluation of smart and sustainable building-city initiatives for a range of stakeholders involved in urban development. These stakeholders may include decision-makers within the construction sector, policymakers, investors, and central-local government all of whom play critical roles in shaping the future of building practices in urban settings.

1.2 Problem Statement

The rapid urban population growth globally poses significant physical and economic challenges, as articulated by Nam & Pardo (2011). This demographic shift leads to escalating demands on urban systems, resulting in several key consequences summarized by Janik & Ryszko (2020):

1. Heightened demand for green spaces and agricultural land to accommodate urban development.
2. Increased environmental threats stemming from air pollution and the rising volume of liquid and solid waste generated by urban populations.
3. Strain on urban resources, including water, food, and fossil energy, due to the surging population.
4. Growing needs for public services encompassing sanitation, public transportation, healthcare, and education.
5. Escalating air pollution and traffic congestion linked to the rising number of vehicles.
6. The necessity of integrating new technologies in urban development and management, which can enhance living conditions for some while presenting adaptation challenges for others.

Ogunmakinde et al. (2024) highlight a significant gap between current achievements and the requisite advancements in areas such as climate change, population dynamics, environmental sustainability, communication technologies, globalization, poverty alleviation, technological innovation, and urban disaster prevention. This disparity is particularly pronounced between the construction sectors in developing and developed nations. Addressing the aforementioned urbanization challenges necessitates a shift

towards smart and sustainable city management. Policymakers, urban planners, and professionals within the Architecture, Engineering, Construction, and Facility Management (AEC/FM) sectors must leverage the information and communication technology (ICT) tools available in the digital era. The rapidly evolving capabilities of these ICT tools are pivotal for enhancing efficiency in both the separate and integrated management of building systems and city information systems. Such technological empowerment is crucial in tackling urbanization challenges. Building Information Modeling (BIM) offers a comprehensive approach to the management of building projects across their entire lifecycle, employing advanced technology tools and software within the AEC/FM industry (Biswas et al., 2024). BIM plays a critical role in cost estimation during construction tenders (Zhiliang et al., 2011) and facilitates various functions including 3D modeling and visualization, clash detection, and logistics management during the design phase (W. Zhang et al., 2023). The integration of cutting-edge technologies in construction, alongside the digitalization of processes, fosters a new paradigm that is conducive to innovation and enhancement in construction management (Biswas et al., 2024). The BIM model effectively merges the properties of building elements with spatial data sets, creating a virtual representation that is continuously refined through real-time information from construction and operational processes via the Internet of Things (IoT) (Tang et al., 2019). This dynamic dataset ensures data accuracy and reliability, heralding a promising future for construction management practices.

The intersection of Building Information Modeling (BIM) and Geographic Information Systems (GIS) presents significant opportunities for enhancing construction and urban planning processes. While BIM provides detailed, building-scale information crucial for construction professionals, challenges remain in integrating this data with broader environmental factors such as shading, landscape analysis, and city-scale dynamics. Effective integration can yield substantial benefits, including improved efficiency and accuracy in construction projects.

GIS, on the other hand, excels in spatial analysis, employing physical and functional representations to understand various environments (Rafiee et al., 2014). Unlike BIM, which contains rich semantic information, GIS is primarily focused on managing and visualizing spatial information, drawing relationships between different geographic elements (Yigitcanlar et al., 2023). The synergistic integration of BIM and GIS

capitalizes on the strengths of both systems, allowing for the combined utilization of their capabilities (Yigitcanlar et al., 2023). Several studies have explored the implications of this integration, highlighting its applicability across various areas. For example, Rafiee et al. (2014) proposed a method to directly integrate a building's IFC BIM model with the GIS environment.

Furthermore, there exists a burgeoning potential for the integration of building operations and city management systems, leading to the development of innovative evaluation models. Such models would assess the integrated use of BIM in the context of smart sustainable buildings and GIS in relation to smart sustainable cities. This dual focus could significantly contribute to the design and function of smart sustainable urban environments, fostering advancements in city planning and management.

1.3 Research Vision

SSB-CIEM is designed to enhance urban services and guide the development of city programs by leveraging the potential of building-city integration. This approach is anticipated to serve as an effective model for investment in infrastructure and superstructure projects by the Ministry of Environment, Urbanization, and Climate Change, which is responsible for devising city management strategies. It will also be beneficial for metropolitan and district municipalities that play a significant role in governance. Furthermore, this model has the capacity to inspire innovative projects that promote collaboration among public institutions, private sector entities, and academic bodies. In this context, all stakeholders and the anticipated impacts of the developed model are summarized in the Table 1.1.

Table 1.1 : Stakeholders affected by SSB-CIEM and Effect' Directions.

Stakeholders	Effects/ Expected benefits
Public Institutions (Republic of Türkiye Ministry of Environment, Urbanisation and Climate Change)	A standardized model allows decision-makers to assess the potential for smart, sustainable buildings and the capacities of cities. It enables the evaluation of these potentials in project investments and aids in the development of strategies and policies.
Public Institutions (Metropolitan and District Municipalities)	A standardized model helps decision-makers determine the potential for smart, sustainable buildings and the capacities of cities. It facilitates the evaluation of these potentials in project investments and supports the implementation of relevant projects.

Table 1.1 (continued) : Stakeholders affected by SSB-CIEM and Effect' Directions.

Stakeholders	Effects/ Expected benefits
Private Sector (Project and Construction Firms and Technology Production Firms)	A standardized model empowers decision-makers to identify the potential for smart, sustainable buildings and cities in construction projects. It allows for the evaluation of these potentials in project investments and promotes the acceleration of research and development (R&D) activities, fostering growth in investments related to smart sustainable city technologies.
Private sector (Material Production)	A standardized model accelerates R&D efforts focused on smart and sustainable building materials in Türkiye, enhancing the appeal of these materials.
Citizens	Residents benefit from living in energy-efficient, environmentally friendly, and comfortable buildings and cities. This approach ensures that the basic needs of future generations are met through the efficient use of the world's resources.
Universities	A standardized model expands knowledge related to smart sustainable buildings and cities, encourages the development of projects through collaboration between public entities, the private sector, and universities, and facilitates the evaluation of building-city integration.

1.4 Scope and Limitations of Thesis

The research topics and goals pursued in this thesis are as follows:

Goal 1: Analyze and delineate the areas and criteria pertinent to smart sustainable cities within the framework of the model.

Goal 2: Analyze and delineate the areas and criteria relevant to smart sustainable buildings within the framework of the model.

Goal 3: Identify and assess intersection areas and criteria within the framework of the model.

Goal 4: Develop and rigorously evaluate the integration evaluation scale.

Goal 5: Construct the model based on the identified criteria and areas.

Goal 6: Assess the reliability and validity of the model through statistical tests.

The construction sector, both globally and in Türkiye, has not yet achieved significant maturity in smart and sustainable building and urban applications. As a result, the model developed offers a forward-looking perspective and is referred to as a “vision model.” To evaluate this model, an assessment was conducted on the current level of integrated use of BIM (Building Information Modeling) and GIS (Geographic Information Systems) technologies by architects, engineers, and urban planners involved in building and urban projects within the construction sector. A crucial factor

to consider when interpreting the model's test results is that the use of these platforms has not yet been standardized or made mandatory.

1.5 Research Questions for Thesis

The thesis outlines a series of research questions aimed at exploring the integration of smart and sustainable building and city concepts. Each question targets a different aspect of this integration, facilitating a comprehensive understanding of the subject:

RQ1. Defining concepts: The first research question seeks to establish a clear and thorough definition of smart and sustainable building-city concepts, alongside integrated approaches that may exist in the field. This will form the foundation for understanding their interplay.

RQ2. Evaluation areas and indicators: The second question is focused on identifying specific intersection areas and indicators that can be used in building-city assessment tools. This is essential for evaluating the effectiveness and efficiency of smart sustainable integration.

RQ3. Digital technology opportunities: The third question examines the transformative potential of advanced digital construction technologies throughout the building life cycle. The aim is to highlight how these technologies can enhance the integration of smart and sustainable practices within building and city frameworks.

RQ4. Model interaction: The fourth question investigates how different areas of the integration evaluation model interact with one another and how these interactions influence overall management integration maturity. Understanding these dynamics is crucial for developing effective assessment models.

RQ5. BIM and GIS integration in Türkiye: Finally, the fifth question emphasizes the importance of utilizing Building Information Modeling (BIM) in conjunction with Geographic Information Systems (GIS) technologies. This inquiry specifically addresses the role of construction professionals including architects, engineers, and urban planners in Türkiye, underscoring the relevance of integrated practices in achieving smart sustainable building-city outcomes.

Through this comprehensive set of questions, the research aims to deepen the understanding of smart and sustainable integration, inform policy and practice, and

ultimately contribute to the development of more resilient and efficient urban environments.

1.6 Research Methodology

The research presented in this thesis employs a combination of qualitative and quantitative methodologies to explore the concept of integration of smart sustainable building-city evaluation. A systematic literature review, augmented by bibliometric analysis, forms the foundation of this research. The quantitative aspect involved collecting and mapping publication data through bibliometric software, while qualitative insights were garnered through content analysis and feedback from an expert panel.

The literature review encompassed a broad range of sources, including influential articles, books, conference proceedings, standards, and reports pertinent to the research topic. Comprehensive content analyses were performed on the acquired publications, with a particular focus on the application of integrated Building Information Modeling (BIM) and Geographic Information Systems (GIS) within the construction sector. This investigation yielded significant findings regarding Smart Sustainable Building-City Integration Evaluation Model (SSB-CIEM), areas and associated indicators, which were further validated through frequency analyses.

To reinforce the findings, an expert panel comprising professionals from the Ministry of Environment, Urbanization and Climate Change participated in face-to-face interviews. Additionally, a survey was administered to professionals in the Turkish construction sector to assess the validity and reliability of the SSB-CIEM framework. The survey data were subsequently analyzed using basic statistical tools with SPSS and advanced techniques, specifically Partial Least Squares Structural Equation Modeling (PLS-SEM), utilizing the Smart PLS software. This multi-faceted approach provides a robust evaluation of the SSB-CIEM, while contributing to the body of knowledge on integrated managed smart sustainable-building city construction practices using the latest digital technologies.

1.7 Structure of Thesis

The studies carried out throughout the thesis are shown in Figure 1.1.

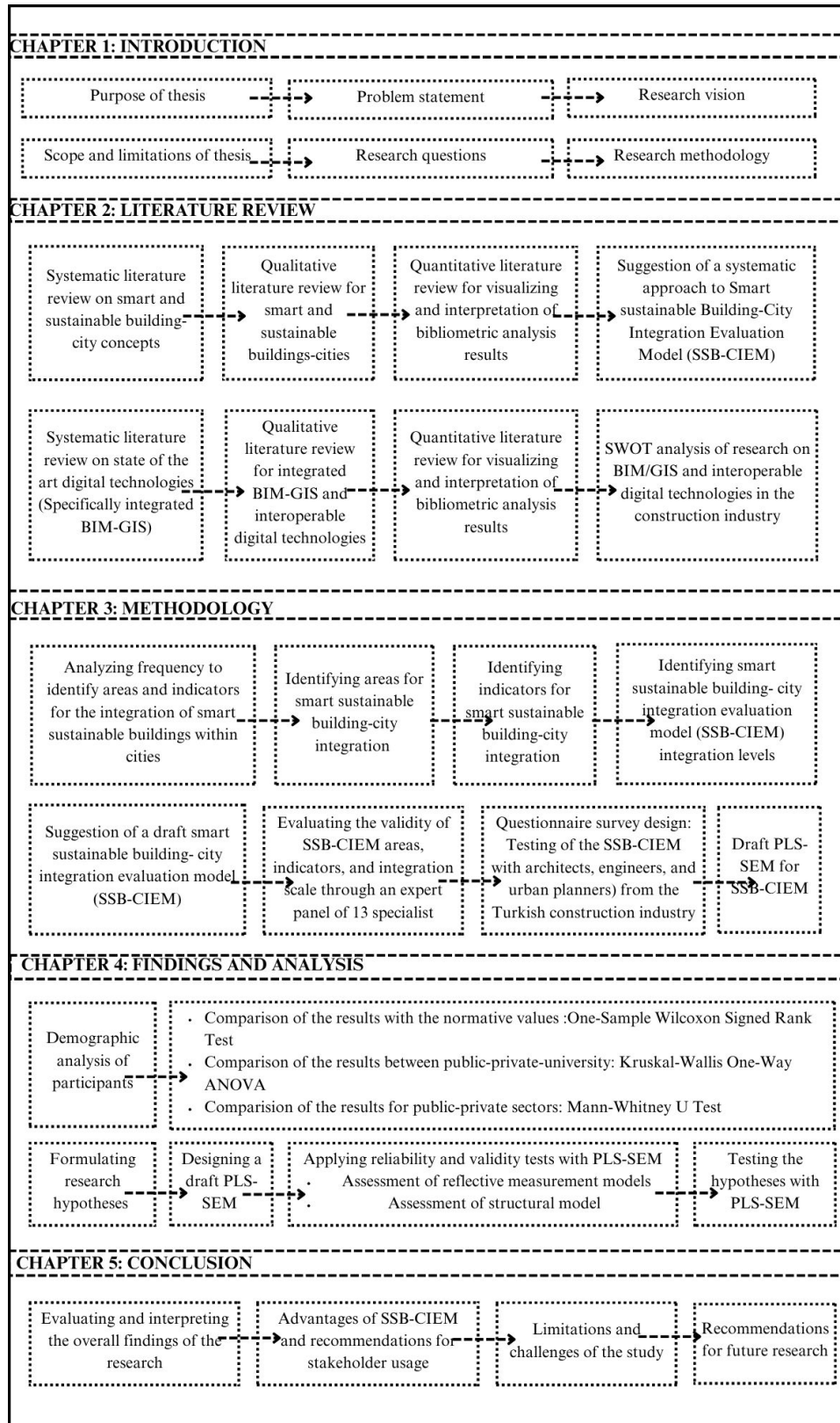


Figure 1.1 : Structure of the thesis.

2. LITERATURE REVIEW

This chapter provides an in-depth examination of sustainability in urban development, emphasizing the critical importance of smart, sustainable building-cities. It explores contemporary evaluation methods that assess the effectiveness of smart and sustainable building-cities. Additionally, it identifies and discusses the challenges related to the Smart Sustainable Building-City Integration (SSB-CI). The chapter also delves into the integration of cutting-edge digital technologies that are fundamental to these concepts. The aim of this review is to establish a robust theoretical foundation for SSB-CIEM, clarifying essential concepts and offering a nuanced understanding of how the application of digital technologies, particularly the integration of Building Information Modeling (BIM) and Geographic Information System (GIS) in construction, influences the seamless integration of smart sustainable buildings and cities. In this context, systematic literature review-1 (SLR-1) and systematic literature review-2 (SLR-2) studies were conducted.

2.1 SLR-1: Smart and Sustainable Building-City

The researchers employed a systematic four-step methodology to develop the Smart Sustainable Building-City Integration Evaluation Model (SSB-CIEM). The process is illustrated in Figure 2.1 and includes the following steps:

1. **Qualitative Literature Review:** This initial step investigates the interrelationships among existing concepts related to sustainability and the integration of smart buildings within urban environments. The focus is framed through the lens of Smart Sustainable Building-City Integration (SSB-CI), examining its applicability to both buildings and cities.
2. **Visualizing and Interpretation of Bibliometric Analysis Results:** This step involves analyzing existing literature quantitatively to identify trends and patterns that inform the understanding of SSB-CI.

3. Critical Analysis of Current Evaluation Tools: The researchers critically evaluate existing tools for assessing building-city integration, identifying strengths, weaknesses, and gaps in the current methodologies.

4. A Systematic Approach to SSB-CIEM: Finally, a coherent framework is proposed that synthesizes insights from the previous steps, offering a systematic approach to evaluate and enhance building-city integration sustainably.

This structured methodology aims to contribute to the discourse on smart sustainable urban development, bridging theoretical frameworks with practical evaluation methods.

The process of visualizing and interpreting bibliometric analysis results (Step 2) is divided into several key steps: planning, filtering, analysis, and reporting. During the planning phase, researchers select specific keywords that aptly describe their research questions, constructing queries to guide their data collection. The chosen sampling method focuses on integrating various areas through building and city evaluation tools using a bottom-up approach. The keywords selected are drawn from the most prevalent terms in recent literature within the field, as highlighted in the literature background. To ensure a comprehensive literature search, all relevant concepts such as "smart building," "sustainable building," "evaluation," "assessment," and "ranking" are input into the Scopus database/search engine. While additional normative concepts could potentially broaden the sample, the research is constrained to the predetermined keywords, which also dictate the sample size.

In the filtering phase, the articles are scrutinized based on their titles, abstracts, and keywords, encompassing all relevant articles from the oldest to the most recent available through Scopus. This is inclusive of studies on both emerging and existing tools for evaluating smart or sustainable buildings and cities. The analysis is limited to articles published in English that contain the searched keywords. While there is an inherent risk of encountering articles that may not directly pertain to the research question, such irrelevant articles are excluded to maintain result accuracy.

The analysis phase focuses on visualization through science mapping, utilizing Bibliometrix (specifically the Biblioshiny interface), an open-source software tool compatible with R Studio (Kim et al., 2021). This tool allows for the visualization of large datasets, including co-occurrence networks of keywords.

Finally, the reporting phase highlights pivotal themes and findings in studies of smart and sustainable building-city evaluations.

The critical analysis of current evaluation tools (Step 3) includes a content analysis of the articles that were bibliometrically analyzed. The results highlight the strengths and weaknesses of smart, sustainable building and city evaluation tools. These identified strengths and weaknesses provide a comprehensive understanding of the intersection areas for SSB-CIEM.

A systematic methodology for SSB-CIEM (Step 4) encompasses the synthesis of insights garnered from prior analyses, complemented by a conceptual diagram and a maturity graph. The conceptual diagram delineates integration areas derived from a content analysis of building and city evaluation studies, resonating with Stieninger's (2016) assertion that "a smart building system changes inputs and outputs in balance with the city." This foundational approach, backed by literature on data integration between buildings and urban environments, underscores the role of cutting-edge digital technologies such as BIM and GIS.

2.1.1 Research Methodology for SLR-1

2.1.1.1 Identifying research questions for SLR-1

Research questions (RQs) serve as essential tools for simplifying the understanding and summarization of investigated concepts (Kim et al., 2021). This study employs a systematic quantitative literature review (SQLR) to identify articles that respond to five specific RQs. These questions focus on evaluations related to smart and sustainable building-city integration (SSB-CI), examining concepts, research trends, and identifying strengths and weaknesses up until January 2023. Through this approach, the review delineates SSB-CI intersection areas, formulates a concept diagram for SSB-CI evaluation methods (SSB-CIEM), and establishes criteria for evaluating SSB-CI maturity.

RQ1: What studies focus on smart/sustainable building-city evaluations and integration evaluations? Articles identified through targeted queries will be analyzed via bibliometric methods and keyword co-occurrence techniques to extract prominent concepts.

RQ2: What are the strengths and weaknesses found in smart/sustainable building-city evaluations? Identified strengths and weaknesses, as noted by various authors, will be emphasized through thorough content analysis.

RQ3: What are the intersection areas of smart and sustainable building-city initiatives? The results of the content analysis will be utilized to define these intersection areas clearly.

RQ4: What framework can be established to facilitate a systematic approach to SSB-CI evaluation model?

This structured examination aims to advance understanding and application within the field, fostering improved methods for evaluating the integration of smart and sustainable initiatives within urban contexts.

2.1.1.2 Database selection for SLR-1

The use of academic databases such as Scopus and Web of Science (WoS) plays a crucial role in identifying relevant studies within a specific research field. According to Pickering & Byrne (2014), adopting a systematic and comprehensive strategy enhances the quality of literature reviews. In this context, Scopus is highlighted as a significant resource, recognized for its extensive coverage of peer-reviewed literature (Harzing & Alakangas, 2016; Jin & Ji, 2018). The platform's Boolean Syntax facilitates the creation of complex keyword combinations, which ensures a meticulous examination of the literature relevant to the field. Furthermore, Scopus serves as a reputable alternative to WoS, contributing to its esteemed status in various international university rankings, including the Times Higher Education rankings (Harzing & Alakangas, 2016). This makes Scopus an essential tool for researchers aiming to conduct comprehensive reviews and analyses.

The focus of academic research often involves balancing the quality and breadth of sources utilized. For instance, while Google Scholar offers a large repository of articles, its quality control mechanisms can be inadequate due to its reliance on scanning various academic-related websites. This often results in a mix of highly credible and less reliable sources.

In contrast, databases like Scopus provide a more rigorous approach to content selection. With over 29,200 active serial titles and contributions from more than 7,000

publishers, Scopus ensures that its materials are not only extensive but also thoroughly reviewed and independently verified (*Scopus Content*, 2024). This makes it an invaluable resource for researchers looking to develop comprehensive literature reviews, especially on niche topics like smart sustainable building and city evaluations.

The preference for Scopus in studies related to construction project management and smart city services underscores its role in academic research. Numerous literature reviews have cited it prominently (Akindele et al., 2023; Akinlolu et al., 2022; Celeste et al., 2022; Rigillo et al., 2023; Sepasgozar et al., 2021; M. Wang et al., 2020) highlighting its reliability and the quality of its indexed content. This makes Scopus a go-to choice for academics aiming to ensure the credibility of their references and the thoroughness of their research findings.

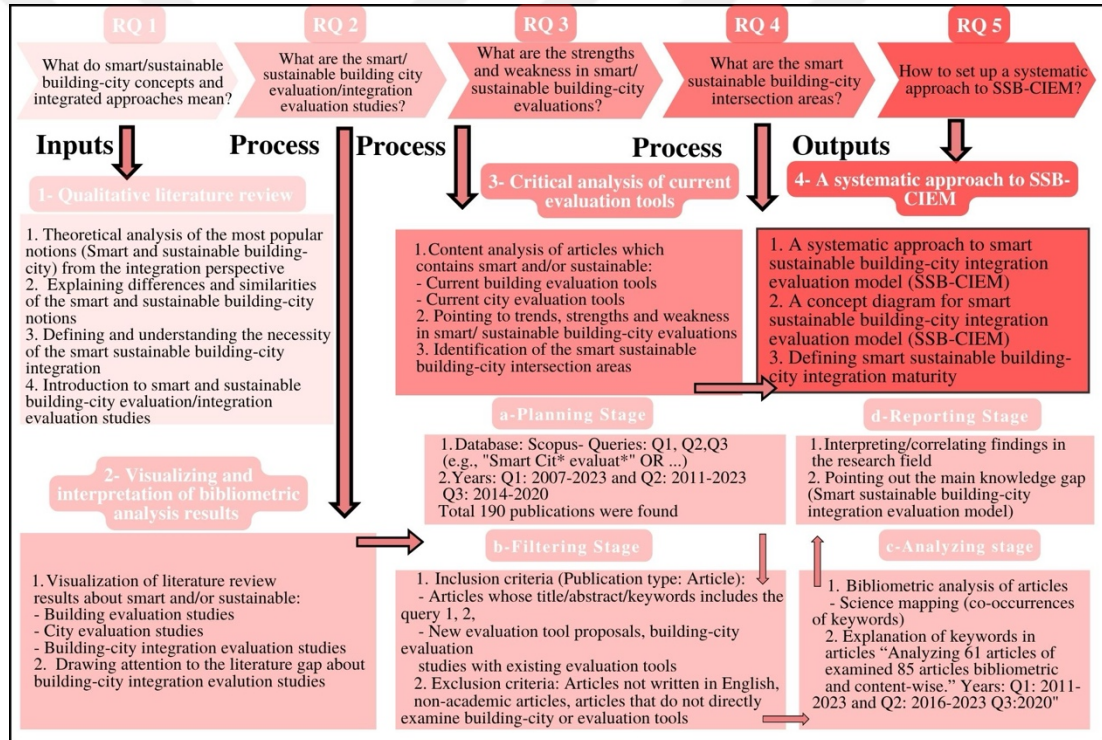


Figure 2.1 : Research methodology for systematic literature review 1 (Sarigül & Günaydın, 2025).

2.1.2 Qualitative literature review

2.1.2.1 Sustainability approach

Currently, 55% of the world's population resides in cities, and this figure is expected to rise to 68% by 2050 as people seek better opportunities in work and education (UN-Habitat, 2022; UN Habitat, 2020). The rapid increase in urbanization has made the need for international policies more urgent. In the 1970s, policymakers began

discussing sustainable development. Since then, numerous international meetings have taken place, including the signing of the Paris Agreement, which included important decisions regarding climate action. In December 2023, the United Nations organized the twenty-eighth session of the Conference of the Parties (COP 28) to address climate issues. COP 28 involved a comprehensive review of the climate change mitigation targets set forth in the Paris Agreement (2016). During this conference, countries acknowledged that progress in reducing greenhouse gas emissions, enhancing resilience to climate change, and providing financial and technological support to vulnerable nations has been slow. There was a particular emphasis on the need to prioritize renewable energy sources over fossil fuels (United Nations, 2023).

Sustainability is a critical concept that encompasses the risks and triggers of environmental crises, as well as social and economic factors. It is essential to recognize that our future could be jeopardized due to ecological and social deprivation, such as resource scarcity, which is exacerbated by increasing social disruptions from a globalized market and a lack of skilled labor (Bibri and Krogstie, 2017). Notably, cities consume 70-80% of the world's resources while occupying only 2% of its land (Bibri, 2018; Hong et al., 2017) highlighting the urgent need for sustainable urban development. To foster sustainable living for citizens, it is necessary to build adaptable, resilient, and high-quality infrastructure that ensures livable, accessible, and safe urban environments (Sala Benites et al., 2022).

Buildings are essential components of cities, responsible for 40% of global energy consumption and 36% of energy-related greenhouse gas emissions (European Commission, 2021). This is primarily due to the energy required for heating, cooling, ventilation, and lighting (Engelsgaard et al., 2020). The necessity of resource optimization, planning, and control is a sine-qua non in high-density urban areas (Akcin et al., 2016; Calvillo and Villar, 2016). Furthermore, the significant use of water and materials in construction compared to other sectors highlights the serious adverse environmental impacts associated with buildings (Ann et al., 2020) and underscores the urgent need to design smart sustainable buildings.

Smart sustainable buildings represent a relatively new approach that merges the principles of ecological buildings such as sustainability, green design, and passive features with the characteristics of smart buildings (Radziejowska and Sobotka, 2021). This integrated approach clarifies the distinction between smart buildings,

which may overlook sustainability, and sustainable buildings, which may not consider information and communication technology (ICT). The concepts of "smart" and "sustainable" in relation to buildings and cities are interconnected, much like two sides of the same coin. "Smartness" enhances the efficiency of achieving "sustainable goals" through innovative methods and technologies.

Given these insights, it is evident that international policies and research have endorsed the practices of smart and sustainable building and city development to create a more livable world, especially in mitigating climate change's impacts. However, the potential benefits of systematically addressing the integrated concept of smart sustainable buildings and cities remain largely overlooked.

2.1.2.2 Smart and sustainable building approach and elements

The impact of buildings on environmental sustainability is significant, but their impact on human health and work efficiency is equally important, as people spend 90% of their time indoors (Stieninger, 2016). The first step in adopting a human-centered approach is to install smart systems that enhance user comfort (Markoska et al., 2019). Sensors collect data from various devices using the Internet of Things (IoT), and this information is stored in real-time in a corresponding database (Yang et al., 2022). A smart building approach that employs control algorithms and IoT one of the information and communication technologies (ICTs) can continuously monitor environmental data, provide management strategies for minimizing energy consumption, and optimize interior comfort (Lin et al., 2020). Additionally, it can manage various tasks such as surveillance, access control, and fire detection (Lam et al., 2023).

The potential for Information and Communications Technology (ICT) to enhance the design, construction, and operation of smart buildings has necessitated a reassessment of the technologies employed in current building production methods (Apanaviciene et al., 2020a; Chiesa, 2020). Cutting-edge technologies in the construction industry enable real-time data collection, monitoring, and control. This optimization of processes adds economic value through online platforms (Piras et al., 2024): Data acquisition (IoTs, UAV (Unmanned Aerial Vehicles)/drones, Geographical Information Systems (GIS), Laser Imaging Detection and Ranging (LIDAR), Global Positioning Systems (GPS), Sensors, Radio-frequency identification (RFID), data

analytics (Big data, artificial intelligence/machine learning), data visualization (BIM, 3D printing, Robotics, DFab (Digital fabrication)), sensing and digital technologies ((BIM), (GIS), (GPS), laser, satellite, light detection and ranging (LIDAR) (Sepasgozar et al., 2019). Gonçalves et al. (2020) developed a machine learning model for smart building energy management using predictive control; Lin et al. (2020) created a solar-powered smart window blind system with automatic controls. Additionally; (Louis and Dunston (2018) simulated a process model that utilized IoT-enabled control and sensor data at the construction site to facilitate real-time and autonomous decision-making.

Integrating digital technologies into construction significantly improves urban planning and land cover management, supporting sustainable development initiatives. According to Barrile et al. (2023), the integration of BIM and GIS enables the combination of detailed physical-geographical data at the building level (microscale) with urban power systems at a broader level (macro-scale). This approach offers an innovative methodology for managing building energy in the Municipality of Reggio Calabria, Italy.

On a related note, Qian and Leng, 2021) introduce the concept of "Community Intelligent Modeling," a three-dimensional simulation platform that serves as a conduit between buildings and advanced environmental analysis software. This platform aggregates data from BIM, GIS, the Internet of Things (IoT), and other cutting-edge technologies to address low comfort levels, inadequate safety, and excessive energy consumption. Collectively, these efforts pave the way for the development of smart sustainable cities, where buildings equipped with digital technologies seamlessly integrate with urban components to promote environmental sustainability and enhance human comfort.

2.1.2.3 Smart and sustainable building definitions

In order to establish a robust framework for this thesis study, it is essential to comprehend the concepts surrounding smart and intelligent buildings. The existing literature offers numerous definitions that delineate smart buildings, intelligent buildings, sustainable buildings, and other related concepts. A selection of these definitions is summarized in Table 2.1, which serves to illustrate the diversity of perspectives within this domain.

Table 2.1 : Smart/intelligent building definitions (1988-2020).

Definition	Author-Year
An intelligent building utilizes predictions based on an integrated database containing building and usage information, automating the control of multiple service systems through information and communication networks.	Leifer, 1988
The buildings that enhance the efficiency of the built environment by optimizing structures, systems, services, and management approaches must consider the relationships among these elements.	Caffrey (1985) (Intelligent Buildings Institute, Washington DC)
They are buildings that can determine and execute appropriate behaviors based on environmental influences.	(CABA, 2008)
These buildings fulfill both the comfort and energy-saving needs of their occupants.	(Meryem et al., 2018; Zhang et al., 2013)
Intelligent buildings strive for sustainability by incorporating advancements in their design.	(GhaffarianHoseini et al., 2013)
Intelligent buildings are structures that integrate intelligence, initiative, control, materials, and construction into a cohesive building system. With adaptability at their core, these buildings aim to meet the criteria of energy efficiency, longevity, comfort, and overall satisfaction in their operation.	(Buckman et al., 2014)
In addition to integrating technology, information, and communication systems, this approach includes environmental, socio-cultural, and economic indicators.	(Meryem et al., 2018)
These buildings depend on remote operation and control for convenience, comfort, cost savings, and energy efficiency throughout their lifecycle. To achieve this, advanced technologies are integrated into the buildings and systems.	(Jia et al., 2019)
Smart buildings are generally buildings that combine sustainable and green building qualities and draw attention to the building's design, construction, and operation phases throughout its life cycle.	(Apanaviciene et al., 2020b).
It is a building with a balanced interaction with the city regarding infrastructure, information and communication technologies (ICT), smart technologies, and energy saving. It includes the concept of "sustainability."	(Froufe et al., 2020)
The building increases the productivity of the building users by keeping the air quality at the appropriate level, ensuring safety, providing lighting and other physical comfort requirements, and taking sanitation and space availability measures.	(Zhuang et al., 2020)

2.1.2.4 Smart and sustainable city approach and elements

The concept of a sustainable city began to emerge in the late 1990s, and it lacks a single, universally accepted definition in the literature (Janik & Ryszko, 2020). The most widely accepted description is "a city approach that can meet the needs of the present without compromising the needs of future generations" (Fink & Kaltenegger, 2016). Additionally, the idea of a "smart" city is a key component of the sustainability movement (Arditi et al., 2015). This concept encourages a re-evaluation of how we build and manage our urban environments (Höjer, M. and Wangel, 2015) and introduces new requirements for cities that must operate with limited resources, ensuring that residents can maintain their well-being (Austin et al., 2020; Azevedo et al., 2018; Sladoljev et al., 2019). The notion of smart cities originated in the 1990s (Albino et al., 2015), but its roots trace back to the Cybernetically Planned Cities of

the 1960s and later evolved into Networked or Computable Cities in the 1980s (Gabrys, 2014). Although there is no universal and inclusive definition of a smart city (Apanaviciene et al., 2020a; X. Li et al., 2019; Lima et al., 2020), it is generally understood as an approach that incorporates modern information and communication technologies (ICTs) in city planning, construction, operation, and management (Xia et al., 2022). In summary, a smart city is an interconnected system that prioritizes people and the environment, aims to improve quality of life, and focuses on monitoring and optimizing resources, management, security, mobility, and technology. It emphasizes the importance of smart ICT, data, and rational decision-making. This perspective supports the argument that studies on smart cities are instrumental in achieving the goals of sustainable urban development through both methodology and technology.

While the smart city concept aims for sustainability, the emergence of the smart sustainable city (Ahvenniemi et al., 2017; Bibri and Krogstie, 2017) highlights the need for cities to be both sustainable (flexible and inclusive) and digitally competent (ITU, 2021). This new phenomenon, which gained momentum in the mid-2010s and is still relatively underexplored (Janik & Ryszko, 2020; Taveres-Cachat et al., 2019), is a testament to the potential for cities to enhance the quality of life for their residents (Kutty et al., 2023).

Global examples demonstrate that integrated 3D geographical information of both the ground and underground in Chongqing, China, enhances urban planning, public facilities management, construction simulation technologies, and emergency response efforts (GIM International, 2017). In contrast, Denmark's relatively easy access to open data promotes collaboration between municipalities and the private sector, which aids decision-makers in developing smart city solutions (Snow et al., 2016). The top three indicators for smart sustainable city rankings show the following for Copenhagen, Denmark: wastewater treatment, e-commerce, and patent applications. For other European cities, the indicators are as follows: Berlin: bicycle network, wastewater treatment, and e-commerce; Paris: wastewater treatment, unemployment, and greenhouse gas (GHG) emissions; Rome: GHG emissions, protected terrestrial areas, and PM10 concentration.

Smart and sustainable cities represent an emerging paradigm in urban development, wherein technological innovations and eco-friendly practices converge to create more efficient living environments. Hong Kong serves as a notable example of a smart city,

utilizing advanced technologies to enhance urban management and improve the quality of life for its inhabitants. Conversely, Masdar City in Abu Dhabi exemplifies an eco-city project focused on sustainable practices aimed at minimizing environmental impact (Oyewobi et al., 2023).

However, a critical challenge arises when smart technologies and sustainable practices are not seamlessly integrated. This disjunction can lead to uneven patterns of urban development, undermining the potential benefits of both approaches (Oyewobi et al., 2023). It underscores the importance of adopting (BIM) alongside sustainability initiatives. These methodologies should be assessed collectively to foster better outcomes in urban planning and construction (Oyewobi et al., 2023).

The latest advancements in technology, particularly IoT-based sensor technology, allow for cost-effective continuous monitoring of urban components (Tripathi et al., 2023). Additionally, artificial intelligence and machine learning provide crucial infrastructure for the digitalization of daily operations within local governments (Siokas et al., 2021). For instance, Ford et al. (2020) developed a conceptual framework for a smart city digital twin that enhances disaster management efforts. Similarly, Austin et al. (2020) proposed a city digital twin architecture that integrates a semantic model and machine learning, applying it specifically to buildings in Chicago. Furthermore, Revelo Cáceres et al. (2023) demonstrated the integration of BIM, GIS, and Life Cycle Assessment (LCA) to analyze the urban densification of high-rise structures in Quito, Ecuador. Their findings indicated that operational energy has the most significant impact on urban development. These studies emphasize the importance of an integrated approach that combines building and city infrastructure with cutting-edge digital technologies to better serve building occupants. Furthermore, there is a pressing need for increased research into the acceptance and implementation of smart and sustainable practices within construction projects. Understanding the factors that influence their integration can provide valuable insights into developing more resilient and adaptable urban environments. Emphasizing the interplay between smart tools and sustainability practices not only advances urban development but also addresses broader social, economic, and environmental challenges faced by cities.

2.1.2.5 Smart city definitions

A thorough understanding of the smart city concept is crucial for establishing the conceptual framework of this thesis study. To aid in this exploration, Table 2.2 presents a range of definitions related to smart and intelligent buildings.

Table 2.2 : Smart city definitions.

Smart city definition	Author-Year
It is a city that does not ignore security while taking it to the next level; it monitors and integrates the conditions of all critical infrastructures, including roads, bridges, tunnels, railways/metros, airports, ports, communications, water, energy, and even large buildings, can better optimize their resources, plan preventive maintenance activities, and maximize services for their citizens.	(Hall et al., 2000)
It is a city based on the smart combination of donations and activities of self-determined, informed, and independent citizens, which performs well forward-looking in six characteristics (economy, governance, people, mobility, environment, and life).	(Giffinger et al., 2007)
It is a city that supports investments in human, social capital, traditional (transportation) and modern (BIT) communication infrastructure, supports sustainable economic development, provides high-quality life, and smart management of natural resources through governance.	(Caragliu et al., 2009)
It is a city where physical, information, social, and business infrastructures are interconnected to leverage the city's shared intelligence.	(Harrison et al., 2010)
It is the city that makes the city services smarter, more interconnected, and efficient with the help of smart computing technologies, the main actors in the infrastructure components of the city, which are effective in city management, education, health services, public security, real estate, transportation services, and other public services.	(Washburn & Sindhu, 2010)
It is a smart planet approach applied to a specific region to provide integrated and informative management of cities.	(K. Su et al., 2011)
It is a new city model representing a community with average technology development, a strong level of interrelationship, a sustainable, high level of welfare, attractive, and without security problems.	(Lazaroiu & Roscia, 2012)
The effective integration of the physical, digital and human systems makes up the built environment stakeholders sustainable, prosperous and inclusive future for city dwellers.	(BSI, 2014)
It is a local government-oriented city that uses information and communication technologies (ICT) by working with many stakeholders to solve the problems faced by the public.	(European Parliament, 2014)
The city approach is constantly shaped in parallel with the developments in technology and urban activities and covers many disciplines.	(Angelidou, 2015)
Using innovative technology; combining energy, mobility, and infrastructure; increasing performance and efficiency; increasing the participation of city residents; It is the understanding of the city that enables innovations and improves the socio-economic texture of the city.	(Bosch & Jongeneel, 2017)

Table 2.2 (continued): Smart city definitions.

Smart city definition	Author-Year
Smart city development; is a development that uses technology, data, and intelligent design to increase the livability, operability, and sustainability of the community.	(Smart Cities Council, 2018)
Using technology to improve the quality of life by improving city services and infrastructure; enhancing the understanding of governance by increasing stakeholder interactions; It is a city that combines intelligence and sustainability approaches.	(Luis Azevedo Guedes et al., 2018)
The city uses ICT to increase its livability, workability, and sustainability.	(Smart Cities Council, 2019)
Expressing a common benefit such as a single building, neighborhood, or even a single infrastructure system, with the city part only for individuals or small parts of a community to benefit; with its smart part, it is a city approach that improves “decision making” to produce a benefit such as interruption or water shortage management, using real-time data collected with the help of information and communication technologies (ICT), smart metering technology for electric power and water systems in the city.	(Ford et al., 2020)
It is a city transformation concept that should aim to achieve an environmentally more sustainable city with a higher quality of life, providing opportunities for the economic growth of citizens, taking into account the characteristics of the city residents living in the area where each local government dominates.	(Toli & Murtagh, 2020)

The definitions presented in Table 2.2 can be distilled into several key components that characterize an effective intelligence tool for urban management:

1. **Holistic Monitoring and Integration:** As an advanced intelligence concept must be capable of continuously monitoring and integrating various dimensions of city infrastructure encompassing physical elements, information and communication technology (ICT), social dynamics, and business activities. This integration aims to enhance citizens' experiences, with particular attention to sectors such as municipal administration, education, healthcare, public safety, real estate, and transportation.
2. **Decision-Making Support:** This concept should bolster decision-making processes by facilitating a comprehensive understanding of urban studies through the real-time collection, evaluation, and processing of relevant city data.
3. **Local Government Relevance:** The functionalities of the concept are closely aligned with the operational needs and responsibilities of local government entities.
4. **Economic and Social Studies:** The concept focuses on essential areas, including economic advancements, governance, demographics, transportation systems, environmental sustainability, and solutions to social challenges, alongside promoting cultural initiatives.

5. Citizen Engagement: The concept fosters a culture of civic awareness, encouraging informed participation among residents.
6. Empowerment of Residents: The concept empowers city dwellers to actively shape their own living environments while also enhancing recreational and entertainment opportunities.
7. Quality of Life: The concept's overarching goal is to elevate the quality of life for residents, which directly correlates with social welfare enhancement.
8. Smart Resource Management: Effective management of natural resources must be prioritized, with a focus on efficiency and environmental sensitivity.
9. Job Creation: This type city concept should facilitate the availability of local employment opportunities, contributing to economic growth and stability.
10. Technological Development: A baseline of technology should be established to support the endeavors of building this type of city concept.
11. Safety and Security: Finally, the ideal smart urban environment is devoid of significant security issues, ensuring the safety and well-being of all citizens. This environment collectively includes modern, sustainable urban features capable of addressing the diverse needs of its inhabitants while promoting growth and resilience.

2.1.2.6 The lens of smart sustainable building-city integration (SSB-CI)

Every new building design within urban environments must be harmonious with existing development plans and the overall urban texture. If an energy-efficient building design leads to a significant transformation of the existing urban landscape, it may negatively impact the energy efficiency of the surrounding neighborhood (Futcher et al., 2017). In other words, the aggregate energy efficiency of the urban form may be inferior to the sum of the energy efficiencies of individual, isolated buildings (Futcher et al., 2017). Moreover, the design and operation of smart, sustainable physical and digital building systems, while considering the existing urban infrastructure, have the potential to enhance resource efficiency in areas where various environmental resources and city services are integrated, similar to developments in the energy sector. A more comprehensive analysis of the interplay between smart buildings and urban environments is presented as follows:

In contemporary architectural discourse, the concept of a designed building is often portrayed as a self-contained entity, akin to an island, isolated from its surrounding human communities, ecological systems, and the broader natural environment. While such buildings may incorporate advanced technologies like solar panels and systems for the recycling of gray water, black water, rainwater, and organic waste, their categorization as "green" or "smart" can be misleading. These buildings may achieve net-zero energy consumption and showcase sustainability innovations; however, their operation typically remains confined to a closed-loop system, comprised solely of rainwater and solar energy as inputs. (Stieninger, 2016).

This perspective raises critical questions about the definition of "smartness" in architecture. A truly smart building should not only excel in material technology and energy efficiency but also engage with the dynamic interplay of a sustainable urban ecosystem. By facilitating a two-way exchange with other components of a smart city thus supporting the principles of reuse and recycling buildings can contribute significantly to the ecological and social fabric of their environments. For a city to thrive sustainably, it must embrace continuous evolution, akin to a living organism, with buildings that provide feedback about their environmental interactions. In this context, a smart city transcends the mere collection of advanced technological features, requiring a holistic approach that fosters balanced exchanges between its built infrastructure and natural systems. Such interactions are vital for promoting a healthy and environmentally responsible urban lifestyle.

In his 2016 work, Stieninger posits that a building cannot be considered "smart" solely based on the incorporation of advanced technologies and smart systems if it is not designed with an integrative approach that encompasses all components of the urban system. This perspective underscores the critical importance of integration in the development of smart buildings. According to Stieninger, the role of smart buildings within the urban framework involves fostering a harmonious and environmentally sustainable relationship with surrounding connected structures and infrastructures. Key aspects of this integration include the effective delivery of essential resources to the building, the management of waste produced by the building, the interaction between the interior and exterior environments, and the facilitation of movement for individuals entering and exiting the building. These elements collectively define the building's integration with both its natural and constructed environments.

The advancement of digital construction technologies has facilitated the emergence of smart buildings and smart cities, which are capable of interconnecting physical, digital, and theoretical frameworks (Kim et al., 2021). Recent studies, such as that by Gao et al. (2024), have integrated Building Information Modeling (BIM), Geographic Information Systems (GIS), and Life Cycle Assessment (LCA) to develop a Multi-information integration-based life cycle analysis technique. This method was employed to assess the spatial distribution of greenhouse gas emissions during the production, transportation, and construction phases in Shenzhen, China.

Further, Mair et al. (2023) introduced a framework for the recycling of construction materials through the utilization of BIM, GIS, and LCA technologies, enhancing the sustainability of building practices. Cinquepalmi et al. (2023) proposed an innovative tool designed for the rapid automatic pre-evaluation of the potential transformation of existing building stocks into residential spaces, leveraging integrated BIM and GIS technologies. In another significant contribution, Costantino et al. (2022) combined BIM, 3D GIS, LIDAR, and Grasshopper (Rhino) to gather numerical cartography and geospatial data from platforms like Open Street Map and airborne LIDAR point clouds. Their analysis and simulations facilitated the visualization of projects ranging from illustrations to photorealistic renderings, thereby advancing the 3D modeling of buildings and urban environments.

The smart city data platform plays a crucial role by receiving and disseminating data among smart city components (Apanaviciene et al., 2020a). Within the framework of a smart city, dynamic and self-learning control systems enable components to interact and optimize energy consumption, thereby enhancing the integration of buildings with the broader city energy management systems (De Groote et al., 2017). Moreover, buildings are essential in managing local stormwater while microgrids ensure access to drinking water and the treatment and reuse of wastewater (Stieninger, 2016). However, it is important to note that not all cities possess an optimal smart-ready environment, which can result in underutilization of advanced ICT capabilities within buildings until the city infrastructure catches up, or vice versa (Apanaviciene et al., 2020a). Consequently, an essential first step in advancing smart sustainable urban development is to evaluate the current level of building-city integration, thereby identifying potential areas for sustainable intersection and improvement.

2.1.2.7 Evaluation approach for SSB-CI

Sustainability in building design has garnered significant attention in recent years, underscored by various certification systems such as Leadership in Energy and Environmental Design (LEED), Building Research Establishment Environmental Assessment Method (BREEAM), and WELL, which focus on performance-based evaluations. These widely accepted frameworks have prompted some academic research to propose new local tools for assessing building sustainability (H. Kang et al., 2016). Notably, countries like Japan and Hong Kong have integrated criteria for both smart and green buildings within their certification systems, while other nations, such as Korea, have adopted entirely distinct approaches to evaluation (Amirhosein Ghaffarianhoseini et al., 2016).

A majority of existing research tends to concentrate on urban environments, utilizing systematic reviews or quantitative methods (Bibri & Krogstie, 2017; Janik & Ryszko, 2020; Kim et al., 2021; Palumbo et al., 2021; Pérez & Oltra-badenes, 2020). However, the literature reflects a gap in studies specifically focused on smart building evaluations (Buckman et al., 2014; Ghaffarianhoseini et al., 2018). The Smart Readiness Indicator (SRI), which emphasizes energy savings and operational efficiency while addressing user and grid needs, has emerged as a prominent research focus, particularly with support from the European Commission (Fokaides et al., 2020; Markoska et al., 2019; Martínez et al., 2021; Ramezani et al., 2021). Additionally, tools such as the Building Intelligent Quotient (BiQ) and the Honeywell Smart Building Score (HSBS) have been referenced in the academic discourse, highlighting the ongoing evolution of smart building evaluation methodologies.

The concept of smart cities has become increasingly integral to national strategies and action plans, with a notable rise in the number of cities adopting smart city networks. A thorough evaluation of applications aimed at enhancing the smartness and sustainability of urban areas is essential. Existing literature spans approximately three decades, concentrating on the assessment and comparison of sustainability and impact performance across cities using widely accepted indicators and various assessment tools. Giffinger et al. (2007) present a seminal study in this field, identifying six critical components of smart cities: smart mobility, smart living, smart environment, smart governance, smart people, and smart economy. Subfields of the study are included in Table 2.3. Despite extensive research, current evaluation tools remain inadequate in

assessing the integration between buildings and urban environments according to contemporary criteria. This gap underscores the need for improved methodologies to analyze the interplay between individual structures and the broader urban ecosystem in the context of smart cities. Therefore, further research is essential to create more comprehensive evaluation frameworks that can effectively reflect this integration.

The latest research emphasizes a holistic multi-scale system-of-systems approach that integrates building and urban scales to optimize performance. A notable example of this integration is the building-city dynamic, which aims to enhance human health and comfort while simultaneously reducing energy consumption (Bi & Little, 2022). However, the evaluation of integrated smart building-smart city is a relatively novel concept. Research by Apanaviciene et al. (2020a) explore how buildings can leverage the capabilities of smart cities to enhance their functionalities in areas such as smart energy, smart mobility, smart living, and smart environment. This study also enhances the reliability of the evaluation framework by rigorously testing the proposed indicators.

In a collaborative effort, Conte & Monno (2012) introduce a conceptual model advocating for a cross-scale evaluation approach. This methodology allows for assessment of a building's performance across various scales, from individual components to the entire structure. The authors stress the importance of applying this model in case studies that involve stakeholder participation to validate the holistic indicators utilized. Central to this evaluative framework is the concept of building sustainability, positioning buildings as dynamic entities akin to living organisms within the constantly evolving urban landscape (Conte & Monno, 2012). This perspective aligns with Stieninger's (2016) assertion that to be truly "smart," buildings must integrate with their urban environments, rather than function in isolation. By addressing the existing separation between buildings and cities, this research advocates for a comprehensive and systematic evaluation approach that fosters integration and synergy.

Table 2.3 : Smart city main topics and indicators, adapted from Giffinger et al. (2007).

Smart Economy	Smart Mobility	Smart Environment	Smart People	Smart Living	Smart Governance
Innovative Spirit, Entrepreneurship, Economic image and trademarks, Productivity, Labor market flexibility, International embeddedness, Transformation capability.	Local accessibility, International accessibility, Availability of ICT infrastructure, Sustainable, innovative and safe transportation systems.	Attractiveness of natural conditions, Pollution, Environmental protection, Sustainable resource management.	Level of competence, Closeness to lifelong learning, Social and ethnic pluralism, Flexibility, Creativity, Cosmopolitical-open-mindedness, Participation in public life.	Cultural facilities, Health conditions, Individual security, Housing quality, Educational opportunities, Tourist attraction, Social solidarity.	Participation in decision making, Public and social services, Transparent governance, Political strategies and perspectives.

The literature review highlights the existence of standards pertaining to smart sustainable cities. U4SSC functions as a global platform to promote public policy and advocate for the integration of Information and Communication Technologies (ICTs) in facilitating the transition toward smart sustainable cities. Table 2.4 presents the standards provided by U4SSC (ITU, 2021).

Table 2.4 : ITU standards (U4SSC).

Standard	Full Name
1 ITU-T Y.4901/L.1601	Key performance indicators related to the use of information and communication technology in Smart sustainable cities
2 ITU-T Y.4902/L.1602	Key performance indicators related to the sustainability impacts of information and communication technology in Smart sustainable cities
3 ITU-T Y.4903/L.1603	Key performance indicators for smart sustainable cities to assess the achievement of sustainable development goals
4 Recommendation Y.4904	Smart sustainable cities maturity model
5 Recommendation Y.4905	Smart sustainable city impact assessment
6 ITU-T Series Y Sup. 32	Guide for city leaders
7 ITU-T Series Y Sup. 33	Master Plan
8 ITU-T Series Y Sup. 34	Setting the stage for stakeholder engagement
9 U4SSC publication	Enhancing innovation and participation in smart sustainable cities

The emergence of smart cities has significantly heightened the necessity for evaluating urban development over time, as well as for drawing performance comparisons between cities, whether within a single country or across different nations (ISB & SEF, 2017). Such comparative analyses encourage municipalities to enhance their health and operational efficiency through a competitive lens, leveraging their diverse objectives as motivational drivers.

The indicators that form the basis of smart city assessment tools are established through comprehensive literature reviews, consultations with experts, and stakeholder engagement (Sharifi, 2019). Currently, it is reported that there are over 200 distinct city assessment frameworks globally (ISB & SEF, 2017) widely recognized model for smart city evaluation facilitates the evaluation of various initiatives, allowing for meaningful comparisons of outcomes across different cities (Hemment et al., 2016). This process not only enhances our understanding of urban performance but also fosters a culture of continuous improvement among cities striving for smart transformation.

2.1.3 Visualizing and interpretation of bibliometric analysis results

2.1.3.1 Main information about publications

In this chapter, a thorough search for concepts within detailed definitions as outlined in previous chapters is conducted. Review approach utilized the titles, keywords, and abstracts of publications to extract relevant information. The results from queries (1, 2, and 3) are documented in tables and maps included in 2.1.3 and chapter 2.1.4. The queries progressed incrementally from the building scale to the city scale, culminating in the integration scale. In total, 190 publications are identified through the Scopus database, categorized as follows: query 1 (q1) yielded 73 publications, query 2 (q2) produced 114, and query 3 (q3) resulted in 3 publications. The search engine efficiently extracted 85 articles (with q1 contributing 47, q2 contributing 36, and q3 providing 2 articles). However, upon review, 23 of these articles were not relevant to research area and subsequently excluded them from further analysis. Ultimately, focused bibliometric analysis on a selection of sixty-one pertinent articles, which comprised 29 from q1, 31 from q2, and 2 from q3 (with one article serving as an intersection between categories). The distribution of the articles by percentage was as follows: 45.90% pertained to the building scale, 50.81% related to the city scale, and 3.27% addressed the building-city integration area.

2.1.3.2 Publication research formulas

Query 1: Searching for publications containing smart and/or sustainable building evaluation

In recent years, the concept of smart and sustainable buildings has gained substantial attention within both academic and practical realms, primarily due to their potential to address critical issues related to energy consumption, environmental impact, and social welfare. A recent comprehensive search conducted using the query 1 parameters "Smart building* evaluat*" OR "Sustainable building* evaluat*" OR "Sustainable building* assessment" OR "Smart building* assessment" OR "Smart sustainable building* evaluat" OR "Sustainable smart building* evaluat *" uncovered a total of 77 publications from 2007 to January 2023. This corpus consists of 47 articles, 22 conference papers, 4 reviews, and 4 book chapters, reflecting the growing body of research in this field.

Notably, the distribution of these publications illustrates a significant focus on engineering (46 publications) and energy (22 publications), with social sciences (23 publications) also being well-represented. The predominance of engineering and energy-related works can be attributed to the building construction industry's substantial energy consumption and the ongoing search for innovative, energy-efficient solutions. Conversely, the notable presence of social sciences indicates a recognition of the role that smart and sustainable buildings can play in enhancing community welfare and quality of life.

These findings highlight the interdisciplinary nature of research in smart and sustainable buildings, as it encompasses technical, environmental, and social dimensions, thereby underscoring the importance of collaborative efforts to advance the field toward achieving broader sustainability goals.

Query 2: Searching for publications containing smart and/or sustainable city evaluation

The analysis of the query 2 reveals significant insights into the research landscape surrounding smart cities and their evaluations. Conducting a search with the keywords ""Smart Cit* evaluat*" OR " Smart cit* assessment" OR "Smart sustainable cit* evaluat" OR "Sustainable smart cit* evaluat*" resulted in a compilation of 93

publications, which includes a variety of formats such as articles, conference papers, reviews, and book chapters, published between 2016 and 2023.

The publication types include 34 articles, 45 conference papers, 3 conference reviews, 3 reviews, and 5 book chapters. Notably, the research focused explicitly on the presence of the keywords in the titles, abstracts, and keywords, which underscores the specificity of the inquiry.

The distribution of these publications spans several fields, with a prominent concentration in computer science (49 publications) and engineering (42 publications). Other fields represented include social sciences (35), energy (20), environmental science (18), mathematics (16), and business management and accounting (11), with less than 10 publications in other areas. This distribution indicates a notable emphasis on technological elements and their integration within smart city frameworks.

The prevalence of research output in computer science is particularly interesting. The advancement of Information and Communication Technology (ICT) serves as the backbone for smart city infrastructures, which explains the high volume of studies in these areas. Additionally, the associated enhancement of urban life through these technologies drives further inquiries in the social sciences, highlighting the multidisciplinary nature of smart city research.

In summary, the findings suggest that while the technological aspects dominate the literature on smart cities, there remains a vital intersection with social sciences, reflecting the overall aim of smart city initiatives to improve citizens' quality of life. Such a holistic approach is essential for fostering sustainable urban environments.

Query 3: Searching for publications containing the concepts of sustainable and/or smart city, building, integration and evaluation

Query 3 as follows: ("smart building* integration" OR "sustainable building* integration") AND ("smart cit*" OR "sustainable cit*") AND (Maturity OR "Maturity Level" OR Assessment OR Tool* OR "Assessment Tool*" OR "Assessment Model" OR Indicator* OR Standard* OR KPI* OR Certificate OR Evaluat* OR Performance OR Rank* OR Index OR Readiness OR Code* OR "City IQ" OR "Key Performance Indicator*" OR "Decision Support System") OR "City Analysis" OR "Reference Model".

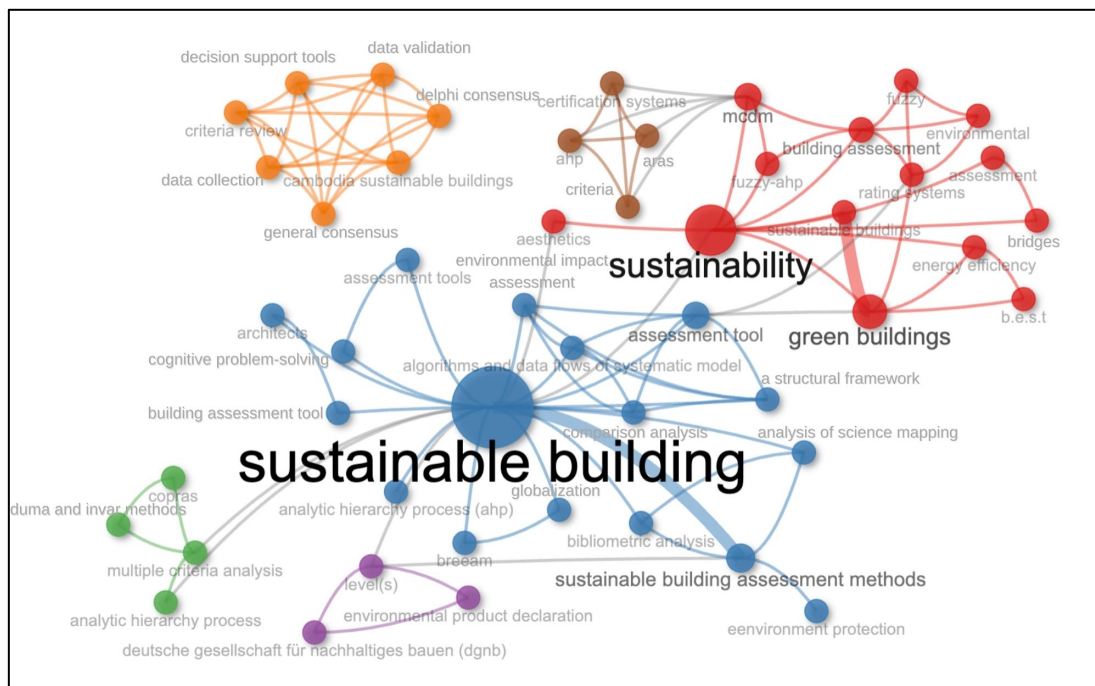
The query is designed to explore the integration of smart and sustainable buildings within the context of smart and sustainable cities, focusing on various maturity levels and assessment tools. The search combines keywords related to building integration with city initiatives and measurement frameworks, resulting in a total of three publications from the years 2014 to 2020. This indicates a relatively niche area of research, possibly highlighting the evolving nature of smart and sustainable urban development during that period.

2.1.3.3 Keyword analysis

The co-occurrence analysis of the author's keywords obtained through Biblioshiny is visually represented in Figure 2.2, Figure 2.3, and Figure 2.4. In these figures, keywords of the same color are grouped into clusters, illustrating their thematic associations. The connections between keywords are indicated by lines, while the size of each node corresponds to the frequency of usage, with larger nodes denoting greater relevance. The prevalence of specific keywords in the literature highlights areas of significant research focus.

In Figure 2.2, a minimum co-occurrence threshold of one was established. Notably, the topic of sustainable building evaluation distinctly emerges as a prominent theme in comparison to smart building evaluation. The concept of sustainable building assessment is intricately linked with various analytical tools such as AHP (Analytic Hierarchy Process), fuzzy AHP, rating systems, and multiple criteria analysis. Additionally, research emphasizes decision support systems, Delphi consensus, general consensus methodologies, as well as data collection and verification processes for establishing criteria in sustainable building evaluation.

These methodologies are well-established in academic literature and offer valuable frameworks for delineating sub-areas related to the proposed Smart Sustainable Building-City Integration Evaluation Model (SSB-CIEM). Lastly, this analysis uncovers initial indications of a relationship between aesthetics criteria and sustainability within the context of a holistic SSB-CIEM approach.



It is seen in Figure 2.3 that the concept of smart city evaluation is directly related to indicators such as economy, connectivity, and quality of life. The strong relationship between the concept of sustainability and smart city stands out. The common goals of these two concepts are improving the quality of life, urban resilience, climate change mitigation, and adaptation. The fuzzy AHP, Bp neural network, extremely learning machine, cloud computing, and frank operator are innovative approaches to preparing smart city evaluation tools.

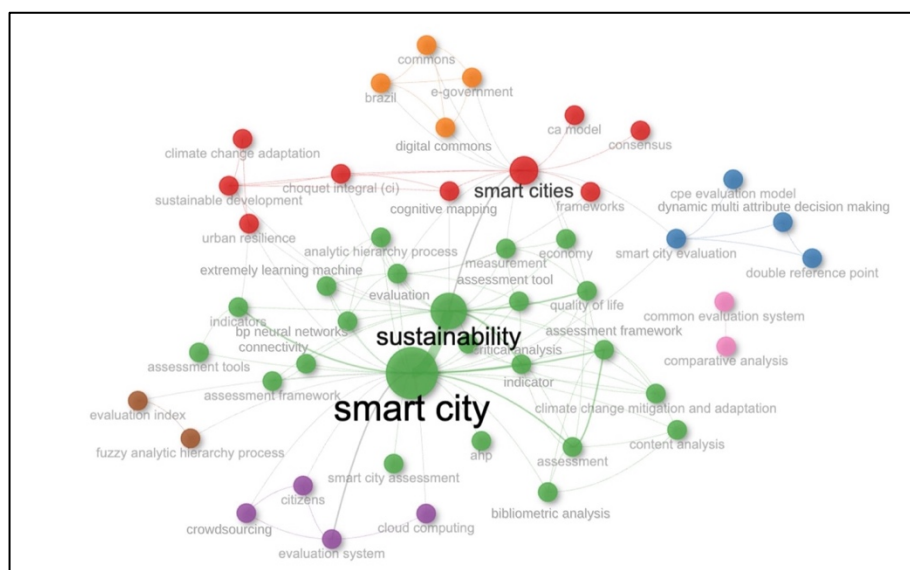


Figure 2.3 : Cluster distribution map for query 2.

Figure 2.4 illustrates that at least one of the keywords in the articles were found to co-occur. The analysis reveals that "smart buildings" and "smart cities" are frequently discussed in relation to interoperability, highlighting the role of Information and Communication Technology (ICT) as a crucial enabler. The development of real estate is closely tied to the complexities of building-city integration. However, the bibliometric analysis indicates a notable research gap regarding the integration of smart cities with smart buildings. This finding emphasizes the necessity for further investigation and encourages additional research to identify the most effective strategies for achieving this integration.

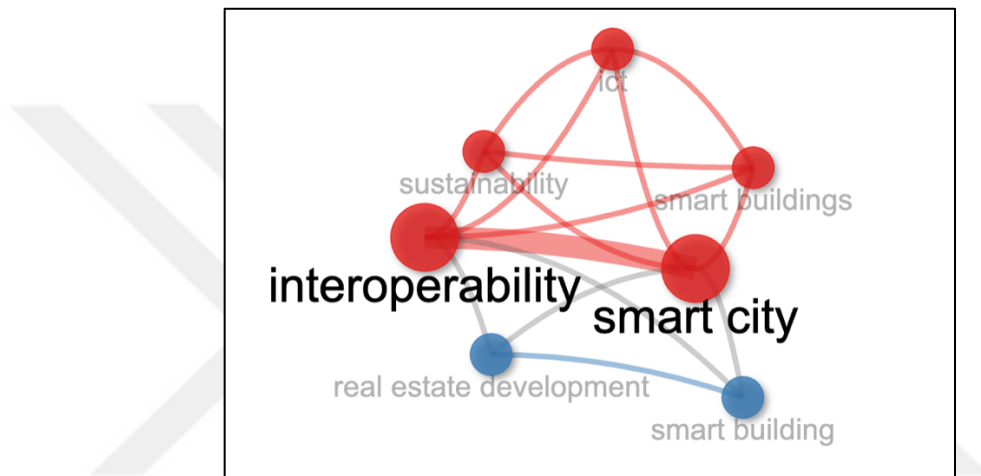


Figure 2.4 : Cluster distribution map for query 3.

2.1.4 Critical analysis of current evaluation tools

This chapter presents a content analysis of the sixty-one articles discussed in the previous bibliometric analyses. The review examines key aspects such as research directions, references, methodologies employed, and the goals achieved throughout these studies. By doing so, it aims to provide insights into the prevailing trends, gaps, strengths and weakness in the existing literature.

2.1.4.1 Content analysis

Content Analysis of Articles about smart and sustainable building evaluation tools

According to the findings presented in Query 1, the research encompasses innovative sustainable building evaluation tools, dimensions of sustainability, extensive literature reviews, multi-criteria decision-making approaches, and the validation of evaluation

criteria, all of which are detailed in Table 2.5. In total, the analysis incorporates twenty-nine articles.

Table 2.5 : Content analysis of articles related to smart and sustainable building evaluation (Sarigül & Günaydın, 2025).

Research direction	Reference	Research methodology
Sustainable hotel evaluation with local evaluation tool	(Mousavi, 2022; Mousavi et al., 2017)	Literature review, interviews and LEED evaluation
Local evaluation tool and ecological and socio-cultural sustainability	(Anshebo et al., 2022)	Expert panel, literature review, AHP
Selection and application of consensus methods	(Chan, 2022)	Comparison of Delphi and general consensus over case study
An exemplary criteria set of the university campus buildings evaluation	(Efe et al., 2022)	Comparison of B.E.S.T. with BREEAM and LEED over case study
Climate zone, building type, and accommodation characteristics for a new tailormade tool	(Bahadiroğlu et al., 2022)	Case study
More life-cycle modules and more comprehensive scenarios for improving EPDs a data	(Del Rosario et al., 2021)	Comparison of certificates over case study
Green smart building	(S. Xu & Sun, 2021)	AHP-FCE over case analysis
Four theory: sustainability aesthetics, genius loci, biophilia, and a regenerative approach.	(Grazuleviciute-Vileniske et al., 2021)	Literature review, examine among the criteria of certificates
Materials & waste management, energy efficiency have highest weight in the technological aspect.	(Reddy et al., 2021)	Literature review, analysis current tools, expert panel, DELPHI
Adding technological advances in sustainable building evaluation tools	(Arukala & Pancharathi, 2020)	Literature review, expert opinion, Fuzzy-AHP
Integrated SDGs evaluation and management approach for sustainable non-residential buildings	(Alawneh et al., 2019)	Literature review, AHP, relative importance index, questionnaire, focus group discussion
A comprehensive view of the status quo and predicts the dynamic directions of future research	(Díaz-López et al., 2019)	Bibliometric analysis, systematic literature review
Sustainable building evaluation tools	(Díaz López et al., 2019b)	Comparative analysis
Indicator usage in sustainable building evaluation	(Al-Qawasmi, 2019)	Context analysis
Urban planning indicators to indicate missing elements such as technology, cultural issues in local region and sustainability	(Stevanovic, 2018)	Literature review
Indoor environment quality, natural and human resources, social, and governance requirements for a local sustainable construction framework	(Al-Jebouri et al., 2017)	Literature review, analysis, survey,
Sustainable building evaluation tool and 3-layer development process framework for project decision makers	(H. Kang et al., 2016)	Mixed-method sequential design, including interviews, workshops, the Delphi survey technique, FD-AHP weight analysis, and scenario analysis
A new sustainable commercial building criteria	(Bhatt & Macwan, 2016)	Fuzzy logic and AHP
A new sustainable building assessment method: INVAR, utility degree and investment values of the projects under deliberation	(Kaklauskas, 2016)	The systems and the values and weights of the quantitative and qualitative criteria express these requirements, case studies
Credibility and applicability of evaluation tools, a new framework	(H. J. Kang, 2015)	Analysis, structural framework
Mobilising sustainable building evaluation models	(Faulconbridge, 2015; Faulconbridge & Yalciner, 2015)	Events along the way', empirical examine

Table 2.5 (continued) : Content analysis of articles related to smart and sustainable building evaluation (Sarigül & Günaydın, 2025).

Research direction	Reference	Research Methodology
Criteria selection for sustainable building evaluation	(Medineckiene et al., 2015)	AHP, Swedish certification system Miljöbyggnad, Saaty's judgement scale and new original scale, ARAS (Additive Ratio Assessment) method, MCDM, LEED
Estonian regulations, sustainability evaluation tool indicators against LEED and BREEAM	(Seinre et al., 2014)	Comparison
Perceptions and preferences for India sustainable building evaluation tool	(Bhatt et al., 2012)	Interviews, statistical analysis
An integrated building-urban evaluation model based on the urban matrix	(Conte & Monno, 2012)	A cross-scale evaluation approach
AHP in sustainable building criteria: weights of parameters	(Bhatt & Macwan, 2011)	Thomas Saaty's rule of Consistency Ratio, comparison

Notably, the topics that fall outside the scope of this research include life cycle assessment (LCA), models for building energy performance, methods for assessing thermal comfort, simulations, building envelope and facade studies, Ad-Hoc networks, user perceptions of sustainable buildings, and the role of sustainable buildings in higher education contexts. The articles examined are categorized according to their features, as shown in Table 2.6.

Table 2.6 : Categories of smart and sustainable building evaluation research (Sarigül & Günaydın, 2025).

	Achieved Goals		
	Current sustainable building evaluation tools and criteria		
	Suitable tool and method selection	Criteria selection, development of criteria, importance/weights of criteria	Current situation analysis and dynamic directions of future research
New local or universal evaluation tools	(Bhatt & Macwan, 2016; Bahadiroğlu et al., 2022; S. Xu & Sun, 2021; Arukala & Pancharathi, 2020; Alawneh et al., 2019; H. Kang et al., 2016; Kaklauskas, 2016; H. J. Kang, 2015; Mousavi, 2022; Mousavi et al., 2017; Anshebo et al., 2022; Conte & Monno, 2012)	(Mu et al., 2022; Chan, 2022; Díaz López et al., 2019a; Del Rosario et al., 2021)	(Faulconbridge, 2015; Faulconbridge & Yalciner, 2015; Díaz-López et al., 2019; Grazuleviciute-Vileniske et al., 2021)

The field of sustainable building research continues to thrive alongside the increasing interest in smart building studies, as highlighted by Anshebo et al. (2022). A noteworthy advancement in this domain is the exploration of green smart building applications, which has been investigated by S. Xu & Sun (2021) as a novel approach. Various studies, including those by Alawneh et al., (2019), Díaz López et al. (2019a), and Efe et al. (2022), provide comparisons of widely recognized sustainable building certifications such as LEED, BREEAM, DGNB, and BEST. Furthermore, Del Rosario et al. (2021) examine the DGNB certification against the European framework

Level(s), specifically focusing on the Environmental Product Declaration (EPD) criterion within Life Cycle Assessment (LCA) evaluations. The use of impactful global evaluation tools serves as a foundational base for developing localized assessment methods, as noted by Mousavi (2022) and Mousavi et al. (2017).

The evaluation of sustainable buildings involves two primary types of parameters: endogenous and exogenous. Endogenous parameters are constants, specifically the global weights assigned to various criteria, while exogenous parameters are variables, reflecting the performance scores of a building based on each criterion (Bhatt & Macwan, 2016). The validation of these parameters, including categories and indicators, is commonly achieved through survey methods that engage academia, construction industry professionals, and sustainability experts (Al-Jebouri et al., 2017).

Among the various multi-criteria decision-making approaches, the Analytic Hierarchy Process (AHP) stands out as the preferred method for selecting sustainable building criteria among researchers (Bhatt & Macwan, 2016; Gong et al., 2017; Medineckiene et al., 2015). A study by (Díaz López et al., 2019a) scrutinizes indicators across eleven widely recognized evaluation tools and highlights a notable deficiency in the indicators representing the economic dimension, particularly when addressing the broader criteria pertinent to the environmental and social dimensions of sustainability. Additionally, (Grazuleviciute-Vileniske et al., 2021) investigate the role of aesthetics within the framework of evaluation tools associated with sustainable building assessment.

Content analysis of articles about smart and sustainable building evaluation tools

This research focuses on the evaluation of smart and sustainable cities, as outlined in query 2. Consequently, any articles that do not pertain specifically to these evaluation frameworks have been excluded from consideration. The analysis is therefore confined to thirty-one articles, detailed in Table 2.7. These include city evaluation studies, comprehensive literature reviews, and proposals for innovative models aimed at developing effective evaluation tools for smart and sustainable cities. The articles examined are categorized according to their features, as shown in Table 2.8.

Table 2.7 : Content analysis of articles related to smart and sustainable city evaluation (Sarigül & Günaydın, 2025).

Research direction	Reference	Research methodology
Measuring smart city performance	(Sotiirelis et al., 2022)	Multiple Criteria Decision Analysis
Municipal waste management	(Jonek-Kowalska, 2022)	Multi-criteria analysis
Multi context evaluation	(De Genaro Chiroli et al., 2022)	AHP to support the process of weights definition and MACBAC.
Featured research/key themes	(Hajek et al., 2022)	Bibliometric analysis, content analysis
Policy implications and investments	(Fang & Shan, 2022)	Principal component and sensitivity analysis, k-means clustering, multi-linear regression
Connectivity to sustainability/resilience	(Sharifi & Allam, 2022)	Taxonomy
Hesitant information	(Y. Wu et al., 2022)	K-medoids clustering to classify experts, DEMATEL method to determine the weights of attributes, consensus-reaching process
The fuzzy comprehensive evaluation model on sustainable development of smart city construction	(J. Xu et al., 2022)	Fuzzy set theory and neural network model for indicators, AHP
ICT, and life quality	(Zou et al., 2022)	AHP
Governance evaluation	(Hsu et al., 2021)	Literature review, expert consensus, the fuzzy AHP
Smart agglomerations, City Intelligence Quotient (City IQ)	(Z. Wu et al., 2021)	Automated information scraping in leading social media platforms, semantic analysis
Sustainability	(Valencia-Arias et al., 2021)	Qualitative descriptive methodology
Renewable energy	(Govindarajan & L.S., 2021)	Climate Smart Cities Assessment Framework (CSCAF)
Impact, performance and sustainability potential	(Kourtzanidis et al., 2021)	Three complementary evaluation axes
Sustainability, technology	(Castanho et al., 2021)	Cognitive Mapping and the Choquet Integral
Development level	(H. Huang et al., 2021)	A double reference point decision making method
Connectivity, sustainability, resiliency	(Suliman et al., 2021)	Literature, case study
Perception	(Orlowski, 2021)	Comparing with rankings or ISO standards
Smart building-city integration for real estate development	(Apanaviciene et al., 2020a)	Comparative case study
Common and sherable framework	(C. Li et al., 2020)	Horizontal comparisons and benchmarks
Comprehensive system framework for smart transportation	(Yan et al., 2020)	Secondary qualitative data analyses, self-organization theory, case study
To maximize smart city capacity	(C. Wang et al., 2020)	Theoretical exploration, indexes and smart city relationship
Scheme (tool) selection	(Sharifi, 2020) (Sharifi, 2019)	Literature review, analyzing
Sustainability, innovation, and quality of life	(Correia et al., 2020)	Literature review
Municipal e-Gov Platform Evaluation Model	(Rotta et al., 2019)	Investigating municipal websites
Sustainable development goals (SDG 11)	(Wendling et al., 2018)	Critically analysis
Smart technologies for cities and citizens: reporting practices, challenges and recommendations	(Caird, 2018)	Case-study, evaluation and reporting
Smart city construction (model accuracy and time cost)	(Shi et al., 2018)	AHP, experts' opinions AHP, AHP-BP and AHP-ELM
Local evaluation tool	(Rocon & de Alvarez, 2017)	Literature review, European Smart Cities evaluation tool
ICT, open innovation/decision-making processes/governance	(Mainka et al., 2016)	Best-practice examples and research frameworks

Table 2.8 : Categories of smart and sustainable city evaluation research (Sarigül & Günaydın, 2025).

Achieved goals	
New evaluation tools	Current smart city evaluation tools
(Sotirelis et al., 2022; De Genaro Chiroli et al., 2022; Fang & Shan, 2022; Y. Wu et al., 2022; J. Xu et al., 2022; Zou et al., 2022; Hsu et al., 2021; Valencia-Arias et al., 2021; Z. Wu et al., 2021; Castanho et al., 2021; Kourtzanidis et al., 2021)	Suitable tool and method selection, literature review and tool comparison City Ranking Current advances and future research directions, improving current tools (Hajek et al., 2022; C. Wang et al., 2020; (Rocon & de Alvarez, 2017; (Mainka et al., 2016; (Govindarajan & L.S., 2021; (Caird, 2018; (Rocon & de Alvarez, 2017; (Mainka et al., 2016)

The evaluation of smart cities has become a crucial area of research, with numerous studies conducted worldwide, including those in China (Fang & Shan, 2022; Hsu et al., 2021; Z. Wu et al., 2021), Brazil (De Genaro Chiroli et al., 2022), India (Govindarajan & L.S., 2021), the United Kingdom (Caird, 2018), Japan (Zou et al., 2022), and Indonesia (Qonita & Giyarsih, 2022). Despite these efforts, the existing evaluation models lack universality (Hajek et al., 2022) primarily due to uncertainties in the evaluation processes, inherent complexities, and the limitations of current evaluation tools. This gap highlights the need for the development of new models that incorporate local characteristics tailored to diverse geographical contexts.

The overall typology of smart city evaluation tools is structured around smartness dimensions and indicators that are gathered from various stakeholder groups, including experts within relevant fields, employing multi-criteria decision-making methods (Castanho et al., 2021; De Genaro Chiroli et al., 2022; Hajek et al., 2022; Y. Wu et al., 2022; Zeng et al., 2023). Experts are tasked with proposing alternatives based on a defined set of criteria, assigning weights, and subsequently evaluating and ranking these criteria (Kaklauskas, 2016). Frequently used methodologies for establishing smart city evaluation criteria include TOPSIS, AHP, and fuzzy-AHP methods. As noted by Sharifi & Allam (2022), a majority of the indicators fall under categories such as Information and Communication Technologies (ICTs), economic performance, and governance.

Some studies focus on a singular dimension of smartness, evaluating aspects like transportation (Yan et al., 2020), governance (Mainka et al., 2016; Rotta et al., 2019), or social and political dynamics (Valencia-Arias et al., 2021). Suliman et al. (2021) argue that smart city evaluation tools can only facilitate the multi-faceted development of urban areas if they broaden their scope to include sustainability, resilience, and connectivity. Correia et al., (2020) propose an evolved model that integrates sustainability, innovation, and quality of life. However, according to the taxonomy provided by Sharifi & Allam (2022) there is a notable lack of compatibility among smart city models concerning environmental sustainability and climate change. The prevailing consensus is that one-dimensional evaluation tools are inadequate and fall short of achieving standardization (Correia et al., 2020; C. Li et al., 2020).

An evaluation model serves to assess the maturity level of smart or sustainable applications within local governments and municipalities, which may encompass areas such as smart governance, smart environment, or smart economy (Castanho et al., 2021; Hsu et al., 2021; Rotta et al., 2019; Suliman et al., 2021). The determination of a city's smart readiness level in terms of its physical infrastructure can significantly influence investment decisions related to smart city initiatives.

However, challenges arise when it is found that the foundational smart city physical infrastructure such as wireless networks and Internet of Things (IoT) capabilities remains underdeveloped. In such scenarios, where the need for physical infrastructure precedes the establishment of digital infrastructure (Yan et al., 2020), the prioritization of data sharing becomes unfeasible (Fang & Shan, 2022). Thus, it is imperative to establish a comprehensive Information and Communication Technology (ICT) infrastructure across the city to facilitate the advancement of smart city projects.

Content analysis of articles about smart and sustainable building-city integration evaluation tools

The findings of Query 3 highlight three articles, of which one is not relevant. The existing literature identifies only one study that concentrates on the evaluation of smart building-city integration. This particular research examined how buildings can leverage the capabilities of smart cities, thereby enhancing their performance in areas such as smart energy, smart mobility, smart living, and smart environment and developed a new evaluation framework (Apanaviciene et al., 2020b). The authors

conducted a detailed case study involving nine office building projects that incorporated smart materials and services, ultimately proposing features of smart construction that cater to the interconnected systems surrounding them (Apanaviciene et al., 2020a). The other article reviewed does not present a new assessment tool. This research conducts a comparative study of real estate development with a focus on smart building integration within a smart city (Apanaviciene et al., 2020a).

2.1.4.2 Strengths and weaknesses

In this chapter, content analysis indicates that the key strengths emerging from the intersection of building and city evaluations create holistic intersection areas. In contrast to existing literature, the economy and technology refrained from categorizing as distinct areas within the model, as both serve as foundational prerequisites for the smart revolution across all areas. Consequently, six primary intersection areas have identified essential for the development of an integrated smart sustainable building-city, addressing Research Question 4 (RQ4): (1) resilience, (2) environment, (3) management, (4) aesthetics, (5) mobility, and (6) welfare-well-being.

In the conclusion of the content analysis, eight significant weaknesses are identified in building-city intersection areas, as it relates to building-city evaluation literature:

1. The inclusion of local city features in building evaluation criteria has become a fundamental requirement. Buildings are often assessed in isolation, typically regarded as closed boxes; it is crucial to incorporate not only universal standards but also the topographic and climatic characteristics unique to cities and regions.
2. There is a pressing need to expand the focus on aesthetics, as well as social and economic criteria, within sustainable building evaluation tools. Current criteria predominantly emphasize environmental sustainability, leaving significant gaps in evaluating other important dimensions.
3. The discourse surrounding the essential criteria for smart building evaluation requires further enhancement. Existing literature predominantly concentrates on the development of sustainable building evaluation criteria, thus neglecting specific metrics relevant to smart technology integration.

4. Research on the maturity of ICT infrastructure in cities is markedly scarce. Given that ICT is a cornerstone of smart city infrastructure, evaluations often overlook the assessment of technological maturity, which is essential for effective development.
5. The reliability of smart city evaluation tools, especially those developed through multi-criteria decision-making methods, is in question. To strengthen their validity, these tools must undergo rigorous testing and validation through complementary techniques.
6. A holistic approach is imperative in smart city evaluations, encompassing all facets of urban life such as mobility, living conditions, and governance. Current evaluation practices tend to focus narrowly on select areas, omitting a comprehensive assessment of city life.
7. Additionally, many smart city evaluations tend to neglect critical indicators such as resilience, connectivity, and sustainability. Recognizing these indicators is vital for fostering a more profound understanding that aligns with the overarching smart sustainable city paradigm.
8. Finally, tools designed for assessing smart city infrastructure and facilitating the integration of smart buildings remain under-explored. While some studies have made preliminary attempts to establish interrelations across scales, a cohesive and widely accepted evaluation framework is still lacking in the literature.

2.1.5 A systematic approach to SSB-CIEM

After conducting a thorough literature review to address Research Question 5 (RQ5), a novel systematic approach for Smart Sustainable Building-City Integration Evaluation Model (SSB-CIEM) was proposed, as illustrated in Figure 2.5. The SSB-CIEM framework is based on six key areas: resilience, environment, management, aesthetics, mobility, and welfare and well-being. Below are examples of implementation drawn from the literature in these six areas, along with suggestions for future research:

Resilience

The integration of BIM and GIS enhances urban resilience by equipping cities with essential information for emergency evacuations and fire interventions (Isikdag et al., 2007). Similarly, it supports effective disaster management through flood risk

assessment and monitoring (Lyu et al., 2016). The adoption of integrated digital technologies in disaster management can significantly bolster urban services in municipalities, ultimately fostering more resilient cities. Future research should concentrate on utilizing BIM/GIS integration to mitigate potential disaster risks such as earthquakes, floods, and fires.

Environment

By enabling the amalgamation of electrical data within building systems managed via BIM with city management systems, GIS supports data visualization, performance analysis, and strategic site selection, employing a bottom-up management approach with smart microgrids (Farooq et al., 2017). During construction, practitioners can optimize the transport of excavated soil through a BIM-GIS-IoT urban system (T. Huang et al., 2022). Recycling construction, operational, and demolition waste in alignment with city facilities ensures effective asset management throughout the lifecycle of buildings. Future research could explore the real-time monitoring of energy output from buildings with photovoltaic panels, enhancing communication with the city grid during electrical failures and thereby facilitating speedy maintenance.

Management

The integration of BIM and GIS streamlines smart city management, transitioning from conventional construction permit applications to fully integrated planning reviews (Shahi et al., 2019). Essential data includes 3D city models, BIM data, and regulatory requirements (Noardo et al., 2020). Furthermore, this integration promotes adaptable and efficient site layout planning (AlSaggaf & Jrade, 2023), enabling the transformation of BIM information into GIS models for the management of mechanical, electrical, and plumbing systems. Ensuring interoperability requires future research to address data format conflicts within BIM-GIS technologies.

Aesthetics

Simulating urban and building functionalities in virtual environments through advanced methods like BIMxD, Big Data, and Digital Twins represents a significant advancing frontier (Redondo, 2023). The incorporation of BIM into environmental planning has become increasingly pertinent (Wilhelm et al., 2021). Studies indicate

that merging BIM models with GIS, which represents urban-scale systems, facilitates design decision-making in a three-dimensional environment, adheres to zoning regulations, and enhances urban aesthetics.

Mobility

Accessibility indicators, such as the proximity of public transport stops and travel frequency, are critical to assessing building accessibility. Additionally, the availability of urban services, including bicycle access, car-sharing options, and electric vehicle charging stations, is integral to smart mobility (Seinre et al., 2014). Subsequent studies should investigate how to refine building and landscape design choices by correlating proximity to urban services with the integrated BIM/GIS frameworks.

Welfare and well-being

Transforming point clouds from scanning into geometric objects that integrate geographical data such as air quality and noise levels contributes positively to human health and well-being (Ellul et al., 2017). Utilizing integrated BIM/GIS in identifying and mitigating aerobiological health risks in urban settings is another promising area of research (Fernández-Alvarado&Fernández-Rodríguez, 2022). Additionally, the integration of socio-cultural activities tailored for residents in affordable housing with city infrastructure through BIM/GIS can enhance human well-being by leveraging smart sustainable features.

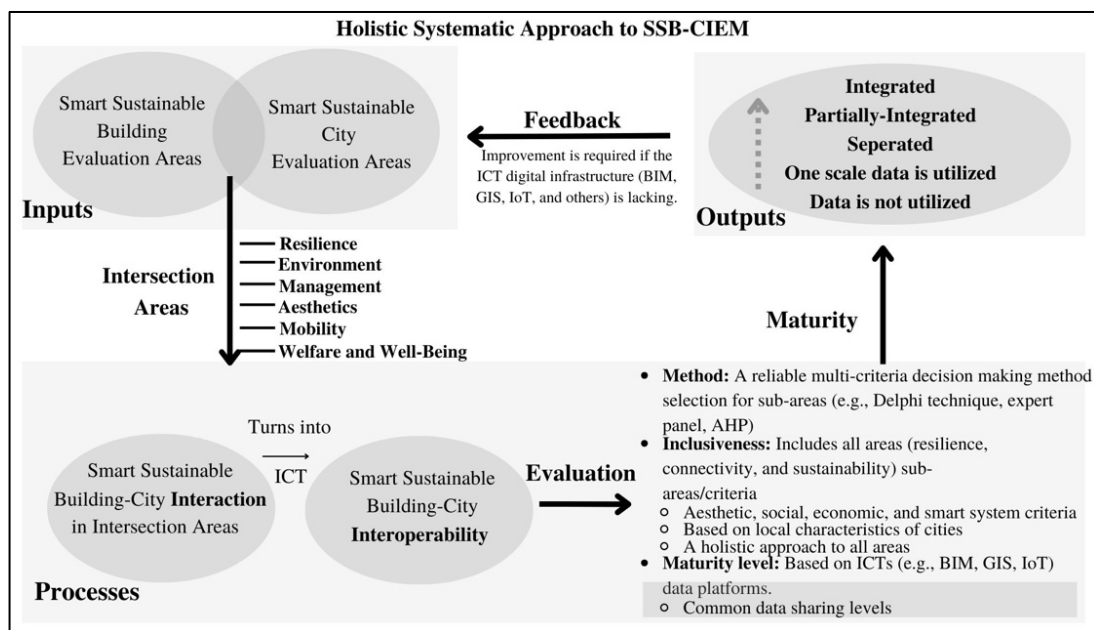


Figure 2.5 : Systematic approach to SSB-CIEM (Sarıgül & Günaydın, 2025).

Even if a building project alone is at a sufficient level of development, integration into smart city networks, interoperability goals, and the ability to adapt to the strategic goals developed, identify integrated smart buildings (Apanaviciene et al., 2020b). A building equipped with smart, sustainable systems will integrate with the city if it can benefit the city's capacity at intersection areas. In environments where "data is not utilized," neither Building Information Modeling (BIM) for buildings nor Geographic Information Systems (GIS) for cities are employed (Level 1). In environments classified as "one scale data is utilized," BIM data (for buildings) or GIS data (for cities) is utilized, but not both (Level 2). In "separated" environments, smart, sustainable buildings and cities do not interact with one another through BIM and GIS (Level 3). In "partially-integrated" environments, buildings and cities begin to collaborate, but their interaction through BIM and GIS is limited (Level 4). In "integrated" environments, building potential and city capacity interact in six main areas, and the level of interaction can be enhanced through BIM and GIS technologies (Level 5). When there is a lack of integration, decision-makers should improve the infrastructure of the missing areas at the intersection by analyzing the building and city potential well. The conceptual presentation of SSB-CIEM in Figure 2.6 demonstrates the potential use of SSB-CIEM based on intersection areas. The building and the city constantly interact with each other through inputs and outputs in the six main intersection areas. Smart sustainable buildings can manage valuable data (e.g., energy and water) on all kinds of urban resources throughout their life cycle (planning, construction, operation, demolition) through a common digital platform with the city. Thanks to the latest developments in ICTs, management platforms that can effectively monitor inputs and outputs in real-time and make high integration possible can be considered BIM for buildings and GIS for cities.

Integration evaluation areas are limited by the dominant headings in existing evaluation tools at the building, city, and integration scales, and an overlooked heading (aesthetics). Every new smart technology and sustainability approach implementing area between the building and the city's building-related infrastructure has the potential to evaluate the existence and level of data integration technologies. Therefore, this chapter discussed implications for future research and practice. Moreover, it is showed that smart, sustainable building-city integration evaluation could be evaluated through BIM-GIS integration. BIM/GIS can provide smart sustainable building-city

integration by integrating data into the city's design, construction, operation, and demolition activities. Since the main areas included in the model cover many sub-application areas/titles, only the findings of the systematic literature review are compared with the existing literature, which is supported by some studies on BIM/GIS integration included in the articles searched in Scopus.

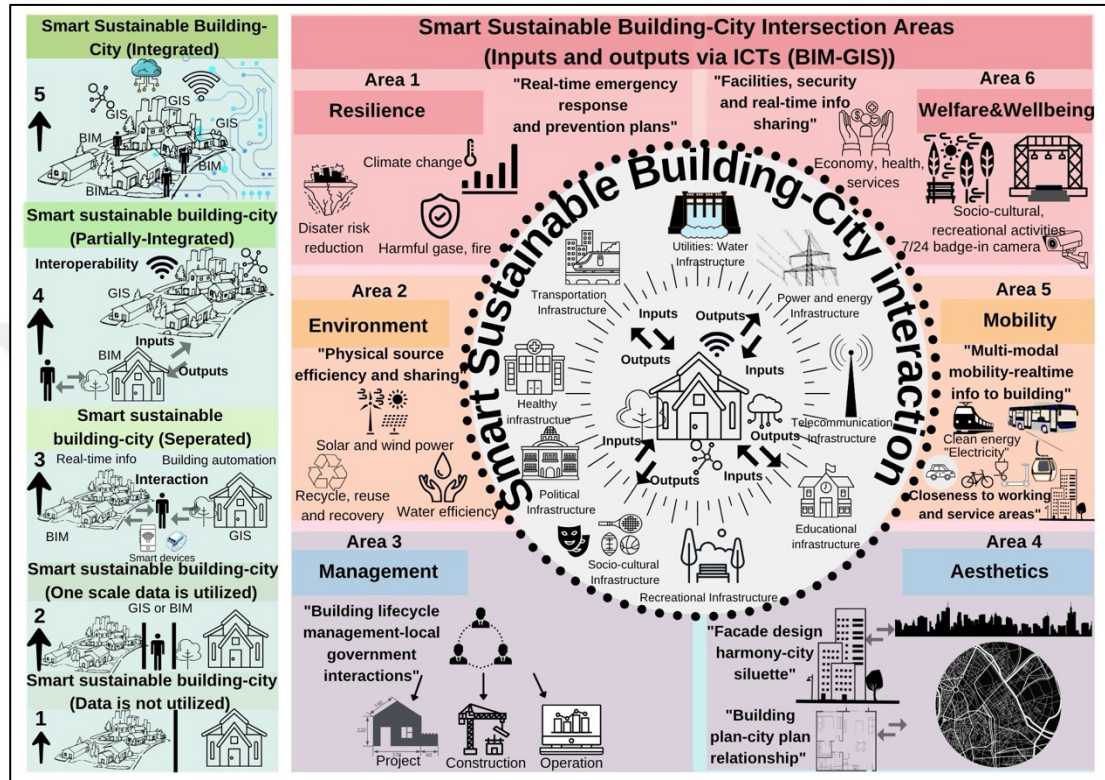


Figure 2.6 : Smart sustainable building-city integration/intersection areas and features (Sarigül & Günaydın, 2025).

Grids, open data platforms, connected transport systems in smart cities, and the proliferation of technologies to automatically manage and monitor resources (González-vidal et al., 2019) allow smart buildings as a small-scale data management points interacting with these systems throughout their life cycle. Data management with ICT (monitoring, storage and interpretation-processing) and real-time information are critical in SSB-CI. Establishing a robust ICT infrastructure in intersection area could increase the maturity of integration. Figure 2.7 represents digital and physical infrastructures of building and city scales that increase the maturity level of integration.

While BIM is useful for 3D interior models with comprehensive meanings, GIS is useful for spatial analytical tools of open spaces (Jiang et al., 2022). BIM and GIS need to be combined for improving the availability and efficiency of information (Pauwels

et al., 2017). Integration of BIM-GIS data in smart cities enables holistic perception of the building and its environment in the digital environment (Karan & Irizarry, 2015). In addition, the fact that data sharing is bidirectional between BIM and GIS is noteworthy in data integration as it minimizes the margin of error in analyzing systems belonging to resources in building-city management and reduces time loss (Farooq et al., 2017). Information models prepared with integrated BIM-GIS, real-time data sources, and other digital platforms can create digital twins (DTs) (Piras et al., 2024). When smart buildings and DTs of cities can work together, the level of integration increases.

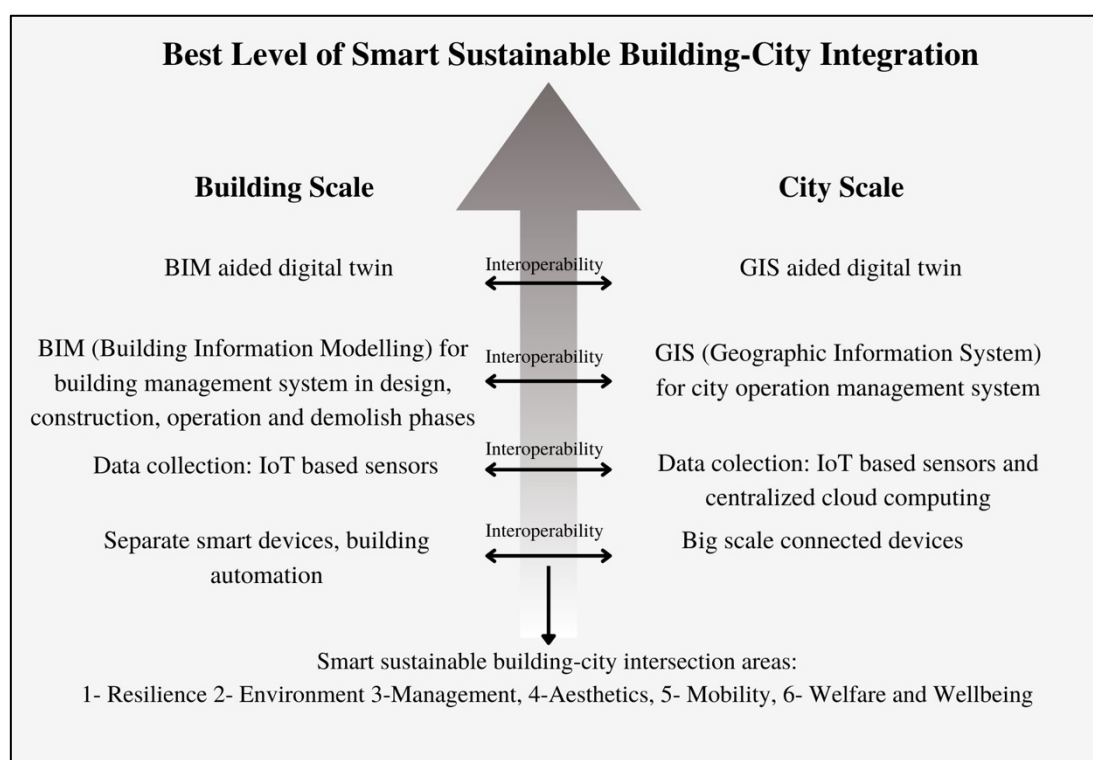


Figure 2.7 : Supported technologies for integration maturity in SSB-CIEM areas (Sarigül & Günaydın, 2025).

2.2 SLR-2: State of the Art in Digital Construction

2.2.1 Research methodology

2.2.1.1 Identifying research phases

This chapter employs a systematic quantitative literature review (SQLR) approach, complemented by bibliometric analysis, to investigate the existing scientific literature surrounding the integration of BIM and GIS in construction management. The methodology for the review is informed by the frameworks utilized by Akindele et al.

(2023), Pickering & Byrne (2014), Shkundalov & Vilutienė (2021), Xia et al. (2022). Consequently, the systematic literature review encompasses the phases (Sarigul & Gunaydin, 2025) as illustrated in Figure 2.8.

Phase 1: Determination of scope.

This phase focuses on addressing the primary research question: "What are the current impacts and future perspectives of integrating BIM, GIS, and related digital technologies into the lifecycle management of building construction projects, as reflected in the existing literature?"

Phase 2: Selection of database. For this review, the Scopus database has been chosen because of its extensive collection of journals, primarily in English, that are relevant to this research field.

Phase 3: Formulation of the search query. A structured search query was created using Boolean syntax for the Scopus database. The search formula written into the search engine consists of the following sequence: `((("BIM" OR "BUILDING INFORMATION MODEL*") AND ("GIS" OR "GEOGRAPHICAL INFORMATION SYSTEM*") AND "BUILDING*" AND "CONSTRUCTION"))`.

Phase 4: Data collection from detected publications. During this phase, a search process is carried out based on the query established in Phase 3. The information collected and exported during this stage is saved for later analysis.

Phase 5: Filtering of search query outputs. The search results from the Scopus database are extensive, but not all of them are relevant to the specific focus of this article. To address this, a thorough filtering process based on predefined inclusion and exclusion criteria was conducted. This research utilizes parameters such as subject area, document type, and language to ensure the selection of accurate data.

Phase 6: Bibliometric analysis of search query outputs. The systematic approach described utilizes a comprehensive methodology often seen in literature reviews. It facilitates the extraction of valuable data concerning the number of publications, their corresponding years, and the geographical and institutional contexts, as well as information about the journals and authors involved. By directly sourcing this data from the database, the method allows for in-depth analysis of co-authorship patterns and the co-occurrence of keywords, thereby providing a detailed perspective on the research landscape in a specific field. This approach not only aids in understanding

trends over time but also highlights the collaborative nature of research across different entities.

Phase 7: Content analysis of search query outputs. The current phase focuses on analyzing existing research directions within the realm of BIM and GIS integration. It addresses pressing problems that require immediate attention, explores potential technical solutions, identifies gaps in the existing literature, and discusses emerging trends that may shape the future of this integration.

Phase 8: Interpretation of results. By systematically analyzing existing literature, researchers can pinpoint literature gaps and propose innovative directions for future research trends, thereby contributing to the overall growth and development of their respective fields.

2.2.1.2 Identifying research questions for SLR-2

This chapter conducts a systematic investigation of five research questions (RQs) (Sarigul & Gunaydin, 2025):

RQ1: To what extent has research explored the integration of BIM, GIS, and related digital technologies in construction projects? What are the trending topics, most prolific authors, leading journals, and countries involved? (This addresses global interest in the research area, trends in the literature, and the scope of previous reviews. Findings are presented in Chapter 2.2.3.)

RQ2: Which cutting-edge technologies possess the potential for integration with BIM and GIS in building construction projects? (This aims to evaluate the interoperability landscape of digital technologies in the construction industry. Findings are discussed in Chapter 2.2.2.)

RQ3: How can we categorize the applications of integrated BIM, GIS, and related digital technologies according to trending topics in the Architecture, Engineering, Construction, and Facility Management (AECO/FM) industry? (This objective seeks to identify specific application areas of integrated digital technologies within the AECO/FM sector. The analysis is provided in Chapter 2.2.4.)

RQ4: How do integrated BIM, GIS, and related digital technologies contribute to lifecycle management in building construction projects? What challenges exist regarding semantic and geometric integration, and what technical solutions are

available? (This focuses on the potential of integrated digital technologies for efficient management of construction projects in relation to time, cost, and quality, along with solutions to the technical integration issues encountered. Answers can be found in Chapter 2.2.5.)

RQ5: What gaps exist in the literature, and what are the future trends concerning the integration of BIM, GIS, and associated digital technologies in the lifecycle management of building construction projects? (This question aims to identify research areas open for development for both researchers and technology developers engaged in digitally integrated lifecycle management of building construction projects. The discussion is presented in Chapter 2.2.5.)

2.2.1.3 Paper retrieval

The systematic and comprehensive approach employed in this review emphasizes the use of SQLR databases, particularly Scopus and Web of Science (WoS), to identify pertinent studies in a specific research field (Pickering & Byrne, 2014). Scopus is utilized here due to its reputation as the most extensive abstract and citation database for peer-reviewed literature (Harzing & Alakangas, 2016; Jin & Ji, 2018). The advantages of Scopus are notable, with its extensive coverage of over 29,200 active serial titles and contributions from more than 7,000 publishers, alongside sophisticated search functionalities that utilize Boolean syntax (Elsevier, 2024).

A significant aspect positioning Scopus as a viable alternative to WoS is its rigorous quality control measures. These measures encompass strict review and selection criteria, ensuring that only high-quality, peer-reviewed literature is indexed, thereby bolstering the database's reliability. Furthermore, Scopus has been highlighted in the rankings of numerous international universities, including the Times Higher Education rankings (Harzing & Alakangas, 2016). In contrast, Google Scholar's quality control procedures are comparatively less stringent, as it broadly scans various academic-related websites, which can result in inconsistencies regarding content quality.

Advanced search techniques allow researchers to unearth published articles on the integration of BIM and GIS in construction projects without omitting significant studies. Thus, Scopus emerges as a comprehensive database for collecting critical information on the current impacts and future directions of BIM and GIS technologies within construction processes. Moreover, it is highly favored in literature reviews that

assess the management of construction projects and urban services through smart technologies, as seen in various works by authors like Akindele et al. (2023); Akinlolu et al. (2022), Celeste et al. (2022), Rigillo et al. (2023), Sepasgozar et al. (2021), M. Wang et al. (2020).

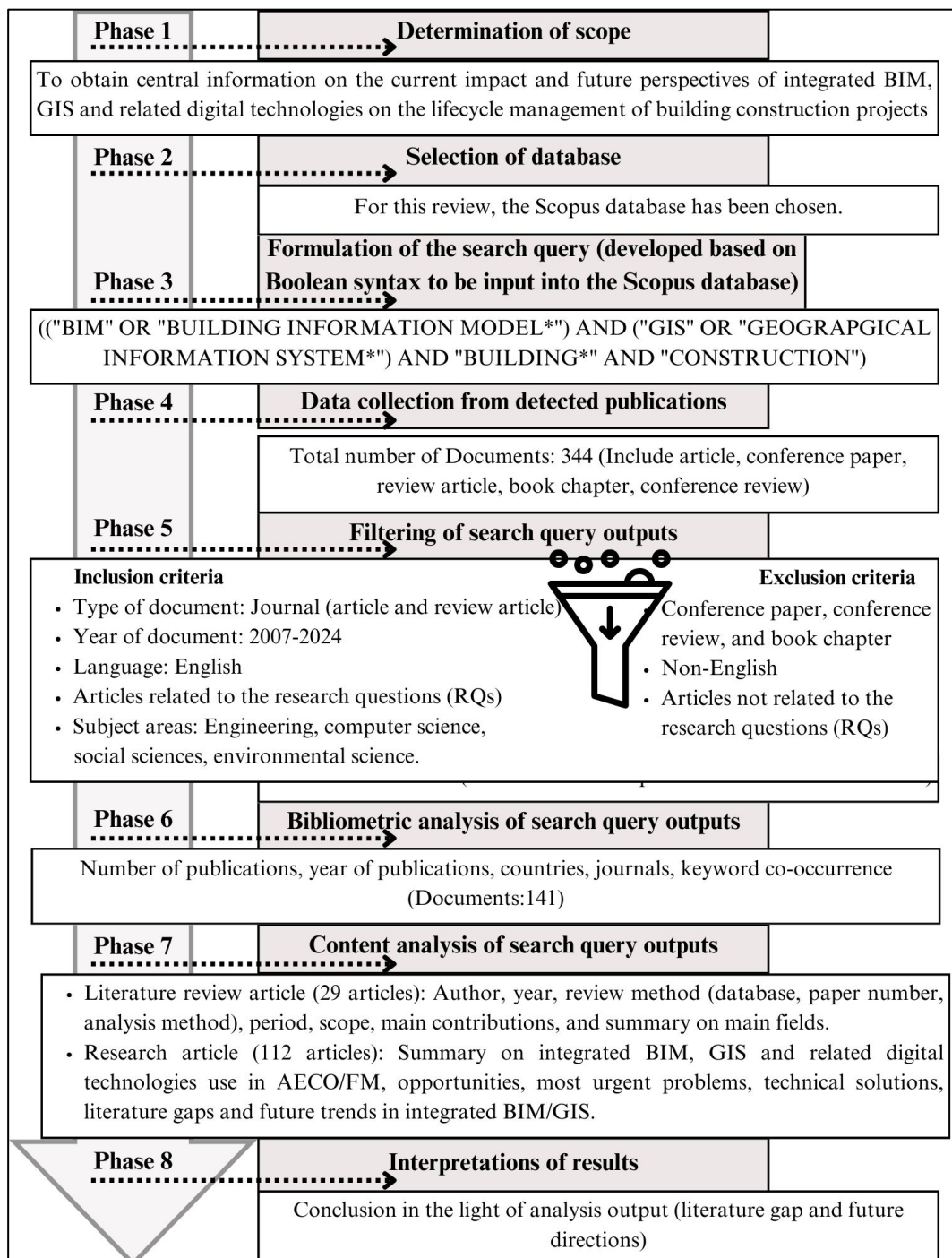


Figure 2.8 : Search methodology for SLR-1 (Sarigul & Gunaydin, 2025).

2.2.2 Qualitative literature review

In recent years, the integration of digital technologies into various facets of construction including planning and design, project management, health and safety, on-site operations, construction methodologies, and building performance has experienced significant growth Chen et al., (2022). Advances in information and communication technologies (ICTs) have rendered many analog, mechanical, and electronic solutions obsolete, thus facilitating a shift towards digital alternatives that enhance productivity in work processes (Aktürk & Irlayıcı Çakmak, 2024). In the contemporary digital landscape, these technologies can markedly improve communication and collaboration among stakeholders, thereby enabling integrated digital delivery in construction project design (Wuni et al., 2024). Implementing the latest digital technologies by construction professionals has the potential to significantly enhance efficiency in terms of time, cost, and quality management throughout all phases of project development.

Chen et al., (2022) critically categorize contemporary technologies employed in the construction industry into several key areas:

1. **Data Acquisition:** This encompasses various technologies such as WLANs, barcoding, machine control (Mc), eye tracking, Zigbee, Bluetooth, wireless sensor networks (WSNs), the Internet of Things (IoTs), unmanned aerial vehicles (UAVs) or drones, ultra-wideband (UWB), geographical information systems (GIS), laser imaging detection and ranging (LIDAR), global positioning systems (GPS), photogrammetry, sensors, and radio frequency identification (RFID).
2. **Data Analytics:** This category focuses on the utilization of big data, artificial intelligence (AI), and machine learning (ML) to extract meaningful insights from collected data.
3. **Data Visualization:** Techniques such as visualization platforms (VP), multidimensional building modeling (nD), information modeling (IM), and building information modeling (BIM) are essential for effectively communicating data.
4. **Communication:** This includes web services and mobile communications (MC), which facilitate project coordination and information-sharing among stakeholders.

5. Construction Automation: Innovations such as additive manufacturing (AM or 3D printing), robotics, and digital fabrication (DFab) play a crucial role in enhancing construction efficiency.

6. Sensing and Digital Technologies: Integration of BIM, GIS, GPS, laser technologies, satellite data, and LIDAR further enhances construction accuracy and monitoring capabilities.

Particularly noteworthy is the integration of BIM and IoT in facility management (FM), which significantly enhances water management through online monitoring and rapid leak detection (Batista et al., 2024). The implementation of BIM in off-site construction methods has been shown to increase productivity and reduce scheduling risks (Kordestani Ghalenoei et al., 2024). Augmented reality (AR) applications are also expanding in the construction sector, with new applications and a burgeoning body of research emerging daily (Adebowale & Agumba, 2024). Furthermore, location acquisition systems, such as GPS, are routinely used to monitor and track workers in real-time on construction sites, contributing to hazard prevention and safety management (Arslan et al., 2018).

In the long view, the continued integration of these technologies is anticipated to yield even more efficient and safer construction practices, putting forth the potential for transformative impacts within the industry.

BIM and GIS represent essential digital technologies that have significantly impacted the construction industry, primarily due to their innovative capabilities and functionalities (Abd et al., 2020). BIM has come to prominence in the Architecture, Engineering, Construction, and Operations/Facility Management (AECO/FM) sectors, demonstrating a rapid increase in application over the last two decades (Song et al., 2017). In terms of production and project management, BIM streamlines the execution of specialized processes related to production, analysis, model visualization, management, data exchange, and building information sharing (Khan et al., 2021; Mignard & Nicolle, 2014; Pakhale & Pal, 2020).

The essence of BIM lies in its capability to create information dimensions that enhance a three-dimensional physical asset with properties such as volume, geographical coordinates, and asset tagging, thereby offering extensive geometric and semantic information throughout a project's lifecycle (Khan et al., 2021; Pakhale & Pal, 2020;

Piras et al., 2024). This multifaceted nature of BIM is clearly transforming the construction landscape (Gharaibeh et al., 2024).

While BIM provides valuable opportunities for microscale data analysis and visualization within construction projects, GIS broadens these capabilities to a macroscale, facilitating the management of topographic and geographical information (H. Wang et al., 2019). GIS systems are designed to manage spatial information that includes both geographical and descriptive relationships, thus enabling the capture, storage, manipulation, analysis, management, and presentation of vast amounts of geographical data pertinent to specific locations (Mignard & Nicolle, 2014; Sun et al., 2020). This functionality significantly enhances collaboration among project stakeholders (Luong et al., 2023).

The integration of GIS and BIM is increasingly recognized for its potential to transform construction management practices. GIS serves as a critical tool in various aspects of design and planning, materials management, market analysis, site monitoring, logistics, and decision-making processes (Arendt et al., 2019; Luong et al., 2023). Its effectiveness extends to site selection and engineering research facilitation, underscoring its multifaceted applications in the field (Arendt et al., 2019).

However, the advancement of BIM and GIS technologies independently has created certain artificial barriers, particularly in the context of utilizing municipal infrastructure services like electricity and water in construction projects (Hijazi et al., 2018). Current literature identifies three primary integration approaches: (1) BIM leads and GIS supports, (2) GIS leads and BIM supports, and (3) parallel operation of both BIM and GIS (H. Wang et al., 2019). Despite the recognition of these integration strategies, challenges persist due to the fundamentally different focuses and digital representation capabilities of BIM and GIS (Pauwels et al., 2017; Karimi & Iordanova, 2021).

As illustrated in Figure 2.9, BIM primarily addresses the internal and structural elements of buildings, whereas GIS specializes in managing and analyzing spatial data related to the Earth's surface (D. M. Azevedo et al., 2021; Karan & Irizarry, 2012; Teo & Cho, 2016; H. Wang et al., 2019). Several studies have identified tools such as Autodesk InfraWorks, which facilitate the translation of local BIM coordinates into

geographic contexts, enhancing interoperability and efficiency in time and cost management for construction projects (Abd et al., 2020).

The synergy achieved through BIM and GIS integration promises significant progress in construction management and coordination. This convergence allows for improved visualization of supply chain dynamics and material flow, as well as enhanced safety measures through the incorporation of additional technologies like cloud computing (Shafiq & Afzal, 2020). The resulting integrated framework strengthens spatial analysis capabilities within the Architecture, Engineering, Construction, and Facility Management (AECO/FM) sectors, effectively linking structural data with essential environmental information, including land use, transportation networks, and adjacent infrastructure (L. Liu et al., 2021).

Given that each building exists within a broader environmental context, comprehensive management throughout its lifecycle is contingent upon understanding its relationship with surrounding resources (Bansal, 2021). Ultimately, the integration of BIM and GIS enhances not only construction and urban management practices but also adds considerable value through comprehensive data analysis, fostering increased confidence in the safety systems established in these projects.

The interoperability of data and tools in BIM and 3D geospatial technologies (H. Wang et al., 2019) has fostered the exploration of comprehensive solutions that integrate both geometric and semantic data (Shkundalov & Vilutienė, 2021). Recent advancements have highlighted two widely recognized semantic models that serve as open-standard data models and exchange formats: the Industry Foundation Classes (IFC), which are used to represent BIM models (Hemalatha & Vidjeapriya, 2021; Zhu et al., 2021), and the City Geography Markup Language (CityGML), employed for Geographic Information System (GIS) models (Karimi & Iordanova, 2021; H. Wang et al., 2019; Yigitcanlar et al., 2023). These models enhance data exchange capabilities and provide an integrated perspective of the built environment.

IFC facilitates the integration of data concerning a building's entire life cycle into a cohesive BIM, thus enhancing interoperability among various stakeholders involved in construction and facility management (Isikdag et al., 2007; Zhan et al., 2021). Conversely, CityGML serves as a globally acknowledged standard aimed at 3D city planning, urban object modeling, and the modification of historical sites and

landscapes (Yaagoubi et al., 2019). This framework organizes various geometric, topological, semantic, and aesthetic characteristics of urban elements, encompassing both natural features, such as hills and vegetation, and human-made structures (Arayici, 2008). The semantic depth afforded by CityGML fosters a more sophisticated representation and analysis of urban spaces, ultimately facilitating enhanced planning and decision-making processes.

The integrated BIM/GIS approach represents a transformative shift in the management of Architecture, Engineering, Construction, and Facility Management (AECO/FM) industries, showcasing its potential as an evolving paradigm ripe for academic exploration (Celeste et al., 2022). This paper aims to scrutinize the latest trends in the combined applications of BIM and GIS, alongside emerging digital technologies, across all phases of construction projects, namely design, construction, operation, and maintenance. This chapter's objective is to pinpoint existing literature gaps and recommend future research directions. Therefore, this study anticipates contributing to the field by providing a comprehensive analysis in several pivotal areas (Sarigul & Gunaydin, 2025):

1. A review highlighting the scope and key contributions of prior literature addressing the integration of BIM, GIS, and associated digital technologies.
2. An examination of trending topics concerning the integrated applications of BIM, GIS, and similar digital technologies within the AECO/FM sector.
3. An exploration of the opportunities and pressing challenges encountered in the construction domain due to the integration of these technologies for project lifecycle management from 2007 to 2024.
4. The identification of research gaps and the development of future research directions relating to the integration of BIM, GIS, and similar digital technologies in managing the lifecycle of construction projects.

Ultimately, this study seeks to offer a comprehensive understanding of the relationship between digital technologies and construction lifecycle management, establishing a foundational reference for future scholarly investigation in this domain.

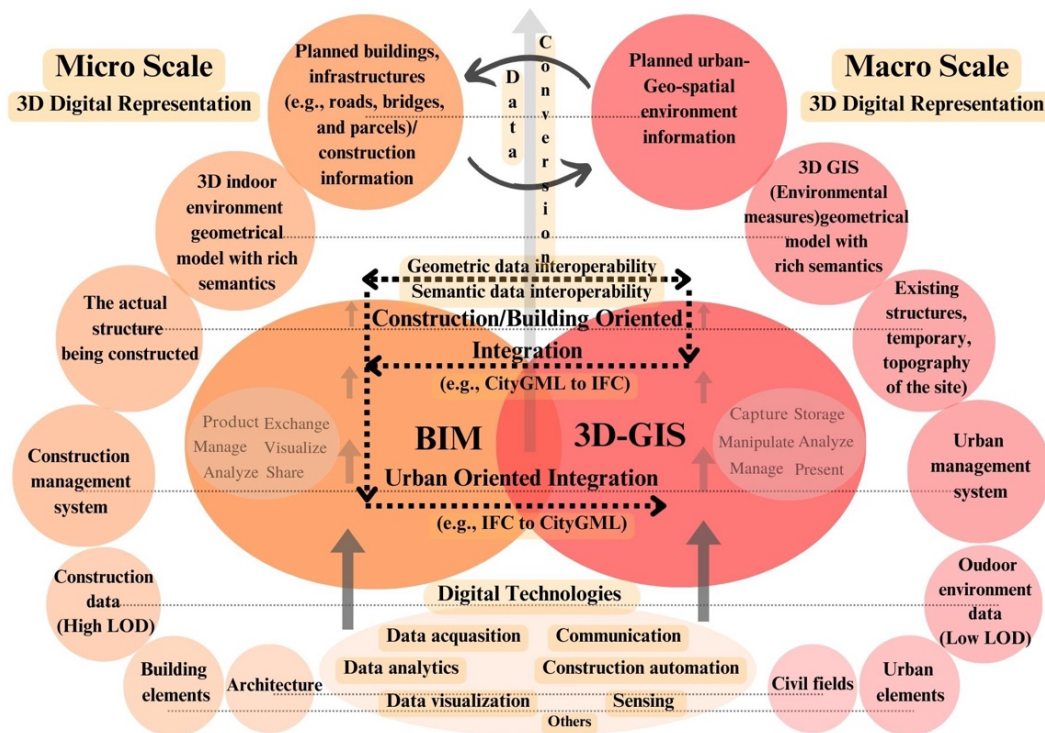


Figure 2.9 : Interoperability between BIM/GIS and related digital technologies (Sarigul & Gunaydin, 2025).

The subsequent chapter presents a thorough examination of the construction lifecycle management, outlining the activities conducted throughout this process and categorizing pertinent application domains. It underscores the potential benefits offered by BIM, GIS, and associated advanced technologies based on historical and contemporary applications (up to February 2, 2024). Furthermore, the review delineates critical technical challenges and anticipates future research directions, contributing to the evolving discourse in this vital field (Sarigul & Gunaydin, 2025).

2.2.2.1 Literature review studies on BIM/GIS integration

The integration of BIM and GIS presents an evolving landscape in construction management, as highlighted by recent literature reviews. Data compiled from 29 articles published in Scopus between 2017 and 2024 reveal a trend toward utilizing systematic literature review techniques, particularly up until 2021. Post-2021, there has been a notable shift toward bibliometric analysis methods, including network visualization, co-occurrence, and co-citation analyses, which investigate key themes, authors, and influential journal studies.

Moreover, this literature delves into critical technological advances alongside BIM and GIS, encompassing information communication technologies (ICTs) such as virtual reality (VR), augmented reality (AR), digital manufacturing (DM), RFID, blockchain, big data, the Internet of Things (IoT), digital twins (DT), and artificial intelligence (AI). These technologies present both opportunities and challenges that could significantly influence future practices in construction.

Furthermore, a comprehensive review of the literature underscores that while significant attention has been directed toward the entire lifecycle of built projects from planning and construction to facilities management and demolition there remains a noticeable gap regarding research on both off-site and on-site construction practices (Sarigul & Gunaydin, 2025). As illustrated in Table 2.9 and Figure 2.10, this gap presents a substantial opportunity for future investigations into how the integration of these advanced technologies can refine construction management and predict upcoming trends in the sector. The exploration of these innovations is crucial for ongoing advancements in construction methodologies.

Table 2.9 : Summary of the previous systematic literature review studies (29 papers) (Sarigul & Gunaydin, 2025).

Review method (database, paper number, analysis method) and period	Author and year, scope and main contribution
A scientometric analysis approach, WoS, 69 papers, co-occurrence analysis using VOSViewer, (Recent years (?-2022)).	(Piras et al., 2024). Emphasize on a notable deficiency in integrating digital twin, BIM, GIS, IoT, and AI technologies. A conceptual framework including critical enablers.
Trends, keywords and publication analysis, categorized type of infrastructure and ICT, (more than 200 papers), VOSViewer.	(Cepa et al., 2023). Integrating BIM-FM through ICTs (BIM, IoT, GIS, big data, blockchain, motion capture) in transport infrastructure. Decision-making based on data analysis and the optimization of available resources.
Scoping review method, Scopus, 62 papers, classified by geographic origin, year of publication, disciplinary field, number of citations, and content analysis, (2016-2022).	(Rigillo et al., 2023). Potentials and limitations of using digital transition technologies (BIM, GIS, VR, AR, DM, blockchain, IoT, DT, AI) for construction and demolition waste management. Digital technologies-circularity culture in the construction sector.
Thematic analysis, Scopus, 60 papers, preferred reporting items for systematic reviews and meta-analyses (PRISMA) checklist, (2011-2022).	(Akindele et al., 2023). GIS application and system integration patterns for project planning. Possible areas where GIS is adopted and future integration opportunities with other emerging technologies.
WoS, 184 papers, bibliometric analysis (keyword, co-country, co-citation and coupling analysis, CiteSpace), (until 2022).	(Xia et al., 2022). Different disciplinary classifications of BIM/GIS functional integration for urban rail transportation engineering. The framework proposal from the perspective of digital twin technologies for sustainable smart cities.
Scopus, Web of Science, Engineering Village, IEEE, SpringerLink and Google Scholar, 175 papers, PRISMA guidelines, (2001-2020).	(Chen et al., 2022). Integrated construction industry technologies (Multidimensional building modeling (nD), BIM, GIS, LiDAR). 26 technologies (5 groups): Data acquisition, analytics, visualization, communication, and design and construction automation.
WoS, 650 papers (88 papers, co-occurrence and co-citation analysis, keywords, authors, and important journals, (until 2022 March).	(Ali et al., 2022). Collaboration and risk issues in construction technologies (BIM, GIS, IoT, AI, AR, digital twin). Needs more further study.

Table 2.9 (continued) : Summary of the previous systematic literature review studies (29 papers) (Sarigul & Gunaydin, 2025).

Review method (database, paper number, analysis method) and period	Author and year, Scope and main contribution
WoS, Scopus and Google Scholar, 52 papers, bibliometric analysis, content analysis, (until 2022 May).	(Jafary et al., 2022). Integrated BIM and GIS, 3D data, AI, and ML real estate valuation models. The existing uncertainties are decreased.
Google Scholar, WoS, Science Direct, American Society of Civil Engineers (ASCE) Library, Taylor and Francis Online, Wiley Online Library, 84 papers, PRISMA 2020 approach, (2000-2020+1 (2022))	(Jiang et al., 2022). Fire emergency evacuation. Identifying four groups: facility geometrical analysis with BIM, GIS, VR, and the combination of these technologies, fire and smoke simulation, the simulation output is incorporated into intelligent fire evacuation system; crowd evacuation simulation software; personalized evacuation system; indoor positioning system and mobile device/IoT to track and evacuate occupants.
Scopus, 34 papers, ontologies and meta models, critical analysis, (2014-2020).	(Celeste et al., 2022). BIM/GIS and related digital systems for asset representation and management with a high degree of integration. A new proposal.
Scopus, 240 papers, bibliometric analysis (co-occurrence network, co-authorship per country, country/region distribution, the number of publications annually, publication source and trend topics), VOSViewer, (2009-2019). Produced a list of application areas of BIM and GIS, and case study.	(Akinlolu et al., 2022). Construction health and safety management with BIM, GIS, VR, UAV, 4D CAD, and wearable robotics technologies. Project health and safety design and planning, visualization and image processing, digital technologies for project monitoring, information management, IoT, automation and robotic systems, accident prevention, and structure evaluation.
WoS, Scopus, Engineering Village, IEEE 236 papers, bibliometric analysis (keyword co-occurrence, co-authorship, citation), and science-mapping, trends, challenges, potentials, and deficiencies, VOSViewer, Gephi, CiteSpace, (period is not provided).	(Bansal, 2021). Existing building lifecycle management processes, to consider surroundings, site constraints, locational effects, and services of nearby facilities. Framework proposal: BIM and GIS coordination from a multidisciplinary perspective.
Scopus, Twitter pages of engineering firms and other relevant industry organisations, a scientometric trends, a set of novel metrics, query-based search, and social network analysis techniques, statistical analysis, 2337 papers. A probit regression model was utilised in the STATA environment (2000-2020).	(Karimi & Iordanova, 2021). Robot positioning and navigation (state-of-the-art technologies) in construction automation). Needs research on the potential of BIM/GIS integration in construction automation. A novel proposal.
Science direct, Google Scholar, ASCE library, ICE library, 219 papers, a scientometrics analysis, bibliometric analysis (co-occurrence, publication, citation, etc.), VOSViewer, (2009-2019).	(S. Sepasgozar et al., 2021). Integrated BIM, GIS, 3D Printing, and geospatial data analysis for recycling and reuse of construction and demolition waste according to countries. New perspectives of geospatial solutions for optimizing the recycling and waste facilities to professionals and practitioners in both new construction and refurbishment projects.
WOS, 111 papers, bibliometric analysis, publications datasets, specifically, co-citation networks, co-authorship networks, and the co-occurrence map of keywords, scientific journal articles, (2010-2020).	(Pereira et al., 2021). Integrated BIM, GIS, laser scanner, and thermographic camera data merging for AECO Industry/ building efficiency and how to reduce environmental impacts. Energy savings need interoperability between BIM, energy analysis tools, and other technologies.
Google Scholar, Scopus, and WoS, 191 papers, critical analysis, (2010-2019).	(Shkundalov & Vilitienė, 2021). Challenges and potential opportunities of BIM, GIS, and Web integration. Unified standard research is disjointed and fragmented and conducted mainly in isolated clusters.
Scopus, Google scholar, PRISMA, critical review, (2011-2020).	(Afzal et al., 2021). The virtual design construction technologies (e.g., BIM, VR, AR, GIS, and gaming technologies) in job site. Improve construction safety.
	(Wei et al., 2021). The state-of-the-art BIM/GIS application methods used in bridge projects' planning, design, construction, operation, and maintenance phases. Guide to the selection of appropriate technologies.

Table 2.9 (continued) : Summary of the previous systematic literature review studies (29 papers) (Sarigul & Gunaydin, 2025).

Review method (database, paper number, analysis method) and period	Author and year, scope and main contribution
Scopus, Web of SCI, American Society of Civil Engineers (ASCE) Library, and IEEE Xplore Digital Library, critical review, (2010-2020).	(M. Q. Huang et al., 2021). BIM in traditional-mechanized tunneling and integrate 3D geological modeling/GIS databases with ML and computer vision. The challenges and perspectives for digitization, automation, and information integration throughout the underground project lifecycle.
Scopus, WoS and Google Scholar, 87 papers, a survey, (2007-2018)	(L. Liu et al., 2021). IFC-based BIM for indoor navigation. Three new directions.
Scopus, WoS, and Google Scholar, (Paper number is not provided), critically review from four outlooks (BIM and other technologies), (period is not provided).	(Darko et al., 2020). BIM, GIS, RFID risk management in modular integrated construction. While schedule and cost-related risks have gained much attention in current research, facility management, sustainability, and safety risks are ignored, mainly.
Scopus, 113 papers, VOSViewer, Scientometric analysis (Co-occurrence of keywords, research topics, countries involved, content analysis, (2010-2020).	(M. Wang et al., 2020). Applications in off-site construction include BIM, RFID, GPS, IoT, GIS, sensors, AR, VR, photogrammetry, laser scanning, AI, 3D printing, robotics, big data, and blockchain. Highlights to each technology's main area of application and limitations.
Not provided, accessed only abstract.	(Rašković et al., 2020). Stock material information for future demolition activities. Individual objects to be deconstructed and whole cities as a basis for managing the anthropogenic stock via integrated BIM/GIS. Describes workflows employable for urban mining in end-of-life building.
WoS, 76 papers, bibliometric analysis (journal, co-occurrence of keyword, co-authorship, time-series), (2008-2018).	(H. Wang et al., 2019). BIM/GIS integration in sustainable built environments. A roadmap for researchers.
WoS, Engineering Valley and Scopus, micro-thematic analysis, critically reviewed by coding and content analysis, (2008-2017).	(S. M. E. Sepasgozar et al., 2019). The existing applications of sensing technologies for measuring construction off-road vehicle emissions (COVE) via web-based GIS, emission sensors, and IoT. The gap in measuring COVE.
Scopus, Google Scholar, 120 papers, a panel of five experts and industry practitioners, research deficiencies and future research directions, (2004-2017).	(Wong et al., 2018). Digital technologies in facility management. Suggestions: Enhancing the interoperability of data, improving the accuracy of point cloud data for developing as-built models for existing facilities, and generating effective BIM/GIS asset database integration.
WoS, 96 papers, research area and publication analysis, trends, benefits etc., (until 2017).	(Song et al., 2017). BIM/GIS integration in the AEC Industry. Articles are analyzed from a spatio-temporal statistical perspective. Opportunities are categorized as the technology, science, and data source hypotheses.
Survey, Chongqing Survey Institute, GIM International.	(GIM International, 2017). Software platform for integrating, managing, disseminating, and applying data (BIM-3D GIS). Combining the indoor and outdoor environment with e-commerce systems.
SCI-indexed 7 journals, (total paper number not provided), (period:the most recent articles).	(Pauwels et al., 2017). BIM, GIS, and semantic web technologies in AEC Industry. Identified three key application areas: (interoperability, linking across domains, logical inference, and proofs) and articulated the opportunities, and challenges of their current practices.

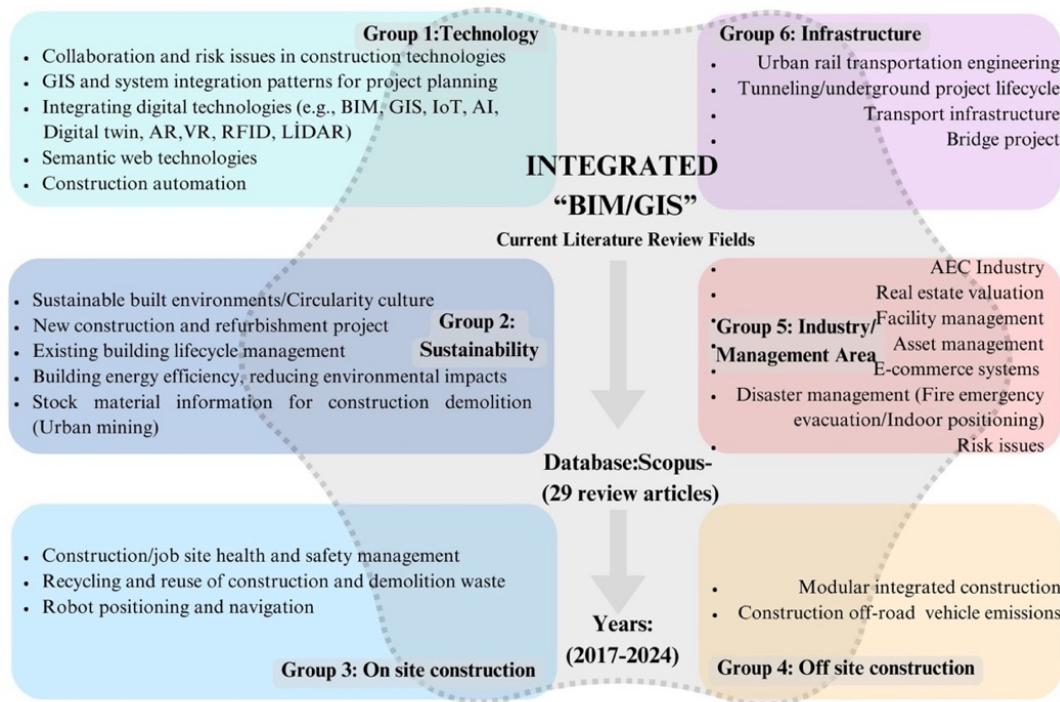


Figure 2.10 : Main fields in previous systematic literature review studies (29 papers) (Sarigul & Gunaydin, 2025).

2.2.2.2 Integrated BIM, GIS, and digitalization in construction

Status quo of BIM-GIS model integration

The evolution of the integration between BIM and GIS can be delineated into three distinct stages. These stages encompass the identification of application domains within the Architecture, Engineering, and Construction (AEC) industry, a comprehensive exploration of research and mapping methodologies, and a comparative assessment of innovations within BIM, GIS and the integrated BIM/GIS systems (Song et al., 2017). In the foundational studies concerning BIM/GIS integration, Isikdag et al. (2008) introduced two essential data models: the schema-level model view and the geospatial data model. The schema-level model serves to streamline BIM data, while the geospatial data model acts as a framework for developing physical files and databases in a geospatial context (Isikdag et al., 2008). Of the trio of software components created during this research, one specifically facilitates the extraction of building information from the BIM environment, whereas the other two enable the conversion of this information into a geospatial format. Furthermore, Arayici (2008) highlighted the capacity of BIM to foster the development of Urban Information Modeling, particularly in the context of regeneration projects.

This is accomplished through the utilization of a parametric design approach that caters to diverse levels of detail, ranging from the scale of individual buildings to broader urban contexts, while incorporating virtual reality models and sophisticated simulation platforms (Arayici, 2008). Most recently, Celeste et al. (2022) have identified a notable gap in the availability of BIM/GIS metamodels and proposed a novel perspective that emphasizes the potential for synergistic applications between metamodels and ontologies. This insight is particularly relevant in the context of emerging technologies such as sensors and machine learning (ML).

Interoperable state of the art supporting technologies with integrated BIM/GIS

The increasing volume, velocity, and variety of data generated in recent years have significantly challenged traditional data analysis methods. However, advancements in digital technologies, particularly through machine learning and computer vision, have equipped us with the necessary tools for efficient big data analysis (M. Q. Huang et al., 2021). To improve our cognitive understanding of a site's environment, we can effectively integrate partitioned datasets, unordered images, geometric models, and surrounding geographical features into Google Earth using Keyhole Markup Language (KML) (D. Li & Lu, 2018). In the construction sector, research on the integration of BIM and GIS highlights the utility of advanced detection and digital technologies, including GPS, laser technology, satellites, and LIDAR (Sepasgozar et al., 2019). The reuse of existing geographic information, such as orthophotos, digital terrain models, and vector layers, combined with various data types like LiDAR point clouds, is vital for constructing accurate and reliable BIM/GIS models of infrastructure (Barazzetti et al., 2020). While a BIM model can be directly generated for new construction projects, developing a BIM model for existing buildings necessitates laser scanning (Ellul et al., 2017). Notably, several commercial BIM software packages incorporate integrated tools for point cloud processing (Barazzetti et al., 2020).

The integration of Virtual Design and Construction (VDC) technologies, such as BIM, GIS, VR, AR, GPS, RFID, and drones, has emerged as a crucial strategy for enhancing safety in the construction sector (Afzal et al., 2021; Shafiq & Afzal, 2020). Specifically, BIM can be combined with RFID technology, which serves as a prevalent tool for automated tracking and monitoring on construction sites (Chen et al., 2022). Furthermore, aerial imagery and videos captured by unmanned aerial vehicles (UAVs)

are stored and utilized in databases to support safety oversight during construction projects (Afzal et al., 2021).

The deployment of drones, equipped with advanced sensors and cameras, presents significant advantages over traditional manual data collection methods, which are often time-consuming and prone to errors (Sestras et al., 2020). Recent advancements have improved UAV-centric methodologies for capturing and processing images, enabling effective alignment of sequential aerial imagery with unordered ground images within a physical coordinate system (D. Li & Lu, 2018). The integration of UAVs, digital cameras, terrestrial laser scanning (TLS), comprehensive site surveys, and Global Navigation Satellite System (GNSS) technologies greatly enhances the preparation of high-quality 3D building reconstructions, particularly for the preservation of historical records and cultural heritage (Sestras et al., 2020).

Low-altitude remote sensing techniques utilizing UAVs and TLSs have become widely adopted to collect geospatial data (Luong et al., 2023). Current enhancements in documenting buildings and urban heritage now include information about material properties. Additionally, the incorporation of ionizing radiation provides non-geometric information to expand existing datasets (Argenziano et al., 2018). Architectural modeling data and environmental radiometric information are systematically integrated within a technical framework, enabling effective designation of building components, roadways, urban furniture, and facades, all managed through BIM/GIS environments linked via a common feature key (Argenziano et al., 2018).

In the context of urban transformation, 3D digital mapping tools like photogrammetry and 3D laser scanning play a pivotal role in facilitating renewal projects of built environments, while BIM methodologies are increasingly applied to existing buildings using data gathered from 3D laser scanning (Arayici, 2008). The application of contemporary data collection and visualization technologies in construction significantly bolsters work efficiency, enhances workforce safety at construction sites, and positively impacts the overall quality and sustainability of projects (Chen et al., 2022). Moreover, a tool that integrates BIM, GIS, the Internet of Things (IoT), and Machine Learning (ML) algorithms has the capability to collect and analyze real-time data regarding building performance and environmental conditions, aligning with municipal construction regulations to enhance energy efficiency measures based on

meteorological influences such as wind, sunlight, and precipitation (Cinquepalmi et al., 2023).

Collectively, these technologies establish a cohesive system architecture that enhances management of quality, costs, contracts, schedules, and information throughout the lifecycle of construction projects (Y. Wang et al., 2022). The innovative integration of digital technologies has significantly advanced the development of new models based on BIM/GIS integration, thus fostering increased efficiency within the construction industry.

2.2.3 Visualizing and interpretation of bibliometric analysis results

This chapter provides a comprehensive literature review that examines preceding review articles through a systematic framework. It evaluates various factors, including the author, publication year, employed review methodologies (such as the specific databases utilized, the total number of reviewed papers, and analysis techniques), the study period, research scope, and key contributions. Articles are categorized based on the author, year of publication, integration field emphasizing the Architecture, Engineering, Construction, and Facility Management (AECO/FM) domains and the integration direction.

Moreover, the chapter incorporates a bibliometric analysis, leveraging advanced software tools to analyze and visualize bibliometric data effectively. For this research, Biblioshiny was opted, a widely used tool in similar studies. Bibliometrix (via Biblioshiny) is an open-source application functioning within the R Studio framework, facilitating a systematic analysis of literature (Kim et al., 2021). This tool enables the examination of articles based on diverse criteria, such as country, institution, journal, author, and keyword information, structured into three categories: conceptual, intellectual, and social. The findings are presented through science mapping, accompanied by graphs and tables for clarity and insight.

2.2.3.1 Annual scientific production

The data regarding publications on BIM/GIS integration from 2007 to 2024 illustrates a notable evolution in research interest over time. As depicted in Figure 2.11, a total of 141 articles were published in Scopus, revealing a gradual uptick in research activities. Initial investigations into BIM/GIS integration began in 2007, and for

several years, the volume of research remained relatively modest until a significant increase starting in 2019. This culminated in a peak of articles in 2021, suggesting an expanding academic focus in this domain.

However, it is important to highlight that the growth rate of new publications experienced a marked decline in 2021 compared to earlier years. This might indicate a period of consolidation or shifting research priorities among scholars. Furthermore, the limited exploration of BIM/GIS integration and its applications within the construction industry underscores a promising landscape for future research, teeming with both opportunities and challenges that warrant further investigation (Sarigul & Gunaydin, 2025).

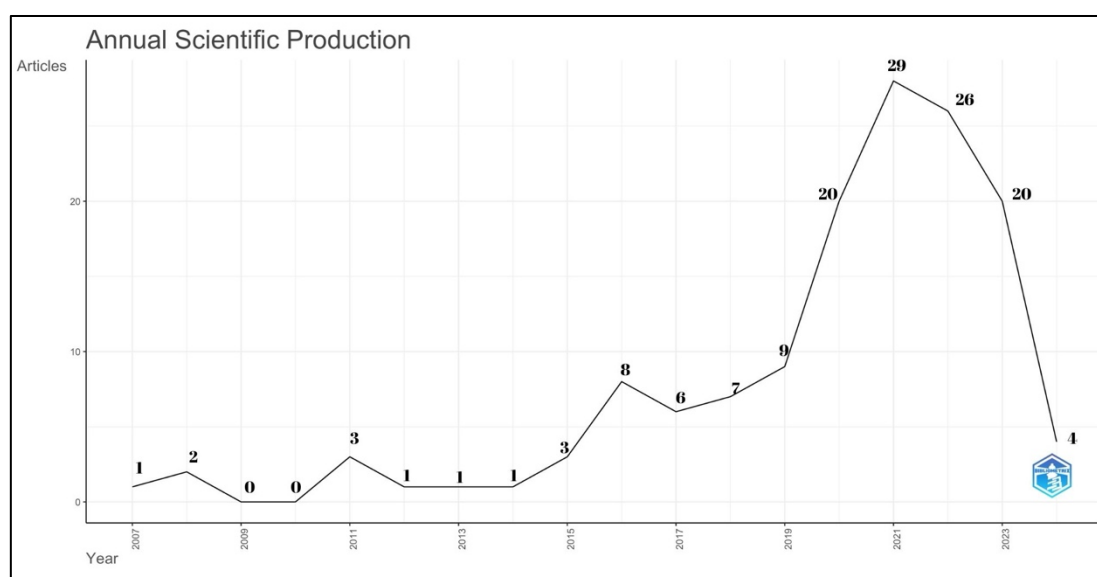


Figure 2.11 : Number of relevant papers published between 2007 and 2024. Figure is generated by Biblioshiny (Sarigul & Gunaydin, 2025).

2.2.3.2 Keyword analysis

The visualization map derived from R Bibliometrix (Biblioshiny), as illustrated in Figure 2.12, categorizes key themes within the intersection of BIM and GIS. This map delineates clusters that encapsulate vital technologies and research areas. Each cluster is distinguished by a unique color, reflecting its associated topic.

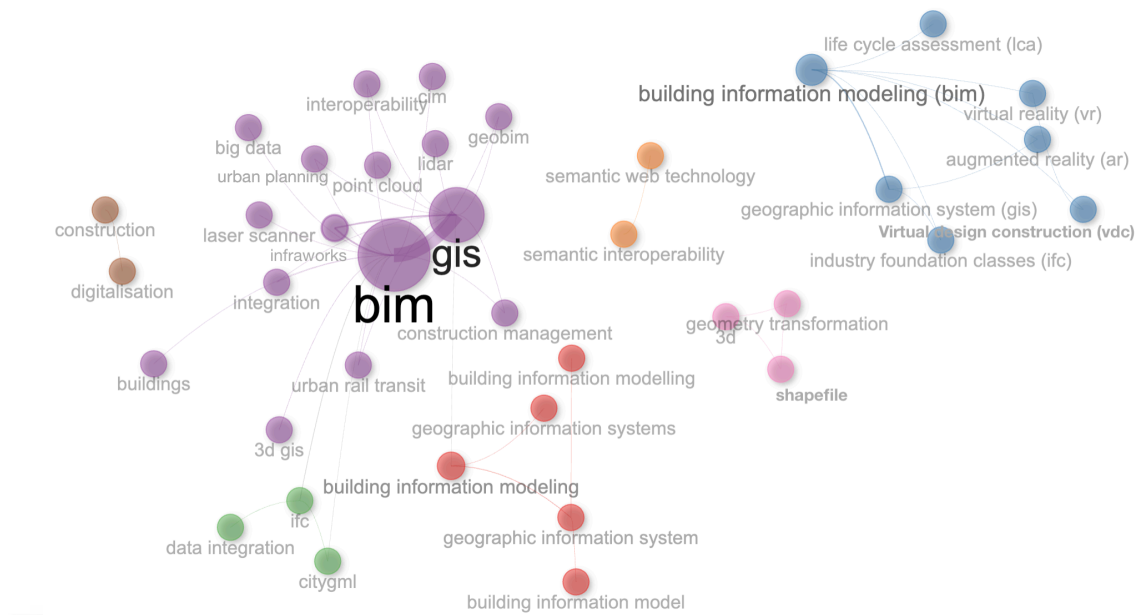


Figure 2.12 : Network of keyword connections of referenced articles. Figure is generated by Biblioshiny (Sarigul & Gunaydin, 2025).

The analysis reveals several noteworthy conclusions across these research sectors (Sarigul & Gunaydin, 2025):

Cluster 1 centers on pivotal terms such as BIM, GIS, GeoBIM, LIDAR, point cloud, Construction Information Modeling (CIM), interoperability, big data, urban planning, laser scanning, Infraworks, construction management, urban rail transit, 3D GIS, and buildings. This cluster introduces an innovative framework known as GeoBIM, which aims to create an integrated model that synthesizes building data with a 3D city model. The goal of GeoBIM is to reduce data loss and discrepancies throughout the planning and execution phases of projects (Noardo et al., 2020).

Cluster 2 addresses the concepts surrounding Building Information Modeling (BIM) and GIS, including geometric representation and the processes involved in geometric modeling.

Cluster 3 focuses on the transformation of geometry, particularly the methods used to convert 3D geometries into shapefiles.

Cluster 4 indicates that Life Cycle Assessment (LCA) research in the context of BIM/GIS integration is enhanced by the latest digital technologies. The interoperability among BIM, GIS, Virtual Reality (VR), Augmented Reality (AR), Virtual Design and Construction (VDC), and Industry Foundation Classes (IFC) is critical for effective integration of BIM and GIS.

Cluster 5 places emphasis on data integration, specifically highlighting the relevance of IFC and CityGML file formats in this domain.

Cluster 6 suggests a strong correlation between the construction sector and the ongoing trend of digitalization.

Cluster 7 underscores the application of semantic web technologies, particularly in promoting semantic interoperability within the integration frameworks of BIM and GIS.

Overall, these clusters underscore the multifaceted relationship between digital technologies and the fields of architecture, urban planning, and construction management.

2.2.3.3 Thematic map

The thematic map is articulated through four principal themes, with keywords strategically organized according to their density and centrality, as depicted in Figure 2.13.

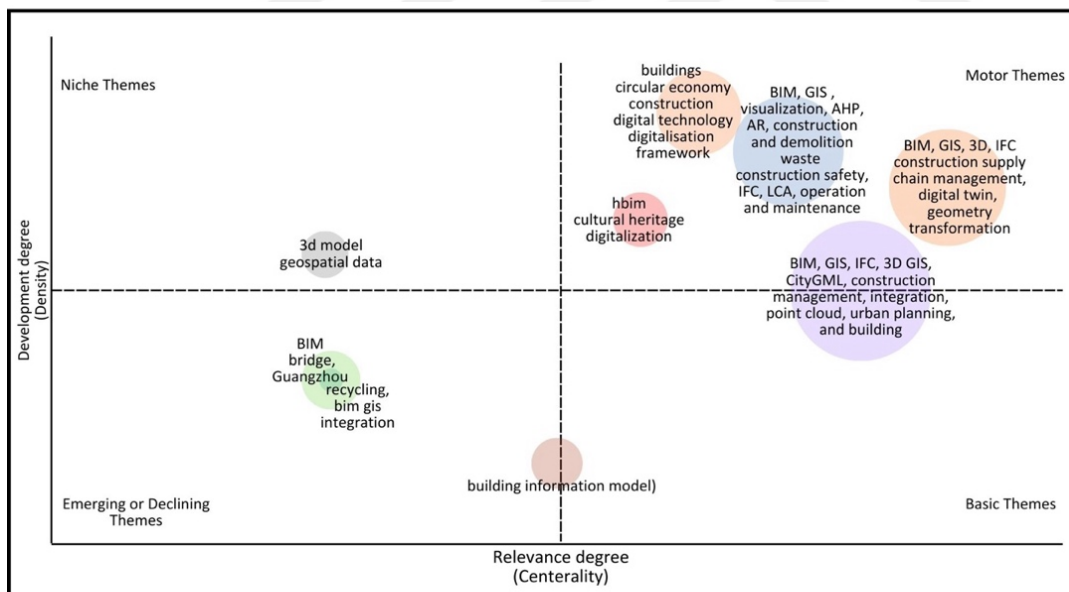


Figure 2.13 : Thematic map (According to walktrap algorithm). Figure is generated by Biblioshiny (Sarigul & Gunaydin, 2025).

The analysis aimed to accentuate the most significant keywords, culminating in the following cluster classifications (Sarigul & Gunaydin, 2025):

Motor themes (upper-right quadrant):

- Cluster 1: Keywords include buildings, circular economy, construction, digital technology, digitalization, and framework.
- Cluster 2: This cluster encompasses Heritage Building Information Modelling (HBIM), cultural heritage, and digitisation.
- Cluster 3: Consists of BIM, GIS, visualization, analytical hierarchy process (AHP), AR, construction and demolition waste, construction safety, IFC, LCA, operation, and maintenance.
- Cluster 4: Comprises BIM, GIS, 3D, construction supply chain management, digital twin, geometry transformation, and IFC.

These clusters represent robust and pertinent themes, although they may occasionally veer towards generality. Their high centrality and density render them pivotal topics for structuring the research landscape, with these influential themes manifesting in numerous studies and forming the bedrock for new research ventures.

Niche themes (upper-left quadrant):

- Cluster 5: Encompasses 3D model and geospatial data. It exhibits substantial internal connections; however, its external connections remain weak. To bolster the integration of BIM and GIS, necessary enhancements should be pursued given its high centrality yet low density characteristics.

Emerging or declining themes (lower-left quadrant):

- Cluster 6: Involves BIM, bridge, Guangzhou.
- Cluster 7: Focuses on recycling and BIM-GIS integration.
- Cluster 8: Centers on Building Information Model.

Although some investigations are currently underway in these areas, they are still in a formative phase concerning BIM/GIS integration. The theme of BIM is on an upward trajectory yet overlaps with fundamental themes, suggesting that unresolved integration challenges persist.

Basic themes (lower-right quadrant):

- Cluster 9: Encompasses BIM, GIS, IFC, 3D GIS, CityGML, construction management, integration, point cloud, urban planning, and building.

These themes, characterized by medium density and high centrality, are positioned at the forefront of research pertaining to BIM/GIS integration, indicating their significance in future work.

2.2.3.4 The most prolific journals, authors, and countries

A three-field plot, commonly referred to as a Sankey diagram, visually represents the interconnections among three significant metadata fields: authors, sources, and countries, specifically relating to BIM/GIS integration research. In the accompanying diagram in Figure 2.14, the top twenty most prolific journals, authors, and countries within this domain are highlighted.

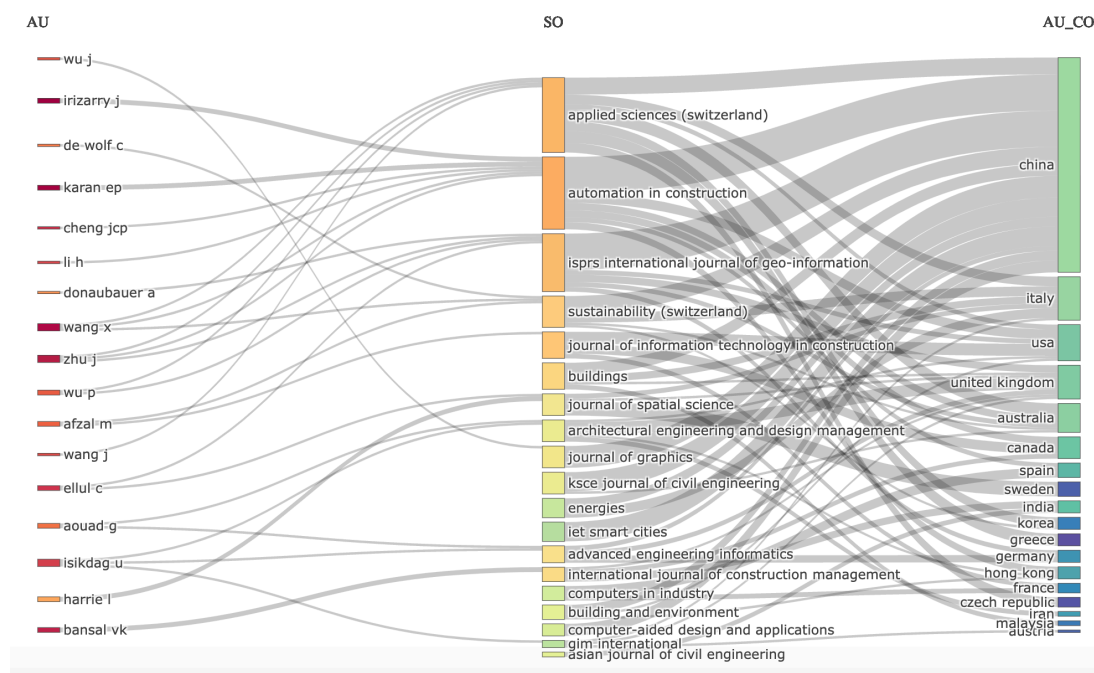


Figure 2.14 : A three-field plot. Figure is generated by R Bibliometrix (Biblioshiny) (Sarigul & Gunaydin, 2025).

According to Figure 2.14, the leading countries contributing to BIM/GIS integration research include China (35 publications), Italy (10), Australia (8), the UK (7), and India (6). Prominent journals associated with this field are Automation in Construction (9 publications), Applied Sciences (Switzerland) (7), ISPRS International Journal of Geo-Information (7), Journal of Information Technology in Construction (5),

Sustainability (Switzerland) (5), and Buildings (4). Notable authors driving research in this area are Irizarry (4 publications), Karan (4), Wang (4), and Zhu (4).

2.2.4 Content analysis of recent studies on integrated digital technologies

This chapter aims to analyze the integration of BIM and GIS, focusing on the latest digital technologies employed throughout the construction project lifecycle, which encompasses design, construction, operation, and maintenance phases. The primary objective is to identify emerging opportunities, critical challenges, technical solutions, and gaps in the existing literature while also suggesting future research avenues.

This analysis includes 112 research articles from Scopus that concentrate on BIM-GIS integration in construction. This thorough analysis is intended to tackle specific research questions. Findings culminated in the classification of the 112 articles into six application-based fields: cutting-edge technologies, lifecycle management, data integration management, disaster management, urban management, and construction activities considering both type and location. Figure 2.15 illustrates a comprehensive framework that delineates these six fields and eleven sub-fields, alongside the latest practical application areas associated with them.

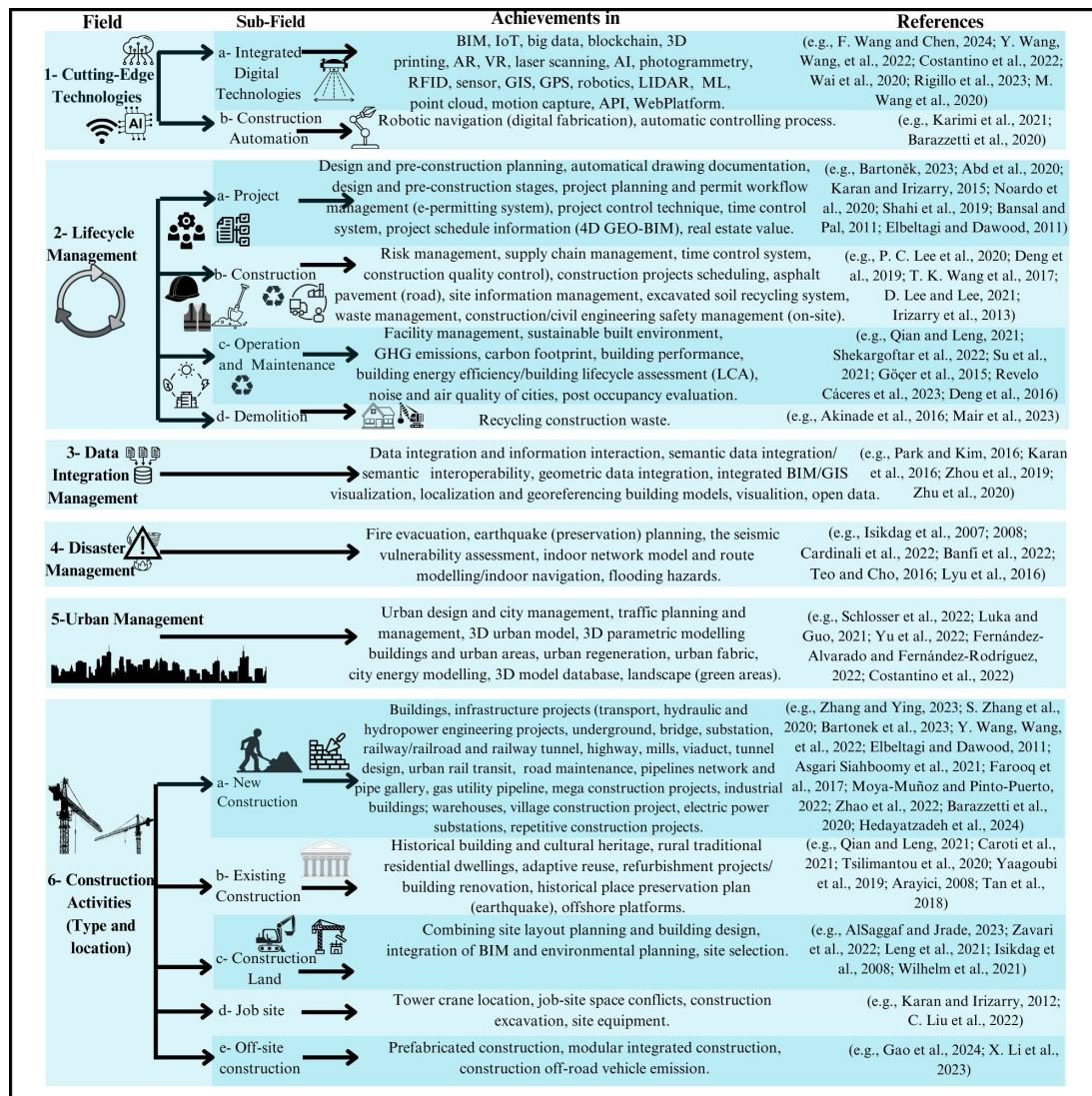


Figure 2.15 : A detailed analysis of the studies (Sarigul & Gunaydin, 2025).

In addition to the research articles, 29 review articles were examined. Table 2.10 compares the findings of research with those from the 29 review articles, highlighting both commonalities and contradictions.

Table 2.10 : Common and contradictory/different findings with previous systematic literature review studies (29 papers) (Sarigul & Gunaydin, 2025)

Common findings	Contradictory or different findings
The potential of digital transformation (integrated digital twin, BIM, GIS, IoT, and AI technologies) for optimizing the management of the built environment throughout the entire life cycle of facilities.	A framework proposal for the seamless integration of digital twin platforms in the construction industry (Piras <i>et al.</i> , 2024).
Incorporating BIM into Facility Management using ICTs facilitates data-driven decision-making and optimizes available resources.	It solely focuses on integrating BIM-FM within transportation infrastructure and is limited to exploring the potential of BIM-GIS, supported by digital technologies (Cepa <i>et al.</i> , 2023).
Construction's digital transition technologies (BIM, GIS, VR, AR, DM, blockchain, IoT, DT, AI) vary in maturity across different countries.	Digital technologies are not widely adopted in construction due to a lack of technical capabilities rather than regulatory issues. (This paper is limited to construction and demolition waste management.) (Rigillo <i>et al.</i> , 2023).

Table 2.10 (continued) : Common and contradictory/different findings with previous systematic literature review studies (29 papers) (Sarigul & Gunaydin, 2025)

Common findings	Contradictory or different findings
Potential areas for GIS adoption and future integration opportunities with emerging technologies.	GIS application and system integration patterns are restricted to the project planning phase (Akindele <i>et al.</i> , 2023).
A professional disconnect and fragmented composition lead to difficulties in GIS and BIM integration.	The proposal outlines a framework that focuses on utilizing digital twin technologies to promote the development of sustainable smart cities. (This paper is limited to urban rail transportation engineering.) (Xia <i>et al.</i> , 2022).
Enhancements in business efficiency, health and safety, productivity, quality, and sustainability are recognized as the key advantages of adopting digital technologies.	The study identified 26 technologies, categorized into five groups based on their roles in the construction process (Chen <i>et al.</i> , 2022).
Integration of BIM, GIS and IoT, barriers to the integration of BIM, sustainability and BIM. The potential research directions are evolving towards digital twin technology, the integration of BIM and AI, and AR with BIM.	Efforts in risk assessment and managing uncertainty in BIM will enhance organizational performance (Ali <i>et al.</i> , 2022).
Potential benefits, challenges, and future practices for the AEC industry's integrated BIM, GIS, 3D data, AI, and ML technologies.	3D elements derived from BIM and 3D GIS can improve real estate valuation models, reducing existing uncertainties (Jafary <i>et al.</i> , 2022).
The integration of these technologies offers considerable potential for the digitalization of the construction industry.	This study highlights that emerging technologies in fire emergency evacuation systems, including a smart and personalized system capable of real-time tracking of evacuees, represent future trends (Jiang <i>et al.</i> , 2022).
BIM-GIS integration needs to address two interconnected challenges: geometric and semantic levels.	The proposal is to apply ontologies and metamodels jointly to perform BIM/GIS integration in the development of asset management software and systems (Celeste <i>et al.</i> , 2022).
BIM, GIS, VR, UAV, 4D CAD, and wearable robotics technologies are emerging research trends in construction safety management.	Research trends: Project health and safety design and planning; visualization and image processing for construction projects; digital technologies for project monitoring; information management and the IoT; automation and robotic systems; health and safety measures for accident prevention; and building assessments (Akinlolu <i>et al.</i> , 2022).
A list of application areas of BIM and GIS which may improve existing building lifecycle processes, specifically, the possible ways to consider surroundings, site constraints, locational effects, and services of nearby facilities/utilities.	Framework proposal: BIM and GIS coordination from a multidisciplinary perspective (Bansal, 2021).
Trends, challenges, potentials, and deficiencies of BIM/GIS integration.	A novel proposal for robot positioning and navigation in construction automation (Karimi and Iordanova, 2021).
Integrated BIM, GIS, 3D Printing, and geospatial data analysis technologies enables recycling and reuse of construction and demolition waste.	New perspectives of geospatial solutions for optimizing the recycling and waste facilities to professionals and practitioners in both new construction and refurbishment projects (Sepasgozar <i>et al.</i> , 2021).
Utilizing interoperability between BIM, energy analysis tools, and other technologies can have a very positive impact on optimizing energy-saving construction solutions in the AECO sector.	There is significant potential to integrate BIM, GIS, laser scanner, and thermographic camera data merging to reduce environmental impacts of buildings (Pereira <i>et al.</i> , 2021).
Challenges and potential opportunities of BIM, GIS, and Web integration. Unified standard research is disjointed and fragmented and conducted mainly in isolated clusters.	The focus is on integrating BIM and GIS into a web-based environment (Shkundalov and Vilutienė, 2021).
Virtual design and construction technologies, such as BIM, VR, AR, GIS, and gaming technologies, facilitate the digitalization of safety measures in construction.	This paper is limited to jobsite (Afzal <i>et al.</i> , 2021).
State-of-the-art methods for integrating BIM and GIS in the management of the construction lifecycle.	Limited to Bridge projects' planning, design, construction, operation, and maintenance phases. Guide to the selection of appropriate technologies (Wei <i>et al.</i> , 2021).

Table 2.10 (continued) : Common and contradictory/different findings with previous systematic literature review studies (29 papers) (Sarigul & Gunaydin, 2025)

Common findings	Contradictory or different findings
Integrated BIM/3D geological modeling/GIS databases with ML and computer vision. The challenges and perspectives. IFC data are excellent for visualizing map and location information because of the complete 3D geometry and the detailed semantics of the building. Further research is needed on the integration of BIM and GIS in modular integrated construction.	Digitization, automation, and information integration throughout the underground project lifecycle (Huang <i>et al.</i> , 2021). The most active research direction is generating navigation models from IFC data; however, there is currently no reliable automation method for this process (Liu <i>et al.</i> , 2021). Limited modular integrated construction. While schedule and cost-related risks have gained much attention in current research, facility management, sustainability, and safety risks are ignored (Darko <i>et al.</i> , 2020). Restricted to applications in off-site construction, this paper highlights each technology's primary area of application and its limitations (Wang <i>et al.</i> , 2020).
The primary applications of digital technologies (BIM, RFID, GPS, IoT, GIS, sensors, AR, VR, photogrammetry, laser scanning, AI, 3D printing, robotics, big data, and blockchain) in construction are summarized, along with their potential and future areas of application. Integrated BIM and GIS can provide information on building materials for future demolition activities across entire cities. Technical optimization of semantic models and third-party integration platforms is essential, and the overall information flow of AEC projects should be enhanced.	Information on stock materials for future demolition activities, detailing workflows applicable for urban mining in end-of-life buildings (Rašković <i>et al.</i> , 2020). Limited to sustainable built environments. A roadmap for researchers (Wang <i>et al.</i> , 2019).
The role of advanced sensing technologies in enhancing digitalization in construction for the measurement and monitoring of emissions.	It points to a crucial gap in utilizing new technologies for automated methods to measure in-use emissions of off-road vehicles based on actual real-time activities (Sepasgozar <i>et al.</i> , 2019).
Digital technologies in facility management enhance data interoperability and generate effective integration of BIM and GIS asset databases.	Improving the accuracy of point cloud data for developing as-built models for existing facilities (Wong <i>et al.</i> , 2018).
Effective BIM-GIS integration in the AEC industry necessitates systematic theories beyond just integration technologies, as well as extensive applications of mathematical modeling methods. Software platform for integrating, managing, disseminating, and applying BIM-3D GIS data. There is a need for comprehensive proposals to completely resolve interoperability issues using semantic web technology.	This includes spatiotemporal statistical modeling in GIS and 4D/nD BIM simulation and management (Song <i>et al.</i> , 2017). Limited to combining the indoor and outdoor environment with e-commerce systems (GIM International, 2017). Semantic web technologies have a key role to play in logic-based applications and applications that require information from multiple application areas (e.g. BIM+ Infra + GIS + Energy) (Pauwels <i>et al.</i> , 2017).

Figure 2.16 and Figure 2.17 elucidate the dominant fields of study by analyzing the frequency of keywords within the publications. Specifically, Figure 2.16 utilizes varying font sizes to illustrate the prevalence of specific concepts in contemporary studies, whereas Figure 2.17 provides a frequency graph of keywords that have been cited at least twice in relation to BIM/GIS concepts. The findings reveal that the most frequently encountered concepts within the realm of construction BIM/GIS integration studies include IFC, CityGML, and 3D GIS. This analysis indicates a limited range of data formats that are commonly employed, with existing integrations of geometric and semantic models predominantly relying on these formats. Moreover, researchers are

particularly invested in resolving challenges associated with data conversion and the compatibility of various data formats.

Additionally, BIM and GIS are advanced technologies that have profoundly influenced the construction industry by leveraging digital information and communication technologies (ICTs) to collect, analyze, visualize, monitor, control, interpret, and optimize real-time data (Piras et al., 2024). While BIM primarily emphasizes the internal elements of buildings, GIS encompasses the external environment surrounding buildings and infrastructure. Despite significant advancements, both BIM and GIS have identifiable areas for enhancement concerning the design, construction, and management of construction projects and urban development. These identified limitations accentuate the necessity for improved interoperability between BIM and GIS systems. The integration of these two technologies holds the potential to yield superior outcomes throughout the building lifecycle, compared to the capabilities of each technology when utilized in isolation. This cohesive integration facilitates expedited and more precise decision-making on a unified platform.

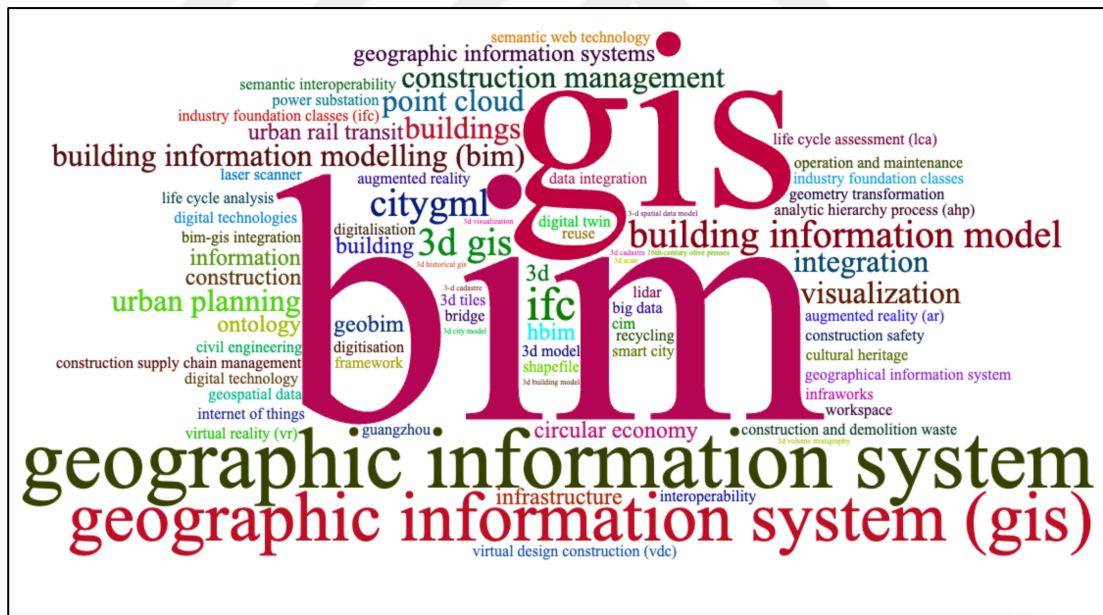


Figure 2.16 : Word cloud for the most used keywords. Figure is generated by R Bibliometrix (Biblioshiny) (Sarigul & Gunaydin, 2025).

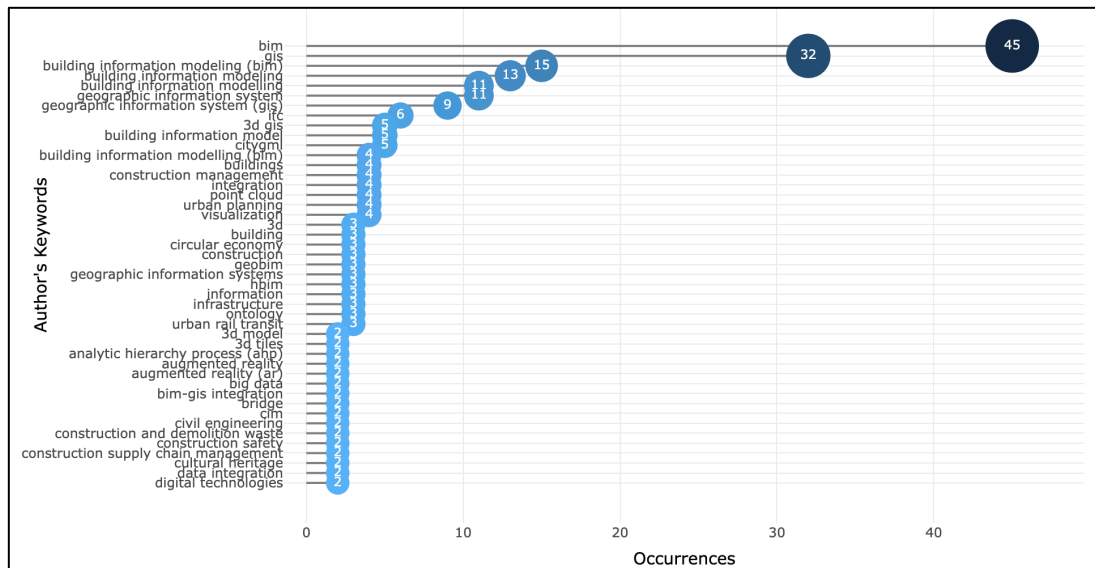


Figure 2.17 : Frequency chart of the keywords. Figure is generated by R Bibliometrix (Biblioshiny) (Sarigul & Gunaydin, 2025).

2.2.5 Opportunities, problems, technical solutions, gaps and future trends

2.2.5.1 Opportunities

This chapter highlights key opportunities in the fields of building, related infrastructure, and landscape that leverage integrated BIM/GIS and advanced digital technologies. The previous section conducted a thorough literature review, analyzing a total of 112 research articles, which have been classified as discussed in the prior chapter. The numbers and letters in parentheses correspond to the classification presented in Figure 2.15. Within this framework, integrated BIM/GIS offers both geometric and semantic information, enabling more informed decision-making and improved project outcomes. Some of opportunities are listed below (Sarigul & Gunaydin, 2025):

- Facilitates visual and aesthetic adjustments in new construction projects, thereby maintaining the character of planned settlements (The GeoBIM approach) (2-a). Furthermore, it enhances the transfer of post-occupancy evaluation data into other databases with GIS-based spatial mapping, enabling comprehensive comparisons of user satisfaction across various locations and seasonal contexts (Göçer et al., 2015). (2-c)
- By providing both geometric and semantic information, effectively reduces construction costs, enhances change planning logistics, and improves responses to maintenance demands (D. M. Azevedo et al., 2021). Additionally,

it fosters real-time information updates and supports accurate monitoring and management of logistics (D. Lee & Lee, 2021) (D. M. Azevedo et al., 2021) (2-b). In evaluating 3D factors from BIM and 3D GIS, this method proves to be a powerful tool for augmenting the accuracy of real estate valuation models (Jafary et al., 2022). (2-a)

- Moreover, the implementation of automated, model-based e-permitting systems can advance smart management systems within municipalities (Shahi et al., 2019) (2-a). By combining noise and air quality data, significantly contribute to urban sustainability efforts (Ellul et al., 2017) (2-c). When coupled with Life Cycle Assessment (LCA), multi-information models can analyze greenhouse gas emissions from prefabricated structures (Gao et al., 2024) and assess building demolition waste (S. Su et al., 2021). (2-c)
- Integrated BIM/GIS plays a critical role in construction safety by managing processes through 3D models and real-time monitoring, which includes operating early warning systems (F. Wang & Chen, 2024); enhances geotechnical modeling and ensures safe construction site selections (Khan et al., 2021) (2-b). Additionally, it offers a framework for managing end-of-life materials, aiding in urban mining, and ensuring the reuse of construction resources (Rašković et al., 2020). BIM-powered waste management tools, linked with GPS and GIS, facilitate material tracking and efficient supply chain management (Akinade et al., 2016). (2-b)
- On a broader scale, the integration of all BIM models with a cloud-based 3D database enables the incorporation of external elements such as infrastructure roads and pipelines contributing to smart city development (GIM International, 2017) (3). This framework allows for rapid geographic information acquisition, thereby improving management efficiency and visual consistency (Zhan et al., 2021) (3). Moreover, it ensures the synthesis of site planning, environmental planning, cadastral survey data, and building design data (Atazadeh et al., 2021; Leng et al., 2021a; Wilhelm et al., 2021) (3).
- The combination of semantic and geometric building data with geospatial information (Karimi et al., 2021); physical properties at the micro-level with geospatial information at the macro-level, which is particularly beneficial for

mega-construction projects (Zhao et al., 2022), and ensures that construction projects are geo-referenced (D. M. Azevedo et al., 2021). (3)

- Furthermore, it allows the integration of layout planning through GIS and BIM across various scales, which can be optimized via geometric algorithms and advanced (web-based) visualization platforms (Leng et al., 2021b). (3)
- The ability to visualize geological and design information for multifunctional pipelines embraces the "sponge city" concept, positioning municipalities at the forefront of effective flood management strategies for the future (Lyu et al., 2016) (4). This integrated approach enables emergency response management, including automated fire management (Isikdag et al., 2007) and strategic route planning for emergency situations at both city- and building-scale (Teo & Cho, 2016) (4). By facilitating mutual data sharing through individual API tools, the integrated BIM/GIS approach fosters more realistic system analyses (Farooq et al., 2017). (3)
- The functionality of the electrical grid is enhanced by methodologies that facilitate the preparation of energy models at the city level. By ensuring the integration of building-level electrical data with the overarching city-level energy grid across the entire lifecycle of the building, these approaches enable more effective management and optimization of energy resources. Additionally, they allow for the visualization and analysis of pertinent data, predict building performance, and support optimal site selection through the use of smart microgrids informed by semantic information. This is achieved by employing a bottom-up management strategy, thereby allowing for a more granular understanding of energy dynamics and synergies among various stakeholders (Farooq et al., 2017). (5)
- Integrated BIM/GIS utilizes BIM-3D geometric data sourced from LIDAR, along with meteorological data such as location and wind, to enhance GIS software capabilities. This integration streamlines the creation of aerobiological risk maps specifically for ornamental trees. Additionally, this method aids in minimizing green areas within urban infrastructure and addressing potential aerobiological health risks (Fernández-Alvarado & Fernández-Rodríguez, 2022). (5)

- The integration of BIM/GIS allows for a more efficient analysis of spatial data, leading to informed decision-making in warehouse site selection processes. This synergistic approach enables a comprehensive understanding of geographic factors, logistical considerations, and infrastructural capabilities, ultimately supporting the development of robust supply chain strategies (Asgari Siahboomy et al., 2021). (6-c)
- The integration of BIM/GIS plays a crucial role in the effective management of urban facilities. This synergy is particularly valuable in addressing challenges related to infrastructure, maintenance, and urban growth (Mignard & Nicolle, 2014). (5)
- Integrated BIM/GIS combines traffic noise evaluations in both outdoor and indoor environments on a single platform, and supports the design and planning of transportation infrastructure for traffic management (Deng et al., 2016); ensures the design and dimensioning of the transportation infrastructure for traffic planning and management (Schlosser et al., 2022). (5)
- The integration of BIM and GIS plays a critical role in standardizing landscape BIM elements, including features like parametric trees, to support their application throughout the full lifecycle of a project. This standardization facilitates better management and analysis of landscape data, enhances collaboration among stakeholders, and improves decision-making processes (Luka & Guo, 2021). (5)
- Integrated BIM/GIS effectively optimizes site layout planning by minimizing the total on-site travel distance for personnel and equipment between facilities. This approach enhances operational efficiency and supports better resource management within construction and project development environments (AlSaggaf & Jrade, 2023; Zavari et al., 2022).6-c)
- The integration of BIM and GIS facilitates the identification of unused or underutilized structures that could be targeted for transformation interventions. This innovative approach allows for comprehensive analysis and visualization of spatial data, making it easier to assess the potential for redevelopment and adaptive reuse of these buildings. By utilizing BIM/GIS integration, urban planners and policymakers can make informed decisions that promote

sustainable development and optimize the use of existing resources (Diana et al., 2022). (6-b)

- The integration of BIM and GIS provides a robust framework for dimensionality reduction and effective extraction strategies of remote sensing data pertinent to construction land. This approach facilitates the efficient analysis and management of spatial data, enabling stakeholders to make informed decisions in the planning and development of construction projects (Y. Wang, Li, et al., 2022). (6-c)
- Integrated BIM/GIS systems play a crucial role in assessing the seismic vulnerability of masonry building aggregates, as highlighted by Cardinali et al. (2022) (4). This integration not only aids in the vulnerability assessment but also enhances spatial HBIM management, which is essential for effective preservation planning in the event of an earthquake, as described by Banfi et al. (2022). These methodologies are particularly valuable for mitigating risks and ensuring the safety of historical structures in seismic-prone areas. (6-b)
- The integration of Building Information Modeling (BIM) and Geographic Information Systems (GIS) plays a significant role in enhancing the effectiveness of building renovation activities. As highlighted by Daneshfar et al. (2022) (2022), the utilization of integrated BIM/GIS maps provides a comprehensive framework for addressing geospatial and environmental considerations, thereby facilitating informed decision-making during renovation tasks. This approach not only improves project efficiency but also ensures that environmental factors are adequately considered, aligning with sustainable development goals within the construction industry. (6-b)
- Integrated BIM/GIS merges 3D Building Information Modeling (BIM) of structures with geographic information system (GIS) data to enhance tower crane placement on construction sites. This integration aids in identifying potential conflict risks and optimizes the positioning of cranes by allowing for visualization and selection of appropriate locations for installation (Karan & Irizarry, 2012; C. Liu et al., 2022). This approach not only improves efficiency but also contributes to the overall safety and effectiveness of construction operations. (6-d)

- The integration of BIM and GIS significantly enhances the reliability of decision-making processes in construction. This integration enables effective monitoring of changes associated with deep excavation works, particularly those that present high-risk factors. By visualizing data sourced from both BIM and 3D GIS, project managers and engineers can better assess and respond to potential hazards on construction sites, ultimately promoting safer and more efficient construction practices (P. C. Lee et al., 2020). (6-d)
- The integration of BIM and GIS with terrestrial LIDAR and traditional surveying methods including transition, leveling, and GPS facilitates the development of 3D Historical Geographic Information Systems (HGIS). This comprehensive approach is particularly significant for documenting historic buildings and heritage sites (Yaagoubi et al., 2019). Furthermore, it enhances the structural assessment of historic buildings and supports rehabilitation projects (Tsilimantou et al., 2020). The integration also plays a crucial role in the documentation of cultural heritage and the implementation of sustainable conservation processes (Argenziano et al., 2018). (6-b)

In light of recent studies, the integration of BIM and GIS presents a robust solution to the multifaceted challenges encountered at the confluence of building and urban scales. These challenges encompass a range of critical areas, including urban infrastructure development, sustainable resource management, waste management, and the preservation of historical structures and sites all while promoting smart construction practices.

By merging data from building and city levels, BIM/GIS integration accelerates the shift towards digitalization in urban management, effectively aligning location data with pertinent geological information relevant to construction projects. This methodology fosters enhanced digital documentation and facilitates real-time information management, which significantly improves operational efficiency throughout the entire construction lifecycle spanning phases from pre-construction to demolition, and applicable to both new builds and renovation efforts.

Figure 2.18 illustrates the opportunities and potential benefits afforded by integrated BIM/GIS applications within the construction sector. This framework not only supports ongoing developments but also encourages innovative solutions to urban

challenges, paving the way for future advancements in sustainable urban planning and development.

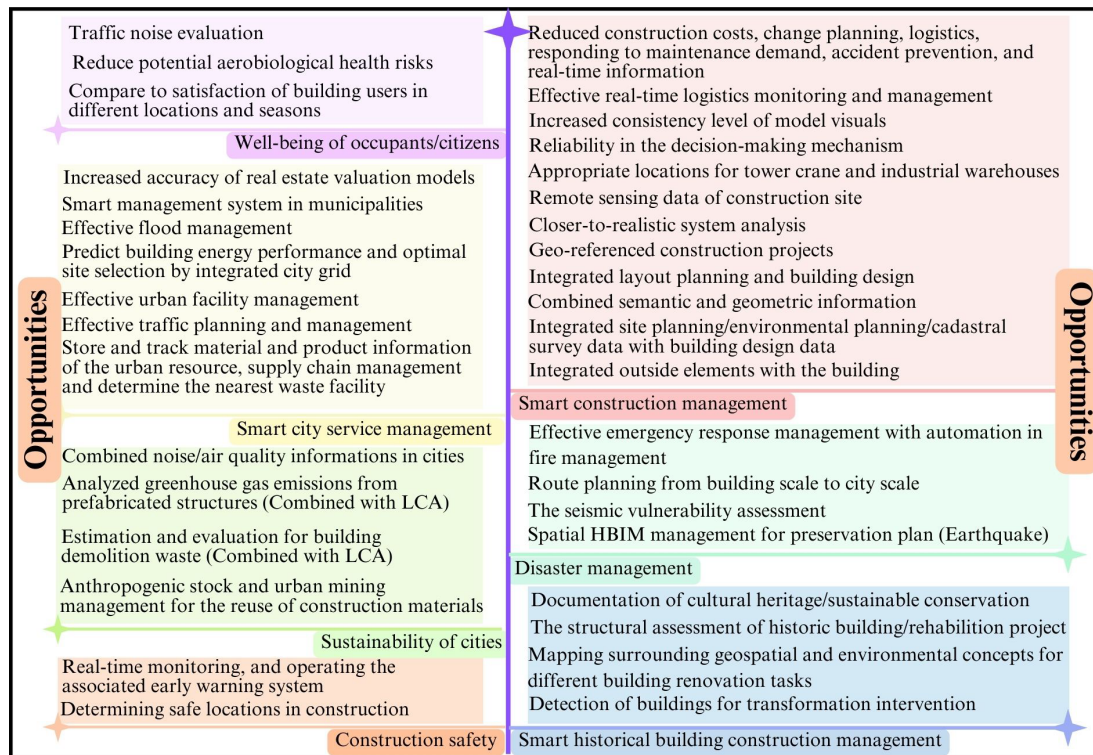


Figure 2.18 : Summary of integrated BIM/GIS opportunities (Sarigul & Gunaydin, 2025).

2.2.5.2 Most urgent problems/obstacles

Integrated BIM/GIS presents significant challenges, especially when shifting between indoor and outdoor environments. X. Liu et al. (2017) highlights the complexities that arise when attempting to fuse building models within broader geospatial contexts. The disparities in scale and service levels among buildings and urban areas further complicate this integration; successful outcomes depend heavily on the synergy of three critical domains: geological surveys, construction practices, and municipal governance (GIM International, 2017).

The primary issues identified in the integration of BIM and GIS, from initial research through to contemporary findings, include (Sarigul & Gunaydin, 2025):

- Geometric and semantic incompatibilities frequently occur during the model conversion from Industry Foundation Classes (IFC) to shapefile formats. This issue has been notably highlighted in the works of Isikdag et al. (2007) and Zhu et al. (2020). Addressing these challenges is crucial for improving

interoperability and ensuring accurate data representation in urban and architectural projects.

- Geometric integration has experienced notable progress in recent years; however, semantic integration continues to present significant challenges. These challenges can be effectively tackled through the application of various commercial software solutions designed to enhance compatibility and understanding among different data systems (Celeste et al., 2022).
- The integration of BIM and GIS into a unified information database is becoming increasingly critical in the fields of architecture, engineering, and urban planning (D. M. Azevedo et al., 2021; Bansal, 2020).
- The transition from Industry Foundation Classes (IFC), which encompasses a wealth of detailed information regarding building elements and structures, to City Geography Markup Language (CityGML), which operates at a comparatively lower Level of Detail (LOD), is typically a straightforward process. However, the reverse transformation from CityGML back to IFC poses significant challenges due to the intricate rules and methodologies involved (H. Wang et al., 2019; Zlatanova & Isikdag, 2016). In general, 3D model data is designed to align with CityGML's LOD specifications, often reaching levels 2 or 3. A subset of models may even achieve LOD 4 when necessary for seamless integration with Building Information Modeling (BIM) data (GIM International, 2017).
- To improve the synergy among BIM, GIS, and web-based platforms, it is crucial to establish a cohesive standard that governs the integration of BIM models. This standard should facilitate effective information sharing, storage solutions, and processing methodologies, thereby promoting a more efficient collaborative environment (Shkundalov & Vilutienė, 2021).
- The current web environment presents a significant gap in the availability of open-source tools and methodologies required for efficient processing of BIM models (Shkundalov & Vilutienė, 2021). This deficiency hampers the potential for collaboration and interoperability in BIM workflows, highlighting the need for the development and implementation of more accessible and effective resources within the domain. Addressing this shortfall would not only enhance

the processing capabilities of BIM models but also foster innovation and knowledge sharing in the architecture, engineering, and construction industries.

- The integration of semantic connections within the fields of construction and robotics is essential for the efficient management of construction sites (Karimi et al., 2021).
- The ArcGIS Python site package, which is a commercial geographic information system (GIS) product, is predominantly restricted to Windows operating systems and exhibits limitations in terms of productivity. As a consequence, there is an increasing demand for a more robust and comprehensive open-source solution that can enhance usability and accessibility across various platforms (Zhu et al., 2020).
- The challenge of collecting 3D urban data has significantly diminished with advancements in technology; however, the present concern shifts towards the efficient utilization of this extensive data for spatial planning and city management (GIM International, 2017).
- The integration of BIM and GIS is fundamentally data-driven. This integration often encompasses a range of information, including details about construction workers and other employees involved in projects. As a result, it raises important concerns regarding privacy and the potential for ethical violations (Chen et al., 2022).
- Interoperability between geospatial data and BIM during the design and preconstruction phases is an area that continues to present significant opportunities for advancement. The integration of these domains is crucial for enhancing collaboration, improving accuracy, and streamlining workflows (Karan & Irizarry, 2015)

The aforementioned studies highlight critical technical challenges that must be overcome to advance the integration of BIM and GIS in the construction industry. Key issues include the harmonization of data formats to ensure seamless integration, the necessity for standardization, the adoption of open-source software solutions, and the imperative of safeguarding personal data. The ability to effectively collect and analyze building and urban information within a cohesive software environment is

fundamentally linked to the success of data initiatives that prioritize detail, formats, and preferences for commercially available software. To effectively tackle these challenges, it is essential to enhance government-supported research and development endeavors. Figure 2.19 provides a comprehensive overview of the most pressing problems and obstacles associated with the implementation of integrated BIM/GIS systems in construction projects.

Problems/Obstacles Field	Sub-fields	References
The model integration process 	Geometric and semantic incompatibilities (IFC to Shapefile or CityGML)	(Isikdag et al., 2007; Zhu et al., 2020)
	The conversion from CityGML (low LOD) to IFC (high LOD) is difficult	(H. Wang et al., 2019; Zlatanova & Isikdag, 2016)
	Interoperability difficulties across the geospatial and BIM domains in design and pre-construction stages	(Karan & Irizarry, 2015)
	Need to an unified standard for BIM model-city model integration	(Shkundalov & Vilutienė, 2021)
Tools/Software Packages/Database 	The web environment does not have the necessary open-source tools and methods for BIM model processing	(Shkundalov & Vilutienė, 2021)
	A more comprehensive open source is needed instead of ArcGIS Python site package	(Zhu et al., 2020)
Information management 	Integrating BIM/GIS into an unique information database	(Azevedo et al., 2021; Bansal, 2020)
	The fields of construction and robotics need to make semantic information connections	(Karimi et al., 2021)
	How large amount of 3D urban information can be used in spatial planning and city management	(GIM International, 2017)
	Privacy and ethical violations for construction workers and other employees	(Chen et al., 2022)

Figure 2.19 : Summary of integrated BIM/GIS most urgent problems/obstacles (Sarigul & Gunaydin, 2025).

2.2.5.3 Technical Solutions for BIM/GIS integration problems

Ellul et al. (2017) identified several recommendations for effectively addressing the technical challenges involved in the integration of Building Information Modeling (BIM) and Geographic Information Systems (GIS). They emphasized the importance of key considerations for BIM, which include:

1. Geo-referencing: Ensuring spatial accuracy by aligning BIM data with geographic coordinates.
2. Compatibility of measurement units: Addressing discrepancies between the millimeter measurements commonly used in civil engineering and the meter measurements used in GIS.

3. Appropriate level of detail for scanning: Tailoring the level of detail in BIM models to meet project requirements.

4. Consistent labeling of BIM geometries: Standardizing labels to enhance clarity and usability of the models.

5. Accurate modeling of spaces in BIM: Utilizing IFCSpace to capture relevant objects and their spatial relationships effectively.

Furthermore, the literature provided recommendations to tackle the broader challenges encountered during the integration of these two systems, focusing on enhancing interoperability and streamlining workflows across disciplines. Some of these suggestions are listed below (Sarigul & Gunaydin, 2025):

- Utilizing GeoBIM information within a harmonized workflow presents a transformative opportunity for the process of obtaining building planning permissions. However, a notable challenge is the requirement for diverse software and procedures tailored to different stages of this workflow. This often necessitates the repeated importing, exporting, and conversion of identical models across various formats. The initiative funded by ISPRS and the ‘GeoBIM benchmark’ (Url-9) EuroSDR aims to explore the available technical alternatives and assess their performance (Noardo et al., 2020).
- To address the heterogeneity in BIM/GIS integration, Mignard & Nicolle, (2014) introduced the Urban Information Modeling (UIM) semantic extension alongside the SIGA3D project. This initiative seeks to improve the lifecycle management of construction projects by establishing clear processes for stakeholders involved in urban development.
- Future research could focus on developing a unified data platform that enhances the integration of BIM into GIS, or on synthesizing all relevant information into a novel platform (Khan et al., 2021) Additionally, Autodesk InfraWorks is proposed as a complementary environment that integrates Autodesk Revit with ArcGIS software. This combination empowers users to visualize models effectively and create a comprehensive digital representation of the real world, encompassing construction and its surrounding environment (Abd et al., 2020; Barrile et al., 2023).

- A reference ontology in the context of semantic web technologies can significantly reduce integration errors by minimizing discrepancies among various data sources. By providing a common framework for understanding and organizing information, it enables consistent interpretation of terms and relationships, thereby facilitating seamless communication between disparate systems (X. Liu et al., 2017).
- Keyhole Markup Language (KML) in conjunction with cloud-based data management systems facilitates the integration of geometric models and panoramic images within a three-dimensional GIS platform. This synergy allows for enhanced visualization and interaction with spatial data, enabling users to effectively analyze and interpret complex geographical landscapes and environments (D. Li & Lu, 2018).
- The integration of BIM and IFC with CityGML presents an opportunity to incorporate cadastral survey data into the BIM model effectively (Atazadeh et al., 2021).
- Individual API tools facilitate the transfer of a diverse array of static and dynamic building data to GIS platforms (Farooq et al., 2017).
- Review indicates a need for APIs to integrate BIM data with three-dimensional urban data, as well as to connect urban data with BIM. Studies have demonstrated that each new approach to geometric and semantic data integration models can enhance this integration process. Figure 2.20 summarizes the technical solutions available for addressing BIM/GIS integration challenges.
- Review highlights the critical role of Application Programming Interfaces (APIs) in facilitating this integration. By serving as a bridge, APIs enable the seamless connection of BIM data with urban datasets, fostering enhanced data interoperability. Various studies have explored innovative approaches to geometric and semantic data integration models, suggesting that these methodologies can significantly improve the integration process.
- The challenges associated with BIM and GIS integration have prompted the development of multiple technical solutions. As illustrated in Figure 2.20, these solutions aim to address the existing barriers and enhance the cohesion between

BIM and urban data frameworks, ultimately leading to more efficient urban planning and management. The continued exploration of these integration techniques will likely contribute to more robust urban analytics and decision-making in the future.

Technical Solutions: Response to the heterogeneity problems	References
Using GeoBIM information in a harmonized workflow has the potential to revolutionize building planning permissions: 'GeoBIM Benchmark'	(Noardo et al., 2020)
The UIM (Urban Information Modeling) semantic extension to BIM to determine processes for stakeholders in urban projects (SIGA3D Project)	(Mignard & Nicolle, 2014)
A unified data platform for integrating BIM into GIS or all information into a new platform	(Khan et al., 2021).
Autodesk InfraWorks for a third environment that combines Autodesk Revit and ArcGIS software for visualizing models/ creating the digital representation of the real world	(Abd et al., 2020; Barrile et al., 2023)
A reference ontology within the scope of semantic web technologies may reduce the error rate in integration	(X. Liu et al., 2017)
Keyhole Markup Language and cloud storage-based data management system allows combining geometric models and panoramic images	(Li & Lu, 2018)
All kinds of static and dynamic data of buildings can be transferred to the GIS platform through individual API tools	(Farooq et al., 2017)
Integrating cadastral survey data into the BIM model may be possible with BIM/IFC-CityGML integration	(Atazadeh et al., 2021)

Figure 2.20 : Summary of technical solutions for BIM/GIS integration problems (Sarigul & Gunaydin, 2025).

2.2.5.4 Gaps and future trends

The integration of digital technologies within the construction industry has been recognized as a significant driver of innovation, presenting both opportunities and challenges across various sub-fields. Although advancements in technology such as Building Information Modeling (BIM), Geographic Information Systems (GIS), Artificial Intelligence (AI), Machine Learning (ML), and the Internet of Things (IoT) are transforming data acquisition, management, and dissemination, there are notable gaps in addressing the comprehensive lifecycle of buildings (Bansal, 2021). Some of these gaps are as follows:

- Current research highlights a prevalent focus on smart construction technologies; however, the facility management phase remains underexplored (Cepa et al., 2023). Enhancements in the capabilities of advanced technologies can significantly elevate the functionality of digital twin (DT) platforms,

fostering a more integrated approach to construction management (Piras et al., 2024). Furthermore, the Semantic Web emerges as a critical tool for creating a globally accessible information framework (Mignard & Nicolle, 2014) that supports the seamless integration of diverse data sources, including GIS, facility management databases, urban planning, regulatory frameworks, and cadastral information (Pauwels et al., 2017).

- Research indicates unexplored avenues for employing BIM to replace traditional 2D cadastral plans during the planning phase, emphasizing the importance of 3D data storage, visualization, and validation (Atazadeh et al., (2021).
- There is a pressing need for studies that promote the interoperability of GIS, BIM, 3D printing, and geospatial data analysis, particularly in the context of effective waste management within the construction sector (Sepasgozar et al., (2021).
- Current literature also suggests an imbalance in research attention towards fire emergency evacuation strategies, often prioritizing facility operation phases over early design and construction stages (Jiang et al., 2022).
- Additionally, the integration of BIM with smart environments and grid optimization, alongside power system analysis software, presents further opportunities for exploration that remain largely untapped (Farooq et al., 2017).
- Expanding research beyond conventional construction applications to encompass landscape elements such as lakes, rivers, and green spaces within geospatial databases as parametric BIM/GIS objects is crucial (Barazzetti et al., 2020). Finally, the role of digital technologies in facilitating the transition to digital twin platforms warrants further investigation, particularly concerning the integration of three-dimensional data from cadastral and urban infrastructure into the BIM framework. Existing studies often fall short of addressing the entire lifecycle of construction from design and construction through to facility management indicating a critical area for future research endeavors.

The integration of BIM and GIS is becoming increasingly vital within the construction industry, as outlined in Figure 2.21, which highlights existing gaps and future trends. The convergence of BIM and GIS on a unified platform fosters enhanced interoperability in both architectural and urban environments. By analyzing and correlating data from BIM and GIS, stakeholders can significantly reduce risks to human life and property during catastrophic events such as earthquakes, fires, and floods.

This synthesis not only aids in managing construction-related hazards but also promotes restoration efforts that honor historical contexts, thereby safeguarding cultural heritage. Additionally, such integration informs urban management policies, paving the way for the development of smart and sustainable buildings and cities. With the proper application of modern construction technologies, it is possible to achieve sustainability alongside quality, cost efficiency, and adherence to timelines in urban development.

Collaboration among public entities and software firms is essential for the successful amalgamation of BIM with GIS. To facilitate this process, administrative incentives, including tax breaks for software developers and the endorsement of open-source software policies, play a significant role. Furthermore, the private sector has a responsibility to highlight the prospective advantages of their innovations to industry stakeholders.

Investing in the enhancement of software capabilities and providing comprehensive training for users can significantly smooth the transition to digital urban services. These services, which are typically provided by local municipalities and central government ministries, can deliver rapid and efficient solutions regarding building permit applications and other construction-related procedures. This transition not only improves citizen welfare but also enhances public satisfaction with government operations (Sarigul & Gunaydin, 2025).

Gaps and Future Trends	References
• The use of digital technologies in facility management	(Cepa et al., 2023)
• BIM, GIS, artificial intelligence, machine learning, and IoT in the construction industry contributes greatly to the functionality of digital twin platforms	(Piras et al., 2024)
• Potential of semantic web for integrating independent building data with GIS, FM, city, material repositories, regulation, and cadaster, etc.	(Mignard & Nicolle, 2014)
• Replacing 2D cadastral plans with BIM at the plan placement stage	(Atazadeh et al., 2021)
• Integrated GIS, BIM, 3D Printing, and geospatial data analysis for effective waste management in construction	(Sepasgozar et al., 2021)
• Fire emergency evacuation in the facility operation stage	(Jiang et al., 2022)
• BIM in smart environments, grid optimization, and integration of BIM with power system analysis software	(Farooq et al., 2017)
• Landscape elements created in geospatial databases and can be parametric BIM/GIS objects need expanded	(Barazzetti et al., 2020)

Figure 2.21 : Summary of integrated BIM/GIS literature gaps, and future trends (Sarigul & Gunaydin, 2025).

2.2.6 Conclusions for integrated BIM-GIS usage

In this chapter, systematic literature review offers an in-depth exploration of the integration of BIM and GIS within the Architecture, Engineering, Construction, and Operations/Facility Management (AECO/FM) industries. Drawing on data collected in February 2024, the analysis encompasses 141 articles, showcasing a bibliometric review that identifies China as the frontrunner in BIM/GIS publications, followed by Italy and Australia in second and third place respectively. The journal "Automation in Construction" emerged as the leading publication outlet, with "Applied Sciences" (Switzerland) and the "ISPRS International Journal of Geo-Information" following closely.

The content analysis presents a structured categorization of achievements into six primary fields and eleven sub-fields that highlight the various areas of integration:

(1) Cutting-edge technologies (which includes integrated digital technologies and construction automation), (2) Lifecycle management (pertaining to project, construction, operation and maintenance, and demolition), (3) Data integration management, (4) Disaster management, (5) Urban management, and (6) Construction

activities (which cover new construction, existing construction, construction land, job site, and off-site construction) (Sarigul & Gunaydin, 2025).

Review articles were further classified into six groups: technology, sustainability, on-site construction, off-site construction, industry/management areas, and infrastructure. The findings underscore a profound influence of digital technologies in the construction sector on a global scale. Notably, technologies such as LiDAR, Augmented Reality (AR), Virtual Reality (VR), Terrestrial Laser Scanning (TLS), Radio-Frequency Identification (RFID), Global Positioning System (GPS), the Internet of Things (IoT), and drones (UAV) are frequently used in BIM/GIS integration. These technologies serve to facilitate the collection, analysis, storage, management, visualization, monitoring, and sharing of both macro (city) and micro (building) data in both real and virtual environments, ultimately fostering an integrated digital environment.

Moreover, the review highlights the evolution of BIM/GIS integration studies across several domains, from semantic integration involving energy efficiency and carbon footprint calculations to geometric integration of small-scale parametric designs into geospatial urban models using software like Rhino. The requirement for open-source BIM/GIS software is increasingly emphasized. While initial studies primarily focused on emergency response management, recent research has shifted toward areas such as environmental impact assessments, carbon footprint analysis, construction and demolition waste management, and overall lifecycle assessments.

Despite notable shifts in focus, successful integration examples, effective data conversion methods, and several potential third-party platforms have been identified. However, challenges persist, particularly concerning preferred data formats like IFC and CityGML, which encounter conversion obstacles due to differences in Levels of Detail (LOD). Additional hurdles include discrepancies in measurement units, ensuring geometric and topological consistency and accuracy, and deriving semantically meaningful data features from images and point clouds.

Review results emphasize the necessity for innovative data environment solutions that tackle issues related to semantic and geometric integration. Infracore is a leading software that effectively combines construction data with its surrounding environment. Given these challenges, establishing standardized data conversion techniques is

crucial. Policymakers in urbanization-related institutions should prioritize the development of standards that improve operational efficiency for the private sector.

Key areas for further development in the integrated approach to BIM and GIS within construction include themes like the circular economy, digital innovation, Heritage BIM (HBIM), visualization, 3D GIS, Analytic Hierarchy Process (AHP), AR, construction and demolition waste management, construction safety, and lifecycle assessments. The findings outlined in this paper aim to benefit professionals engaged in research and development within the construction sector, inform investment strategies in new technologies, and assist municipal decision-makers and academics in advancing their research.

The complete integration of BIM and GIS will necessitate collaboration among expert teams across all sectors of the construction industry, ensuring that the latest digital technologies are leveraged effectively. By doing so, contemporary challenges such as construction delays, inefficiencies, cost overruns, subpar quality, sustainability concerns, and potential crises can be effectively addressed. Ultimately, the results underscore the pressing challenges of integrating BIM and GIS areas that warrant further attention from construction researchers and software developers alike.



3. METHODOLOGY

3.1 Smart Sustainable Building-City Integration Evaluation Model Creation

The methodological framework of this doctoral thesis is structured around three principal phases, centering on the development and validation of the Smart Sustainable Building-City Integration Evaluation Model (SSB-CIEM). The requisite stages for developing and validating the SSB-CIEM are illustrated in Figure 3.1. Initially, the research identifies factors influencing the maturity of smart sustainable buildings (SSB) among Turkish construction professionals. The relevant area indicators and a five-tier evaluation scale were established through an extensive literature review detailed in Chapter 2, which incorporated dual systematic literature reviews employing both qualitative and quantitative methodologies.

In Chapter 3, a frequency analysis was performed on the identified areas and indicators derived from the literature. Subsequently, the preliminary draft of the SSB-CIEM was subject to evaluation by an expert panel. Following this evaluation, a survey design was implemented to empirically test the conceptual SSB-CIEM, allowing for feedback from Turkish construction sector professionals. The statistical analysis of the survey results facilitated a determination of the maturity level of the Turkish construction industry in the realms of integrated Building Information Modeling (BIM) and Geographic Information Systems (GIS), as well as smart sustainable building-city integration areas.

Given that the SSB-CIEM emerges from an exploratory investigation, the PLS-SEM (Partial Least Squares Structural Equation Modeling) method was employed to assess the model's reliability and validity, as well as to gauge the predictive capabilities and impact strength of the specified fields and indicators. The formation of six hypotheses marked the outset of the first phase in the model development process. Subsequently, as articulated in Chapter 4, the analysis segment referenced established threshold values to conduct model testing through the SmartPLS software. In pursuit of

validating and reinforcing the model's integrity, modifications were made to the hypotheses, ultimately refining them to a total of four.

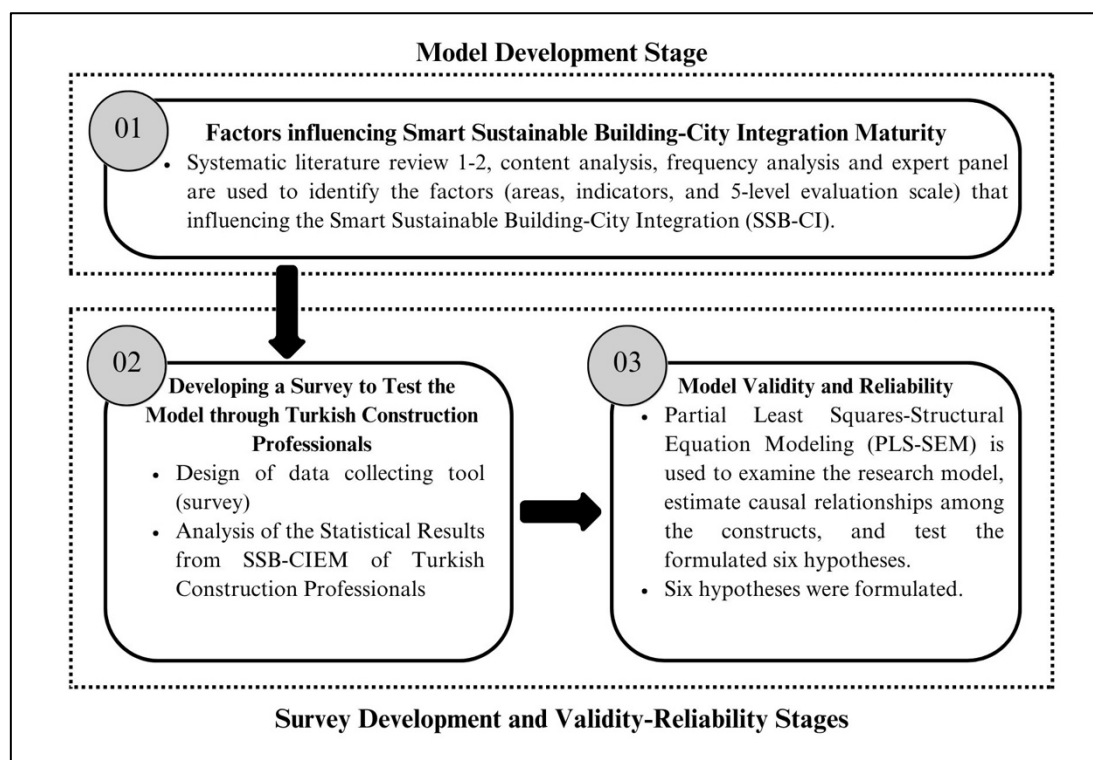


Figure 3.1 : Stages for validation and reliability of SSB-CIEM.

3.1.1 Factors affecting SSB-CI maturity evaluation

The determination of the area, indicator, and the 5-level integration evaluation scale in SSB-CIEM was conducted through a systematic literature review as outlined in Chapter 2. This chapter incorporates frequency analysis and expert panel evaluations to ensure a comprehensive integration evaluation model.

3.1.1.1 Frequency analysis for SSB-CIEM areas and indicators

In this chapter, the frequency analysis was conducted on the areas and indicators identified through the literature review in the preceding chapter. The analysis, presented in Table 3.1 and Table 3.2, aimed to identify the areas and indicators that are prevalent across various tools designed for evaluating smart or sustainable buildings and cities. In these tables, the cells highlighted in black for the evaluation tools indicate that the factors or areas directly correspond to the six main areas listed in the columns. Conversely, the cells marked in red contain factors that have similar meanings, even though they are labeled differently. Based on the findings, these areas and indicators were systematically categorized to align with the integrated application

of BIM-GIS technologies, ensuring a cohesive framework for this thesis study. As seen in Table 3.1, Criteria are based on the LEED certification system credit categories, as this table primarily incorporates those criteria. The IPM criterion necessitates the use of Building Information Modeling (BIM) in smart sustainable buildings (SSB) and is therefore best evaluated under the technology category. Following the frequency analysis, the main criteria for SSB are defined.

Table 3.1 : Frequency analysis for smart/sustainable building evaluation tools (Sarigul&Gunaydin, 2022).

No	Title	En	M&R	W	WM	T&I	T	S	I&WW	Other criteria
1	MIASBP (Meryem et al., 2018)	✓	✓	✓	✓	✓			✓	Socio-cultural, economic
2	The evaluation for smart buildings (Omar, 2018)	✓	✓			✓				Smart facades, passive design, sensors, building automation system, building management system
3	The EU Smart Readiness Indicator (SRI) scheme (Verbeke et al., 2018; Url-8)	✓	✓			✓	✓		✓	Heating, domestic hot water, cooling, ventilation, lighting, electricity, electric vehicles, dynamic façade, monitoring and control heads, energy saving, maintenance and error estimation, comfort, convenience, user information
4	MATOOOL (R. Bassi, 2005; Fantana, 2013)		✓	✓	✓				✓	Built environment, responsiveness, functionality, economic, suitability
5	HSBS (Url-1)	✓	✓	✓			✓	✓	✓	Green, productive
6	The intelligence of IBs (Huang, 2014)					✓				Function, economy
7	TIBA (Url-2)	✓				✓		✓	✓	Structured cabling system, compliance, facility management, integration system, Space utilization and flexibility, valued quality for lifetime costs, operating efficiency and effectiveness, culture (meeting customer expectations), construction and management processes, health and sanitation
8	The intelligence of IBs (So, Wong and Wong, 2011)	✓	✓	✓	✓	✓		✓		More brown space instead of green space (green architecture)
9	BiQ (Katz & Skopek, 2009)	✓	✓	✓	✓				✓	Working efficiency, culture, management practice& security, cost effectiveness, health and sanitation, space, green, safety& structure, high-tech image
10	IBI (Chow & Leung, 2005)	✓				✓		✓	✓	No difference
11	Green Mark (BCA) (Url-10)	✓	✓			✓			✓	

Table 3.1 (continued) : Frequency analysis for smart/sustainable building evaluation tools (Sarigul&Gunaydin, 2022).

No	Title	En	M&R	W	WM	T&I	T	S	I&WW	Other criteria
12	ASGB (Wang, 2019)		✓					✓	✓	Environmental livability
13	CASBEE (IBEC, 2018)	✓	✓						✓	Land
14	Green Star (GBCA) (Url-3)	✓	✓	✓		✓	✓	✓	✓	Management, Land use and ecology, emissions
15	(BREEAM) (Url-4)	✓	✓	✓	✓	✓	✓		✓	No difference

En: Energy, M&R: Material and Resources, W: Water, W&R: Waste Management, T&I: Technology/Innovation/integration project management, T: Transportation, S: Security, I&WW: Indoor environmental quality, well-being, welfare
 BCA: The Building and Construction Authority, BREEAM: Building Research Establishment Environmental Assessment Method, CASBEE: Comprehensive Assessment System for Built Environment Efficiency, TIBA: (Taiwan Intelligent Building Association) ABRI (The Architecture and Building Research Institute), IBI: Intelligent Building Index, BiQ: The Building Intelligent Quotient, HSBS: The Honeywell Smart Building Score 2.0, ASGB: Assessment Standard for Green Building, MIASBP: The Main Indicators For The Assessment of Smart Buildings Performance

Based on an analysis of 21 selected smart/intelligent and sustainable building evaluation tools, the frequency of the criteria is as follows: Land (6), Transportation (9), Green Spaces (10), Welfare (15), Socio-Cultural (3), Indoor Environmental Quality (17), Economy (4), Energy (11), Materials and Resources (2), Technology/Innovation (17), Water (12), Waste Management (13), Integrated Process Management (IPM) (3), and Security (5). Additionally, the research emphasizes information and communication technology (ICT), which relates to all the listed criteria.

As seen in Table 3.2, the areas and indicators included in the evaluation tools are closely related to the categories identified by Giffinger et al. (2007). In fact, some indicators from these tools serve as the main criteria for others. The most commonly used main criteria in the evaluation tools are economy, environment, governance, people, mobility, and quality of life, followed by technology and infrastructure.

Table 3.2 : Frequency analysis for smart or sustainable city evaluation tools (Sarigul&Gunaydin, 2022).

No	Title	Ec	En	Go	Pe	Mo	Li	Other criteria
1	Happiness Driven Smart City (Zhu et al., 2022)	✓	✓	✓	✓	✓	✓	Efficient and green physical infrastructure, Labour-friendly and innovative economy, inclusive and attractive society, sustainable and eco-friendly natural environment
2	U4SSC (ITU, 2021)	✓	✓	✓	✓	✓	✓	Society, culture
3	Global Power City Index (GPCI) (Norio Yamato, et. al, 2020)	✓	✓	✓	✓	✓	✓	Research and development, cultural interaction, livability, accessibility

Table 3.2 (continued) : Frequency analysis for smart or sustainable city evaluation tools (Sarigul&Gunaydin, 2022).

No	Title	Ec	En	Go	Pe	Mo	Li	Other criteria
4	LRSC (Akande et al., 2019)	✓	✓	✓	✓	✓	✓	Society
5	SSCC (Li et al., 2019)	✓	✓	✓	✓	✓	✓	Technological innovation, smart infrastructure, smart services.
6	CIMI (Handa Gustiawan, 2019)	✓	✓	✓	✓	✓	✓	Human capital, social cohesion, transportation, urban planning, international outreach, technology, city/country cluster
7	CSC (Smart cities council, 2018)	✓	✓	✓	✓	✓	✓	Strategic, connected, aware, responsive, innovative
8	CSCP (Shen et al., 2018)	✓	✓	✓	✓	✓	✓	Infrastructure
9	Assessing Smart City Initiatives for the Mediterranean Region (Velazquez-Romera et al., 2017)	✓	✓	✓	✓	✓	✓	No difference
10	Smart Cities Index- A Tool for Evaluating Cities (ISB & SEF, 2017)	✓	✓	✓	✓	✓	✓	No difference
11	A methodology for Northern Italy (Dall' O et al., 2017)	✓	✓	✓	✓	✓	✓	Energy
12	CITYkeys (Bosch & Jongeneel, 2017)	✓	✓	✓	✓	✓	✓	Planet, prosperity, propagation
13	CKPI (Hemment et al., 2016)	✓	✓	✓	✓	✓	✓	Transport, culture, health, energy
14	Smart Cities Readiness Guides (Smart Cities Council, 2015)	✓	✓	✓	✓	✓	✓	Built environment, telecommunications, energy, health and human services, payments and finance, public safety, waste management, water and wastewater, transportation.
15	Boyd Cohen Wheel (Cohen, 2014)	✓	✓	✓	✓	✓	✓	Government

Ec: Economy, En: Environment, Go: Governance, Pe: People, Mo: Mobility, Li: Living
U4SSC: United 4 Smart Sustainable Cities, CKPI: Community KPIs for the IoT and Smart Cities, CSCP: China Smart City Performance, LRSC: Lisbon Ranking for Smart, Sustainable Cities, CIMI: Cities in Motion Index, CSC: Code for Smart Communities, SSCC: Smart sustainable cities China

The tools used to evaluate smart sustainable buildings and cities have revealed that many of them incorporate common areas and indicators. While some assessment tools are tailored to specific aspects, others aim to provide a comprehensive assessment approach by including additional areas and indicators. In this thesis, it was decided that the Smart Sustainable Buildings and Cities Integration Evaluation Model (SSB-CIEM) should be designed holistically and reflect the latest digital technologies in construction. In this context, the draft SSB-CIEM includes the following areas and indicators:

- Smart Sustainable Resilience: Six indicators
- Smart Sustainable Environment: Eight indicators
- Smart Sustainable Management: Seven indicators

- Smart Sustainable Aesthetics: Five indicators
- Smart Sustainable Mobility: Five indicators
- Smart Sustainable Welfare and Wellbeing: Five indicators
- Smart Sustainable Building-City Integration Maturity: Six indicators

Table 3.3 details the indicators, along with their respective phases in the project life cycle, and relevant references that contribute to the discourse on smart and sustainable building-city evaluations.

Table 3.3 : List of indicators according to project life cycle derived from the smart and sustainable-building-city evaluation literature.

Indicator code	Indicator definition	Phases of project lifecycle	Related reference or utilizable
SSR1	Compatibility of building projects with city-specific natural disaster (fire, earthquake, flood, landslide, etc.) plans	P	(UN, 2017)
SSR2	Selection of safe land/site for building location (in disaster risk areas)	P	(UN, 2017)
SSR3	Materials resistant to structural damage in buildings, suitable for the region/city	P/C	(Bosch & Jongeneel, 2017)
SSR4	Installation and operation of building disaster (fire, earthquake, flood, landslide, etc.) detection and response systems	P-C	(Url-1)
SSR5	Disaster (fire, earthquake, flood, landslide, etc.) response and emergency evacuation planning for buildings	P	(Url-1)
SSR6	Seismic vulnerability/structural assessments of historical structures/settlements, improvement strategies, restoration or reconstruction works.	C	(Lima et al., 2020)
SSE1	Use of energy (electricity) produced from renewable sources (sun, wind, water, etc.) in buildings	P/P-C	(Norio Yamato et. al, 2020; Akande et al., 2019; UN, 2017; Bosch & Jongeneel, 2017; Omar, 2018; Url-5)
SSE2	Smart or sustainability certified (life cycle assessment has been made, low carbon emission), local (regional/micro-climate appropriate) materials in buildings	P/C	(Url-11; Bosch & Jongeneel, 2017; Url-6; Url-7; Url-5)
SSE3	Domestic waste management plans for buildings (such as collection, separation, reuse, recycling and disposal of waste)	P/P-C	(Shen et al., 2018; Norio Yamato et. al, 2020; X. Li et al., 2019; UN, 2017; Url-11)
SSE4	Construction and demolition waste management (recycling or reuse)	C/P-C	(X. Li et al., 2019; Url-11)
SSE5	Reduction of water consumption in interior spaces or landscape irrigation (rainwater management, etc.) through water measurement and water monitoring	P-C	(UN, 2017; Url-5)
SSE6	Management of energy required for heating, cooling, ventilation (HVAC) systems and lighting (demand management, supply, distribution, consumption, monitoring, control, etc.)	P-C	(UN, 2017; Url-8; Url-5),
SSE7	Energy efficiency (electrical grid optimization, energy analysis, geographic and environmental data consideration in building design, etc.)	P/ P-C	(Velazquez-Romera et al., 2017; UN, 2017; Taveres-Cachat et al., 2019; Omar, 2018; Url-6)
SSE8	Wastewater management	P-C	(Akande et al., 2019; UN, 2017)

Table 3.3 (continued) : List of indicators according to project life cycle derived from the smart and sustainable-building-city evaluation literature.

Indicator code	Indicator definition	Phases of project lifecycle	Related reference or utilizable
SSMa1	The building management system and city operation management system collaborate for building maintenance and fault prediction by utilizing sensor data for monitoring and control processes	P-C	(UN, 2017; Url-8; Omar, 2018)
SSMa2	Automated drawing creation, including 3D model generation and documentation	P	(Url-5)
SSMa3	Construction supply chain management, featuring real-time logistics monitoring and simulation, as well as the consolidation of supplier sites and materials, and supplier selection	C	(Li et al., 2019)
SSMa4	Consideration of surrounding environments and topography in site layout planning, including temporary facilities, conflict detection, and route planning	C	(Url-5)
SSMa5	Construction cost estimation	P	(X. Li et al., 2019)
SSMa6	Management of real-time information at both micro-scale (building level) and macro-scale (city level)	C/ P-C	(X. Li et al., 2019; UN, 2017; Omar, 2018)
SSMa7	Interoperability of data acquired through digital technologies in construction, including sensors, GPS, Light Detection and Ranging (LIDAR), and unmanned aerial vehicles (UAVs)/drones by utilizing sensor data for monitoring and control processes	C	(Li et al., 2019)
SSA1	Enhancing the quality of views from buildings by considering the urban landscape, including building layout, facade, and interior design	P	(Taveres-Cachat et al., 2019; Url-5)
SSA2	Preventing physical deterioration, such as staining of facade claddings due to humidity and condensation, by addressing local climate characteristics	P/P-C	(Velazquez-Romera et al., 2017; Lazar & Chithra, 2021)
SSA3	Preserving the natural aesthetics of the environment by maintaining the ecological integrity of the land on which the building sits, efficiently utilizing space, and minimizing the parking footprint to protect green areas	P/C	(Shen et al., 2018; G. Li et al., 2018; Norio Yamato et. al, 2020; Bosch & Jongeneel, 2017; Url-5)
SSA4	Utilizing techniques like 3D modeling and photorealistic visualization to predict how new structures will harmonize with existing surroundings, particularly in historic building restorations	P	(Lima et al., 2020)
SSA5	Ensuring the quality of newly constructed buildings aligns with previously established urban aesthetics standards or adheres to current architectural and artistic trends	P	(UN, 2017)
SSMo1	Designing building layouts prioritizing proximity to public transportation, making access to various city services (healthcare, commerce, education, socio-cultural opportunities, etc.) more convenient through multi-modal transit options (metro, bus, bicycle, etc.)	P	(Velazquez-Romera et al., 2017; UN, 2017; Url-5)
SSMo2	Promoting environmental density and diverse land uses, including healthcare, commerce, education, and socio-cultural activities	P	(Lima et al., 2020), Url-5
SSMo3	Installing electric vehicle charging stations close to the building.	P/C	(Url-8; Url-5)
SSMo4	Ensuring local accessibility by being near public transport networks	P-C	(Norio Yamato et. al, 2020)
SSMo5	Implementing secure bike-sharing services facilitated by IoT (Internet of Things) technology	P-C	(Norio Yamato et. al, 2020; UN, 2017; Hemment et al., 2016 Hemment et al., 2016)
SSWW1	Information related to building and urban services, including health, education, and cultural activities	P-C	(Velazquez-Romera et al., 2017; Hemment et al., 2016)

Table 3.3 (continued) : List of indicators according to project life cycle derived from the smart and sustainable-building-city evaluation literature.

Indicator code	Indicator definition	Phases of project lifecycle	Related or utilizable reference
SSWW2	Sharing thermal data between buildings and cities	P-C	(Norio Yamato et. al, 2020; Taveres-Cachat et al., 2019; Url-5)
SSWW3	Sharing air pollution data between buildings and cities.	P-C	(Shen et al., 2018; G. Li et al., 2018; Norio Yamato et. al, 2020; X. Li et al., 2019 Hemment et al., 2016; Url-11; Taveres-Cachat et al., 2019)
SSWW4	Sharing acoustic data (noise levels) related to traffic, construction, and other sources between buildings and cities.	C/ P-C	(G. Li et al., 2018; (Taveres-Cachat et al., 2019; LEED)
SSWW5	A security monitoring and access control system.	P-C	(Bosch & Jongeneel, 2017; Lazariu & Roscia, 2012; HSBS, 2015; TIBA, 2014)

Additionally, Table 3.4 provides references pertinent to the same indicators in the context of integrated BIM-GIS applications within the construction sector. This structured approach facilitates a comprehensive understanding of how these indicators interplay within both theoretical and practical realms of smart and sustainable infrastructure development.

Table 3.4 : List of indicators according to project life cycle derived from the integrated BIM/GIS literature.

Indicator code	Indicator definition	Phases of project life cycle	Related or adaptable reference
SSR1	Compatibility of building projects with city-specific natural disaster (fire, earthquake, flood, landslide, etc.) plans	P	(Lyu et al., 2016)
SSR2	Selection of safe land/site for building location (in disaster risk areas)	P	(Isikdag et al., 2008; Kumar & Bansal, 2016)
SSR3	Materials resistant to structural damage in buildings, suitable for the region/city	P/C	(Banfi et al., 2022)
SSR4	Installation and operation of building disaster (fire, earthquake, flood, landslide, etc.) detection and response systems	P-C	(Isikdag et al., 2007)
SSR5	Disaster (fire, earthquake, flood, landslide, etc.) response and emergency evacuation planning for buildings	P	(Isikdag et al., 2007; Jiang et al., 2022; L. Liu et al., 2021; Rašković et al., 2020; Teo & Cho, 2016)
SSR6	Seismic vulnerability/structural assessments of historical structures/settlements, improvement strategies, restoration or reconstruction works	C	(Arayici, 2008; Cardinali et al., 2022; Caroti et al., 2021; Gigliarelli & Pontrandolfi, 2020; Qian & Leng, 2021; Tsilimantou et al., 2020; Yaagoubi et al., 2019)
SSE1	Use of energy (electricity) produced from renewable sources (sun, wind, water, etc.) in buildings	P/P-C	(Revelo Cáceres et al., 2023)

Table 3.4 (continued) : List of indicators according to project life cycle derived from the integrated BIM/GIS literature.

Indicator code	Indicator definition	Phases of project life cycle	Related or adaptable reference
SSE2	Smart or sustainability certified (life cycle assessment has been made, low carbon emission), local (regional/micro-climate appropriate) materials in buildings	P/C	(Bansal, 2021)
SSE3	Domestic waste management plans for buildings (such as collection, separation, reuse, recycling and disposal of waste)	P/P-C	(Hannan et al., 2015)
SSE4	Construction and demolition waste management (recycling or reuse)	C/P-C	(Akinade et al., 2016; Mair et al., 2023; Rašković et al., 2020; Rigillo et al., 2023; Sepasgozar et al., 2021; S. Su et al., 2021)
SSE5	Reduction of water consumption in interior spaces or landscape irrigation (rainwater management, etc.) through water measurement and water monitoring	P-C	(Batista et al., 2024)
SSE6	Management of energy required for heating, cooling, ventilation (HVAC) systems and lighting (demand management, supply, distribution, consumption, monitoring, control, etc.)	P-C	(Göçer et al., 2015; Piras et al., 2024; H. Wang et al., 2019)
SSE7	Energy efficiency (electrical grid optimization, energy analysis, geographic and environmental data consideration in building design, etc.)	P/ P-C	(Bansal, 2021; Farooq et al., 2017; Göçer et al., 2015; Pereira et al., 2021)
SSE8	Wastewater management	P-C	(Bansal, 2016)
SSMa1	The building management system and city operation management system collaborate for building maintenance and fault prediction by utilizing sensor data for monitoring and control processes	P-C	(Piras et al., 2024; Wong et al., 2018)
SSMa2	Automated drawing creation, including 3D model generation and documentation	P	(Abd et al., 2020; Bartoněk, 2023)
SSMa3	Construction supply chain management, featuring real-time logistics monitoring and simulation, as well as the consolidation of supplier sites and materials, and supplier selection	C	(Deng et al., 2019; Irizarry et al., 2013; D. Lee & Lee, 2021)
SSMa4	Consideration of surrounding environments and topography in site layout planning, including temporary facilities, conflict detection, and route planning	C	(Karimi et al., 2021)
SSMa5	Construction cost estimation	P	(Park et al., 2014; Wei et al., 2021)
SSMa6	Management of real-time information at both micro-scale (building level) and macro-scale (city level)	C/ P-C	(D. M. Azevedo et al., 2021; Farooq et al., 2017; Mignard & Nicolle, 2014; Yang et al., 2022)
SSMa7	Interoperability of data acquired through digital technologies in construction, including sensors, GPS, Light Detection and Ranging (LIDAR), and unmanned aerial vehicles (UAVs)/drones by utilizing sensor data for monitoring and control processes	C	(Barazzetti et al., 2020; Celeste et al., 2022; Chen et al., 2022; Piras et al., 2024)
SSA1	Enhancing the quality of views from buildings by considering the urban landscape, including building layout, facade, and interior design.	P	(Mignard & Nicolle, 2014)
SSA2	Preventing physical deterioration, such as staining of facade claddings due to humidity and condensation, by addressing local climate characteristics	P/P-C	(Sestras et al., 2020; Song et al., 2017)
SSA3	Preserving the natural aesthetics of the environment by maintaining the ecological integrity of the land on which the building sits, efficiently utilizing space, and minimizing the parking footprint to protect green areas	P/C	(Fernández-Alvarado & Fernández-Rodríguez, 2022)

Table 3.4 (continued) : List of indicators according to project life cycle derived from the integrated BIM/GIS literature.

Indicator code	Indicator definition	Phases of project life cycle	Related reference or adaptable
SSA4	Utilizing techniques like 3D modeling and photorealistic visualization to predict how new structures will harmonize with existing surroundings, particularly in historic building restorations	P	(Caroti et al., 2021; Costantino et al., 2022; Tsilimantou et al., 2020; Yaagoubi et al., 2019)
SSA5	Ensuring the quality of newly constructed buildings aligns with previously established urban aesthetics standards or adheres to current architectural and artistic trends	P	(Noardo et al., 2020)
SSMo1	Designing building layouts prioritizing proximity to public transportation, making access to various city services (healthcare, commerce, education, socio-cultural opportunities, etc.) more convenient through multi-modal transit options (metro, bus, bicycle, etc.)	P	(Abd et al., 2020)
SSMo2	Promoting environmental density and diverse land uses, including healthcare, commerce, education, and socio-cultural activities	P	(Mignard & Nicolle, 2014)
SSMo3	Installing electric vehicle charging stations close to the building	P/C	(Schlosser et al., 2022)
SSMo4	Ensuring local accessibility by being near public transport networks.	P-C	(Abd et al., 2020; Schlosser et al., 2022)
SSMo5	Implementing secure bike-sharing services facilitated by IoT (Internet of Things) technology	P-C	(Schlosser et al., 2022)
SSWW1	Information related to building and urban services, including health, education, and cultural activities	P-C	(Mignard & Nicolle, 2014)
SSWW2	Sharing thermal data between buildings and cities	P-C	(Daneshfar et al., 2022)
SSWW3	Sharing air pollution data between buildings and cities	P-C	(Daneshfar et al., 2022; Fernández-Alvarado & Fernández-Rodríguez, 2022; Sepasgozar et al., 2019)
SSWW4	Sharing acoustic data (noise levels) related to traffic, construction, and other sources between buildings and cities	C/ P-C	(Daneshfar et al., 2022; Deng et al., 2016)
SSWW5	A security monitoring and access control system	P-C	(Arslan et al., 2018)
SSR: Smart Sustainable Resilience, SSE: Smart Sustainable Environment, SSMA: Smart Sustainable Management, SSA: Smart Sustainable Aesthetics, SSMo: Smart Sustainable Mobility, SSWW: Smart Sustainable Welfare-Wellbeing, P: Pre-construction, C: Construction, P-C: Post-construction			

Smart Sustainable Building-City integration is evaluated based on the usability of both physical and digital infrastructure in urban areas and specific projects. A comprehensive literature review has led to the development of a five-level evaluation scale for evaluating indicators of this integration:

1. No data used.
2. BIM data or GIS data used.
3. BIM data and GIS data used separately.
4. BIM data and GIS data used in a partially integrated.
5. BIM data and GIS data fully integrated.

This evaluation aims to determine the maturity of integration across defined areas and criteria.

3.1.1.2 Expert panel (interviews)

Expert selection strategy and expert characteristics

The thesis study involved a face-to-face expert panel held on May 24, 2024, at the Ministry of Environment, Urbanization, and Climate Change. The panel included 13 experts, consisting of twelve professionals from the Smart Cities Department of the General Directorate of Geographic Information Systems comprising architects, engineers, urban planners, managers, and a general manager and one expert who is the Head of Department in the Energy Efficiency and Installation Department of the General Directorate of Professional Services. Table 3.5 provides general information, including professional knowledge, academic qualifications, experience, and positions of 13 experts, coded as E1-E13.

Table 3.5 : General information from experts.

No	Profession of expert	Academic qualification	Experience	Position
E1	Engineer (Geomatic)	Master or above	>8years	Manager (Department)
E2	Architect	Master or above	2-4 years	Architect
E3	Other (Economy-econometrics)	Master or above	>8years	General Manager
E4	Engineer (Geomatic)	Bachelor	>8years	Manager (Department)
E5	Architect	Master or above	4-8 years	Architect
E6	Engineer (Civil)	Master or above	2-4 years	Engineer
E7	Urban Planner	Master or above	2-4 years	Engineer
E8	Engineer (Geomatic)	Bachelor	>8years	Engineer
E9	Urban Planner	Bachelor	2-4 years	Other
E10	Urban Planner	Master or above	1-2 years	Other
E11	Urban Planner	Bachelor	>8years	Head of Department
E12	Engineer (Geomatic)	Master or above	>8years	General Manager
E13	Engineer (Electrical and electronics)	Master or above	>8years	Head of Department

In contrast, Table 3.6 presents statistical analyses related to this general information (The numbers in the columns indicate the frequency of the number of experts who made the assessment). These experts are actively involved in the collection of data regarding smart city projects across 81 provinces and work on creating a Smart City Project Inventory. Additionally, they focus on smart city maturity assessment models and contribute to the development of the National Smart Cities Strategy and Action Plan. The head of the Energy and Installation Department has a strong background in national and international green certifications and has represented the ministry as a keynote speaker at various national conferences related to smart and sustainable buildings and cities

Table 3.6 : Statistical analysis of expert's profile.

Experience				Position			
		Frequency	Percent			Frequency	Percent
Valid	1-2 years		1	7.7	Officer	7	53.8
	2-4 years		4	30.8	Manager	2	15.4
	4-8 years		1	7.7	General Manager	2	15.4
	8 years and above	7	53.8	Head of Department	2	15.4	
	Total		13	100.0	Total	13	100.0
	Profession of expert			Academic qualification			
		Frequency	Percent			Frequency	Percent
Valid	Architect		2	15.4	Bachelor	4	30.8
	Urban Planner		4	30.8	Master or above	9	69.2
	Engineer		5	38.5	Total	13	100.0
	Other		2	15.4			
	Total		13	100.0			

Prior to the interviews, the experts received comprehensive information about the Smart Sustainable Building-City Integration Evaluation Model (SSB-CIEM), the central topic of the thesis. The experts were tasked with evaluating the areas of integration concerning smart sustainable buildings and cities, along with the SSB-CIEM integration scale, which was derived from a thorough review of existing literature followed by frequency analysis. Their evaluations were recorded through an online survey via Google Forms.

Expert panel results for SSB-CIEM areas, indicators, and integration scale

In the expert panel implemented within the scope of the thesis study, experts were expected to evaluate the SSB-CIEM areas (SSR, SSE, SSMA, SSA, SSMo, and SSSW) and indicators in Table 3.3 in accordance with the 5-level Likert scale (strongly disagree (1), disagree (2), neutral (3), agree (4), strongly agree (5)). Key statistics such as the mean, standard deviation, and significance (Sig.) values are included in Table 3.7. Notably, all areas received mean agreement scores exceeding 4.00. The standard deviations range from 0.439 to 0.961, and significance values are all below 0.003, demonstrating a high level of consensus among the experts. The mean values reflect the overall ratings assigned to each indicator, while the standard deviation shows the level of consensus among the experts. Given that the number of data points is less than 50, the Shapiro-Wilk test is utilized. Since $p < 0.05$, H_0 (null hypothesis) is rejected and it is concluded that there is a significant difference between the data. According to the normality test results, the data is not normally distributed.

Table 3.7 : Descriptive statistic of SSB-CIEM areas evaluation results.

Area	Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)	Mean	Std. Deviation	Sig.
SSR	0	0	0	3	10	4.77	.439	<.001
SSE	0	0	0	4	9	4.69	.480	<.001
SSMa	0	1	0	5	7	4.38	.870	<.001
SSA	0	0	5	3	5	4.00	.913	.003
SSMo	0	1	1	3	8	4.38	.961	<.001
SSWW	0	0	0	4	9	4.69	.480	<.001

Table 3.8 presents descriptive statistics for the SSBCIEM indicators based on expert evaluations. Each indicator, ranging from SSR1 to SSW5, is rated on a scale from 1 (Strongly Disagree) to 5 (Strongly Agree). The mean scores for these indicators vary from 4.15 to 4.85, indicating a general consensus among experts. The standard deviations range from 0.376 to 1.301, with the indicator SSMo3 exhibiting the highest variability at 1.301. All significance values are equal to or less than 0.011, demonstrating a statistically significant agreement among the experts.

Table 3.8 : Descriptive statistic of SSB-CIEM indicators evaluation results obtained from experts.

Indicator	Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)	Mean	Std. Deviation	Sig.
SSR1	0	0	0	2	11	4.85	.376	<.001
SSR2	0	0	0	2	11	4.85	.376	<.001
SSR3	0	0	0	2	11	4.85	.376	<.001
SSR4	0	0	0	4	9	4.69	.480	<.001
SSR5	0	0	0	2	11	4.85	.376	<.001
SSR6	0	0	0	7	6	4.46	.519	<.001
SSRE1	0	0	1	4	8	4.54	.660	<.001
SSE2	0	0	1	2	10	4.69	.630	<.001
SSE3	0	0	1	5	7	4.46	.660	.002
SSE4	0	0	1	5	7	4.46	.660	.002
SSE5	0	0	1	1	11	4.77	.599	<.001
SSE6	0	0	0	3	10	4.77	.439	<.001
SSE7	0	0	0	2	11	4.85	.376	<.001
SSE8	0	0	1	1	11	4.77	.599	<.001
SSMa1	0	1	0	3	9	4.54	.877	<.001
SSMa2	0	1	0	3	9	4.54	.877	<.001
SSMa3	0	0	0	4	9	4.69	.480	<.001
SSMa4	0	1	0	3	9	4.54	.877	<.001
SSMa5	0	1	0	3	9	4.54	.877	<.001
SSMa6	0	1	0	3	9	4.54	.877	<.001
SSMa7	0	0	0	4	9	4.69	.480	<.001
SSA1	0	0	2	3	8	4.46	.776	<.001
SSA2	0	0	2	3	8	4.46	.776	<.001
SSA3	0	0	0	5	8	4.62	.506	<.001
SSA4	0	0	2	3	8	4.46	.776	<.001
SSA5	0	0	2	3	8	4.46	.776	<.001
SSMo1	0	1	0	2	10	4.62	.870	<.001
SSMo2	0	1	2	3	7	4.23	1.013	.004
SSMo3	1	1	3	3	5	3.77	1.301	.041

Table 3.8 (continued): Descriptive statistic of SSB-CIEM indicators evaluation results obtained from experts

Indicator	Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)	Mean	Std. Deviation	Sig.
SSMo4	0	1	0	2	10	4.62	.870	<.001
SSMo5	0	1	0	2	10	4.62	.870	<.001
SSWW1	0	0	1	4	8	4.54	.660	<.001
SSWW2	0	0	1	3	9	4.62	.650	<.001
SSWW3	0	0	1	3	9	4.62	.650	<.001
SSWW4	0	1	1	3	8	4.38	.961	<.001
SSWW5	0	1	2	4	6	4.15	.987	.011

Table 3.9 presents a comprehensive statistical analysis of the integration scale evaluation results provided by experts, focusing on the utilization of Building Information Modeling (BIM) and Geographic Information Systems (GIS) data across five distinct levels, ranging from 1 to 5. The ratings assigned by the experts span from Strongly Disagree (1) to Strongly Agree (5).

Observations reveal a clear upward trend in mean scores correlated with the increasing integration levels. Specifically, Level 1, indicative of no utilization, recorded a mean score of 4.23, while Level 4, categorized as partially integrated, achieved a higher mean score of 4.77. In contrast, Level 5, designated as fully integrated, saw a mean score of 4.69.

Variability in responses was noted, with standard deviations ranging from 0.439 to 1.481. Notably, Level 1 demonstrated the highest variability at 1.481, suggesting a broader range of opinions among experts regarding the non-utilization of BIM and GIS data.

All significance values associated with the evaluations were found to be less than 0.001, confirming a strong statistical significance in the level of agreement among experts on the benefits of integration in these technologies.

Since the evaluation results of the experts are mostly agree (4) and strongly agree (5), all of the SSB-CIEM areas, indicators and integration scale levels obtained from the literature and then subjected to frequency analysis were approved in the expert panel evaluation.

Table 3.9 : Staistical analysis of integration scale evaluation results obtained from experts.

Integration Scale Level and Description	Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)	Mean	Std. Deviation	Sig.
Level 1: Data is not utilized.	2	0	0	2	9	4.23	1.481	<.001
Level 2: Either BIM data or GIS data is utilized	1	1	0	1	10	4.38	1.325	<.001
Level 3: BIM data and GIS data are used separately	0	0	1	2	10	4.69	.630	<.001
Level 4: BIM data and GIS data are used in a partially integrated manner	0	0	0	3	10	4.77	.439	<.001
Level 5: BIM data and GIS data are used in a fully integrated manner	0	1	0	1	11	4.69	.855	<.001

3.1.2 Design of data collecting tool (questionnaire survey)

The preparation phase for the survey questions devised within the framework of this thesis encompasses four distinct chapter. Firstly, a comprehensive review of the literature was conducted to identify the primary areas and indicators pertinent to smart sustainable building-city integration, alongside a frequency analysis. The second chapter focused on expert interviews with the technical staff of the Ministry of Environment, Urbanization, and Climate Change, Department of Smart City were carried out to evaluate the scope and scale of the proposed model. The third chapter involved the selection of an appropriate sample for the survey. Finally, the fourth chapter entailed reaching out to participants via online platforms for data collection.

For the Smart Sustainable Building-City Integration Evaluation Model (SSB-CIEM) developed in this research, an online survey was executed utilizing Google Forms as the primary data collection tool (Survey questionnaire link: <https://docs.google.com/forms/d/1yfM1SR6fZaDSHnliEopTXesGQenbZkeZ4Ytlh45wssI/edit#response=ACYDBNiCnAfCQe4bdjg8TTToIeD3ihIkrisS3emp6N8sqNOfsUPBpcXf19BmGL5Ak8Jlm6iM>). The survey is structured into three chapters: the first part comprises demographic inquiries and BIM/GIS familiarity; the second chapter

focuses on maturity in SSB-CIEM areas. This chapter investigates the maturity of Turkish construction sector professionals across six main categories, as determined by the literature and refined by an expert panel. The third chapter is dedicated to evaluating indicators of smart sustainable building-city integration.

The latter chapter is crucial as it furnishes essential data necessary for testing the proposed model. It measures the extent to which buildings are leveraging their smart and sustainable features in alignment with the capacities of urban environments, facilitated through digital construction technologies, such as BIM and GIS. Subsequently, the survey addresses the status of integrated BIM-GIS usage by these professionals in their projects, delineated through thirty-six indicators grouped under the six areas.

The evaluation of integration scale, based on the integrated BIM-GIS approach, is stratified into five levels, reflective of the BIM and GIS usage by individuals or institutions. Notably, Table 3.10 details the finalized evaluation areas Smart Sustainable Resilience (SSR), Smart Sustainable Environment (SSE), Smart Sustainable Management (SSMa), Smart Sustainable Aesthetics (SSA), Smart Sustainable Mobility (SSMo), Smart Sustainable Welfare and Wellbeing (SSWW), indicators, and integration scale for smart sustainable building-city integration. Smart sustainable building-city integration areas, indicators and integration scale.

Table 3.10 : Smart sustainable building-city integration areas, indicators and integration scale.

Areas and indicators	Scale
Evaluate the indicators of the Smart Sustainable Resilience by taking into account the integrated use of BIM-GIS technologies (in your own projects/projects in your institution).	
1. Compatibility of building projects with city-specific natural disaster (fire, earthquake, flood, landslide, etc.) plans	1. Data is not utilized.
2. Selection of safe land/site for building location (in disaster risk areas)	2. Either BIM data or GIS data is utilized.
3. Materials resistant to structural damage in buildings, suitable for the region/city	3. BIM data and GIS data are used separately.
4. Installation and operation of building disaster (fire, earthquake, flood, landslide, etc.) detection and response systems	4. BIM data and GIS data are used in a partially integrated manner.
5. Disaster (fire, earthquake, flood, landslide, etc.) response and emergency evacuation planning for buildings	5. BIM data and GIS data are used in a fully integrated manner.
6. Seismic vulnerability/structural assessments of historical structures/settlements, improvement strategies, restoration or reconstruction works	

Table 3.10 (continued) : Smart sustainable building-city integration areas, indicators and integration scale.

Areas and Indicators	Scale
Evaluate the indicators of the Smart Sustainable Environment by taking into account the integrated use of BIM-GIS technologies (in your own projects/projects in your institution).	
1. Use of energy (electricity) produced from renewable sources (sun, wind, water, etc.) in buildings	1. Data is not utilized.
2. Smart or sustainability certified (life cycle assessment has been made, low carbon emission), local (regional/micro-climate appropriate) materials in buildings	2. Either BIM data or GIS data is utilized.
3. Domestic waste management plans for buildings (such as collection, separation, reuse, recycling and disposal of waste)	3. BIM data and GIS data are used separately.
4. Construction and demolition waste management (recycling or reuse)	4. BIM data and GIS data are used in a partially integrated manner.
5. Reduction of water consumption in interior spaces or landscape irrigation (rainwater management, etc.) through water measurement and water monitoring	5. BIM data and GIS data are used in a fully integrated manner.
6. Management of energy required for heating, cooling, ventilation (HVAC) systems and lighting (demand management, supply, distribution, consumption, monitoring, control, etc.)	
7. Energy efficiency (electrical grid optimization, energy analysis, geographic and environmental data consideration in building design, etc.)	
8. Wastewater management	
Evaluate the indicators of the Smart Sustainable Management by taking into account the integrated use of BIM-GIS technologies (in your own projects/projects in your institution).	
1. The building management system and city operation management system collaborate for building maintenance and fault prediction by utilizing sensor data for monitoring and control processes.	1. Data is not utilized.
2. Automated drawing creation, including 3D model generation and documentation.	2. Either BIM data or GIS data is utilized.
3. Construction supply chain management, featuring real-time logistics monitoring and simulation, as well as the consolidation of supplier sites and materials, and supplier selection.	3. BIM data and GIS data are used separately.
4. Consideration of surrounding environments and topography in site layout planning, including temporary facilities, conflict detection, and route planning.	4. BIM data and GIS data are used in a partially integrated manner.
5. Construction cost estimation.	5. BIM data and GIS data are used in a fully integrated manner.
6. Management of real-time information at both micro-scale (building level) and macro-scale (city level).	
7. Interoperability of data acquired through digital technologies in construction, including sensors, GPS, Light Detection and Ranging (LIDAR), and unmanned aerial vehicles (UAVs)/drones by utilizing sensor data for monitoring and control processes.	
Evaluate the indicators of the Smart Sustainable Aesthetics by taking into account the integrated use of BIM-GIS technologies (in your own projects/projects in your institution).	
1. Enhancing the quality of views from buildings by considering the urban landscape, including building layout, facade, and interior design.	1. Data is not utilized.
2. Preventing physical deterioration, such as staining of facade claddings due to humidity and condensation, by addressing local climate characteristics.	2. Either BIM data or GIS data is utilized.
3. Preserving the natural aesthetics of the environment by maintaining the ecological integrity of the land on which the building sits, efficiently utilizing space, and minimizing the parking footprint to protect green areas.	3. BIM data and GIS data are used separately.
4. Utilizing techniques like 3D modeling and photorealistic visualization to predict how new structures will harmonize with existing surroundings, particularly in historic building restorations.	4. BIM data and GIS data are used in a partially integrated manner.
5. Ensuring the quality of newly constructed buildings aligns with previously established urban aesthetics standards or adheres to current architectural and artistic trends.	5. BIM data and GIS data are used in a fully integrated manner.
Evaluate the indicators of the Smart Sustainable Mobility by taking into account the integrated use of BIM-GIS technologies (in your own projects/projects in your institution).	
1. Designing building layouts prioritizing proximity to public transportation, making access to various city services (healthcare, commerce, education, socio-cultural opportunities, etc.) more convenient through multi-modal transit options (metro, bus, bicycle, etc.).	1. Data is not utilized.
	2. Either BIM data or GIS data is utilized.
	3. BIM data and GIS data are used separately.

Table 3.10 (continued) : Smart sustainable building-city integration areas, indicators and integration scale.

Areas and Indicators	Scale
2. Promoting environmental density and diverse land uses, including healthcare, commerce, education, and socio-cultural activities.	4. BIM data and GIS data are used in a partially integrated manner.
3. Installing electric vehicle charging stations close to the building.	5. BIM data and GIS data are used in a fully integrated manner.
4. Ensuring local accessibility by being near public transport networks.	
5. Implementing secure bike-sharing services facilitated by IoT (Internet of Things) technology.	
Evaluate the indicators of the Smart Sustainable Welfare&Wellbeing by taking into account the integrated use of BIM-GIS technologies (in your own projects/projects in your institution).	1. Data is not utilized.
	2. Either BIM data or GIS data is utilized.
1. Information related to building and urban services, including health, education, and cultural activities.	3. BIM data and GIS data are used separately.
2. Sharing thermal data between buildings and cities.	4. BIM data and GIS data are used in a partially integrated manner.
3. Sharing air pollution data between buildings and cities.	5. BIM data and GIS data are used in a fully integrated manner.
4. Sharing acoustic data (noise levels) related to traffic, construction, and other sources between buildings and cities.	
5. A security monitoring and access control system.	

Table 3.11 shows, questions for smart sustainable integration maturity. In compliance with ethical standards, approval for all prepared survey questions was secured from the Istanbul Technical University Social and Human Sciences Scientific Research and Publication Ethics Committee, under project no: 565, dated November 4, 2024 (Appendix A).

Table 3.11 : Smart sustainable building-city integration maturity.

Please evaluate your (your institution/project) readiness for integrating BIM-GIS and other digital construction technologies for Smart Sustainable Building-City Integration maturity	1. Strongly disagree
	2. Disagree
	3. I am not sure/Neutral
Smart Sustainable Building-City Integration Maturity in the six main areas (SSR, SSE, SSMa, SSMo, SSA, SSWW).	4. Agree
	5. Strongly agree

3.2 Turkish Construction SSB-CIEM Results Statistical Analysis

Statistics is a discipline focused on the collection, organization, summarization, description, and analysis of quantitative data. The goal is to enable interpretation and informed decision-making across nearly all scientific fields. For this research, multivariate statistical analysis methods were employed to examine the collected data. In the context of multivariate statistical analysis techniques, two primary categories of methodologies are recognized: first-generation and second-generation methods.

This doctoral thesis includes the evaluation of data on the level of BIM and GIS usage for SSB-CI in projects undertaken by construction professionals. The collected data were analyzed with nonparametric statistical tests using the Statistical Package for

Social Sciences (SPSS) Version 29.0.2.0.(20). To determine the smart sustainable building and city integration levels of stakeholders in the Turkish construction sector, the responses of 215 participants were compared with the determined norm value. The analysis also examined significant differences between the public and private sectors. The evaluation focused on various indicators of smart sustainable building-city integration across different sub-sectors, including public, private, and academic institutions. The tests conducted in this context are as follows:

- Construct reliability and validity of scales
- Descriptive statistics (Mean, median, standard deviation, skewness, Normal distribution of the scales (Kolmogorov-Smirnov Test))
- Non-parametric One Sample Wilcoxon Signed Rank Test (comporison with norm value for one group)
- Kruskal Wallis One-Way ANOVA
- Mann-Whitney U Test

3.3. PLS-SEM for Concept SSB-CIEM and Initial Hypotheses Formulation

The conceptual model developed the characteristics of the prepared model indicate limitations in sample size, rendering covariance-based SEM analysis impractical. Consequently, Partial Least Squares Structural Equation Modeling (PLS-SEM) was selected as the preferred explanatory technique, as noted by (J. F. Hair et al., 2022). PLS-SEM has gained recognition as a prominent analytical method (J. F. Hair et al., 2022; Sakarya et al., 2023). In scenarios where the assumptions underlying covariance-based structural equation modeling are not satisfied, or where the research objective is to estimate complex models rather than merely validate structural relationships, PLS-SEM emerges as the method of choice (J. F. Hair et al., 2011, 2012; Sarstedt et al., 2017). Specifically, researchers may gravitate towards PLS-SEM when the assumption of multivariate normality fails to hold (J. F. Hair et al., 2011; Sakarya et al., 2023; Sarstedt et al., 2017; Wold, 1982).

The comparative analysis conducted by Batra (2024) highlights the application of PLS-SEM across various disciplines, emphasizing its usage in construction management relative to other fields. The study evaluates factors such as article

prevalence, data and model characteristics, and assessments of measurement and structural models alongside advanced modeling techniques. The findings reveal that the mean sample size in construction management is notably lower (190) compared to several disciplines: marketing (279), hospitality (332), tourism (487), supply chain management (274.42), operations management (246), and management information systems (238.12), while surpassing that of strategic management (154.90). PLS-SEM, with its predictive method feature, has been used in many construction-related studies in the recent past and today. Some of these are: the model of the transition of the building construction industry to a circular economy (Oluleye et al., 2024), real estate owner's thoughts on lean integrated project delivery (Gil Sebastián & Soler Severino, 2025), interplay among project management, BIM, strategic and operational skills (Correa et al., 2025), analysis of the barriers to the adoption of green buildings labels (Santana et al., 2023), building information modeling effectiveness (Caglayan & Ozorhon, 2023), construction management (Batra, 2024), effects of barriers and drivers on blockchain adoption in construction (Oyewobi et al., 2023) and, investigating the use of PLS-SEM in construction management research (Batra, 2024).

Covariance Based Structural Equation Modeling (CB-SEM) is particularly effective in modeling latent variables and rectifying measurement errors prevalent in survey-based research, showcasing its strong capability in parameter estimation of well-established theoretical frameworks (Dijkstra, 2015). The conceptualization of CB-SEM can be traced back to Karl Jöreskog, its pioneer (Mateos-Aparicio, 2011). In contrast, PLS has been introduced as a "causal-predictive" approach to SEM (Jöreskog & Wold, 1982) which focuses on explaining the variance in the model's dependant variables (J. F. Hair et al., 2022). CB-SEM imposes stringent requirements, including the need for multivariate normality and sufficiently large sample sizes (J. F. Hair et al., 2011). Conversely, the PLS approach adopts a "soft" methodology for estimating the coefficients in structural equation systems (J. F. Hair et al., 2012; Mateos-Aparicio, 2011; Wold, 1982; Vinzi et al., 2010). PLS-SEM is recognized for its explanatory approach, distinguishing it from the confirmatory approach used in CBS-SEM. Unlike CBS-SEM, which targets the replication of the sample covariance matrix (Vinzi et al., 2010). This methodology is flexible, as it does not impose restrictions on the data's distribution and can effectively handle smaller sample sizes. MacCallum et al. (1996) stated that a minimum sample size of 200 to 400 cases is necessary under exploratory

conditions (Vinzi et al., 2010). When implemented with sufficiently large sample sizes and numerous indicators for each latent variable, the accuracy of the PLS-SEM model improves under conditions of consistency, as noted by Jöreskog and Wold (1982). Additionally, the high efficiency of parameter estimation in PLS-SEM demonstrates that this method possesses strong statistical power compared to CB-SEM, which can positively influence the significance level of the relationships within the model (J. F. Hair et al., 2022).

The origins of PLS methods trace back to the work of Swedish scholar Herman Wold, who served as a mentor to Karl Jöreskog. Wold (1974, 1982) proposed PLS as an alternative to Jöreskog's covariance-based structural equation modeling approach (Mateos-Aparicio, 2011). PLS encompasses a suite of regression-based techniques designed to Analyze high-dimensional data where the underlying structure is minimal (Dijkstra Theo K., 2010). PLS-SEM represents a conceptual fusion of theoretical frameworks with empirical data analysis (Falk, 1992).

A structural equation model or PLS path model incorporates two key components: the structural model and the measurement model. In the PLS-SEM model, constructs are measured indirectly, that is, through indicator sets called observed/manifestvariables (Henseler, 2009). In a measurement model, each indicator represents a separate aspect of a more comprehensive concept/latent variable and thus the mysterious structure of the model is solved (Mateos-Aparicio, 2011). The measurement model delineates the relationship between latent variables (constructs) and their corresponding observable indicators (Sakarya et al., 2023). This model can be formulated in either a formative or reflective structure. A reflective model asserts a causal influence from the latent variable to the observations, while a formative model posits that the observable indicators contribute to shaping the latent construct (Diamantopoulos & Siguaw, 2006). In reflective models, alterations in latent variables drive changes in observable variables; conversely, in formative models, it is the observed variables that influence the latent variable's value. Thus, the directionality of causal arrows in path model diagrams elucidates the nature of the relationship: reflective if directed from the latent variable to indicators, and formative if directed from indicators to the latent variable.

Figure 3.2 represents typical PLS-SEM structure. Essentially, the structural model serves to interconnect constructs (depicted as circles or ovals) (also referred to as the internal model within PLS-SEM), illustrating the paths and relationships among

constructs (J. F. Hair et al., 2011). The measurement model (also known as the exogenous model within PLS-SEM) visually represents the correlation between constructs and their indicator variables (rectangles). Within the diagram, two distinct measurement models may be present: one for exogenous latent variables (constructs that elucidate other constructs) and one for endogenous latent variables (constructs being explained in the model) (J. F. Hair et al., 2022).

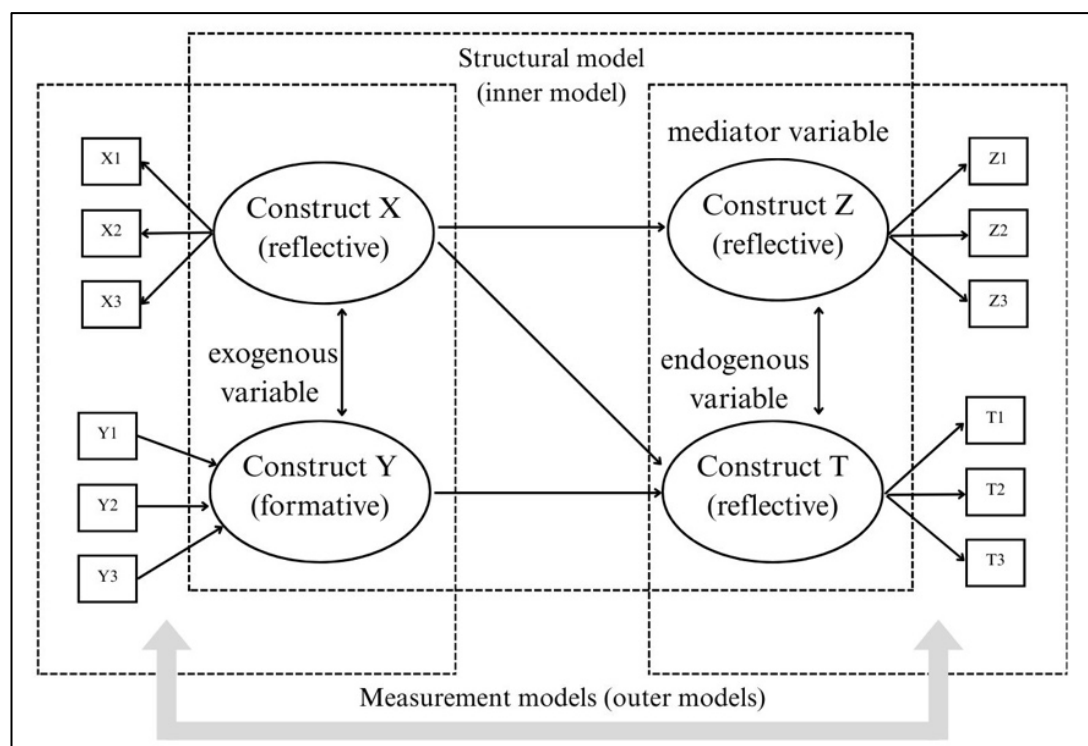


Figure 3.2 : Measurement models and structural model in PLS-SEM path model diagram, adapted from J. Hair & Alamer (2022), Henseler et al. (2009), Russo & Stol (2021), Sakarya et al. (2023).

PLS-SEM is designed to explore relationships and identify significant effects, making it particularly advantageous in exploratory research contexts where theoretical foundations may be limited (Chin, 2010). The method exhibits high statistical power, which is beneficial for uncovering strong relationships. Additionally, PLS-SEM remains a viable option for coefficient estimation even in the absence of multicollinearity in the measurement models or structural equations. It offers more precise estimates compared to alternative methods (Mateos-Aparicio, 2011). Thus, PLS-SEM serves as a robust tool for researchers aiming to extract meaningful insights in the early stages of theory development. Figure 3.3 summarizes the key features of PLS-SEM research.

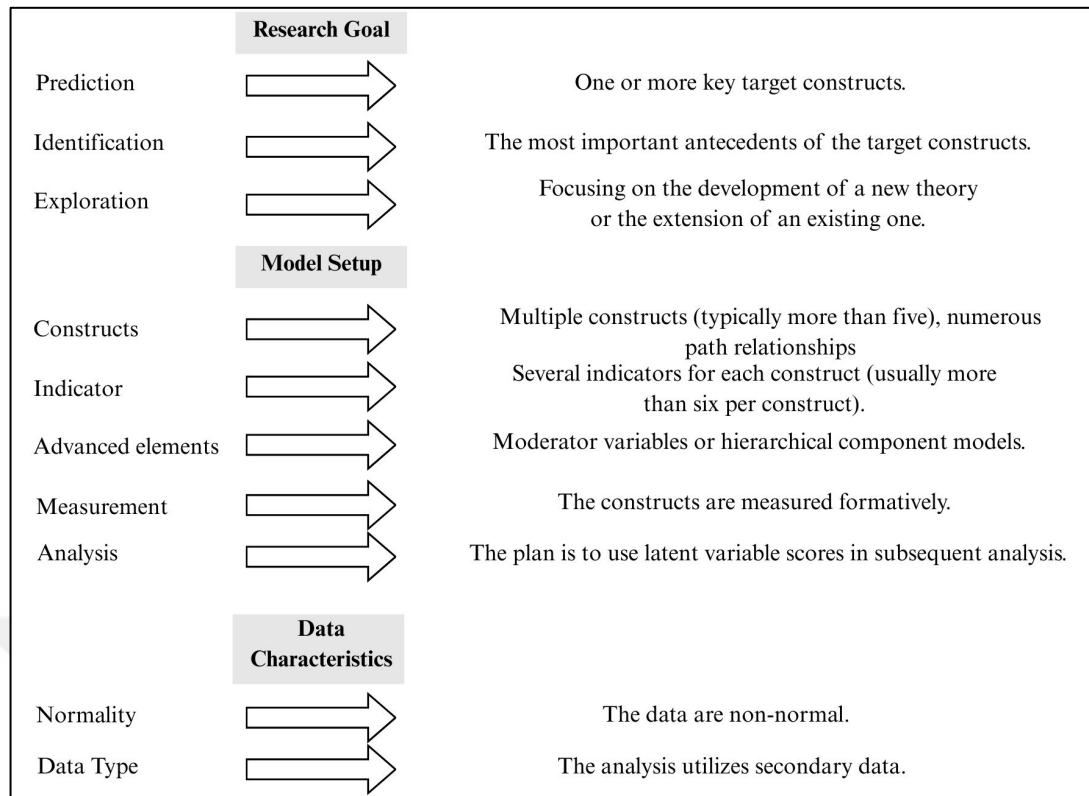


Figure 3.3 : PLS-SEM features, adapted from Sarstedt et al. (2014).

The SSB-CIEM developed in this thesis meets the specific criteria for conducting PLS-SEM studies. Once these criteria are validated, the methodological phases illustrated in Figure 3.4 are systematically implemented.

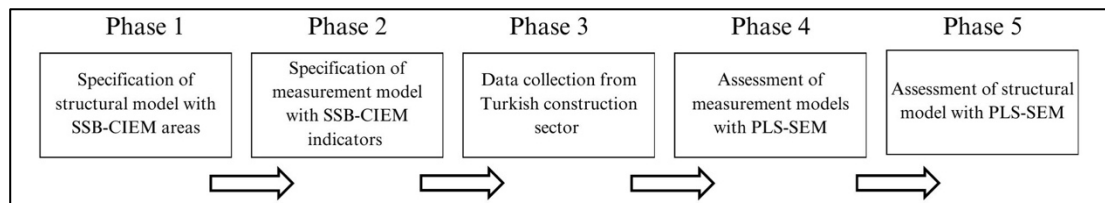


Figure 3.4 : Flowchart of the most relevant phases of a PLS-SEM method, adapted from Russo & Stol (2021).

Throughout the execution of the phases illustrated in Figure 3.3, the evaluation stages detailed in Table 3.12 are followed. To ensure that all necessary threshold values specified in Table 3.13 are achieved during the evaluation tests.

Table 3.12 : PLS-SEM evaluation stages for measurement models and structural model, adapted from Sarstedt et al. (2019).

Reflectively measured constructs	Formatively measured constructs	Evaluation criteria (Structural model)
Indicator Reliability	Convergent validity	Collinearity
Internal consistency reliability	Collinearity	R ² explanation of endogenous latent variables
Convergent validity	Significance and relevance of indicator weights	Predictive relevance Q ²
Discriminant validity		Significance and relevance of path model
		F ² and Q ² effects size of path coefficients
		Holdout sample validation

Table 3.3 shows the desirable values compiled from the literature for assessment stages in PLS-SEM. In the analysis of SSB-CIEM, the values in this table must be provided for the reflective measurement model and structural model.

Table 3.13 : Assessment stages and desirable values for PLS-SEM.

Assessment stage	Description	Test/Measure	Desirable values	Reference
Reflective Measurement Model				
Construct Internal Consistency Reliability	Type of reliability to evaluate result's consistency across items. The aim is to discover if the correlation between items are high enough, suggesting similarities between the items of the same latent variable.	Cronbach's alpha; Composite Reliability (Rho_a; Rho_c)	0.70 (satisfactory) to 0.90 (good); 0.60-0.70 acceptable for exploratory research; ≥0.95 (problematic)	(Cronbach, 1951; K. G. Jöreskog, 1970) (Diamantopoulou et al., 2012)
		Confidence intervals	Minimum threshold above lower bound of the 95% bootstrap confidence interval	
Convergent Validity	Indication of which items correlate positively with different items of the same latent variable	AVE	≥0.50	(Fornell & Larcker, 1981; J. F. Hair et al., 2020)
Outer loading relevance testing		Indicator reliability	≥0.708	(Fornell & Larcker, 1981; J. F. Hair et al., 2020)
Discriminant validity	Indicates if a latent variable is measuring a distinct construct and the degree of which items exemplify the target construct When comparing a variable to itself, it must be greater than all other values in the corresponding row and column of the table.	(Heterotrait-monotrait ratio) HTMT	<0.90 if constructs are conceptually similar, otherwise <0.85 (95%CI (one sided))	(Henseler et al., 2015)
		Fornell-Larcker Criterion		(Fornell & Larcker, 1981)
		Bootstrapping	Bootstrapped confidence interval of HTMT should not contain 1.0	(Henseler et al., 2015)

Table 3.13 (continued) : Assessment stages and desirable values for PLS-SEM.

Assessment Stage	Description	Test/Measure	Desirable Values	Reference
Structural Model				
Asses for multicollinearity		Variance Inflation Factor (VIF)	Probable (i.e. critical) collinearity issues when $VIF \geq 5$ Possible collinearity issues when $VIF \geq 3-5$ (soft cut-off value) Ideally show that $VIF < 3$ (hard cut-off value) $VIF < 10$	(Becker et al., 2015; J. F. Hair et al., 2011) (Kline, 2011; Hair JR. et al., 2013; Kutner et. al., 2005)
Size and significance of path coefficients	Assesses how strongly two constructs relate to each other	Standardized path coefficients	Closer to $ 1 $ =stronger; 95%CI Standard cut-off values are 0.05 and 0.01; sometimes a cut-off of 0.10 is used to highlight weak support	(Fienberg et al., 1993)
In-sample predictive ability	Measure of the predictive accuracy of the structural model	R^2 endogenous variables	≥ 0.25 (weak); ≥ 0.50 (moderate); ≥ 0.75 (strong)	(Henseler et al. 2009; Hair et al. 2011)
Effect size of predictive ability	Measure of the impact of the exogenous construct on the endogenous one	f^2 Effect size	0.02-0.15 (small); 0.15-0.35 (medium); 0.35 (large)	(Cohen, 1988)
Out of sample predictive ability	Predictive value of latent variables.	PLSpredict (Q^2) RMSE (Root Mean Squared Error)	Prediction errors < linear model naive benchmark > 0.00	(Shmueli et al., 2016)

3.2.1 Constructing the concept model and hypotheses

Following literature review, frequency analysis and expert panel studies, a conceptual partial least square structural equation model was prepared. In accordance with the conceptual structural equation model presented in the Figure 3.5, the following hypotheses were developed:

Hypothesis 1 (H1): The usage of BIM-GIS technologies in the area of smart sustainable resilience (SSR) among Turkish construction professionals positively impacts the integration maturity of smart sustainable management (SSMa).

Hypothesis 2 (H2): The usage of BIM-GIS technologies in the area of smart sustainable environment (SSE) among Turkish construction professionals positively impacts the integration maturity of smart sustainable management (SSMa).

Hypothesis 3 (H3): The usage of BIM-GIS technologies in the area of smart sustainable mobility (SSMo) among Turkish construction professionals positively impacts the integration maturity of smart sustainable management (SSMa).

Hypothesis 4 (H4): The usage of BIM-GIS technologies in the area of smart sustainable welfare-wellbeing (SSWW) among Turkish construction professionals positively impacts the integration maturity of smart sustainable management (SSMa).

Hypothesis 5 (H5): The usage of BIM-GIS technologies in the area of smart sustainable aesthetics (SSA) among Turkish construction professionals positively impacts the integration maturity of smart sustainable management (SSMa).

Hypothesis 6 (H6): The usage of BIM-GIS technologies in the area of smart sustainable management (SSMa) among Turkish construction professionals positively impacts the general integration maturity of smart sustainable maturity (SSMaturity) includes (SSE, SSR, SSMa, SSMo, SSA, and SSWW).

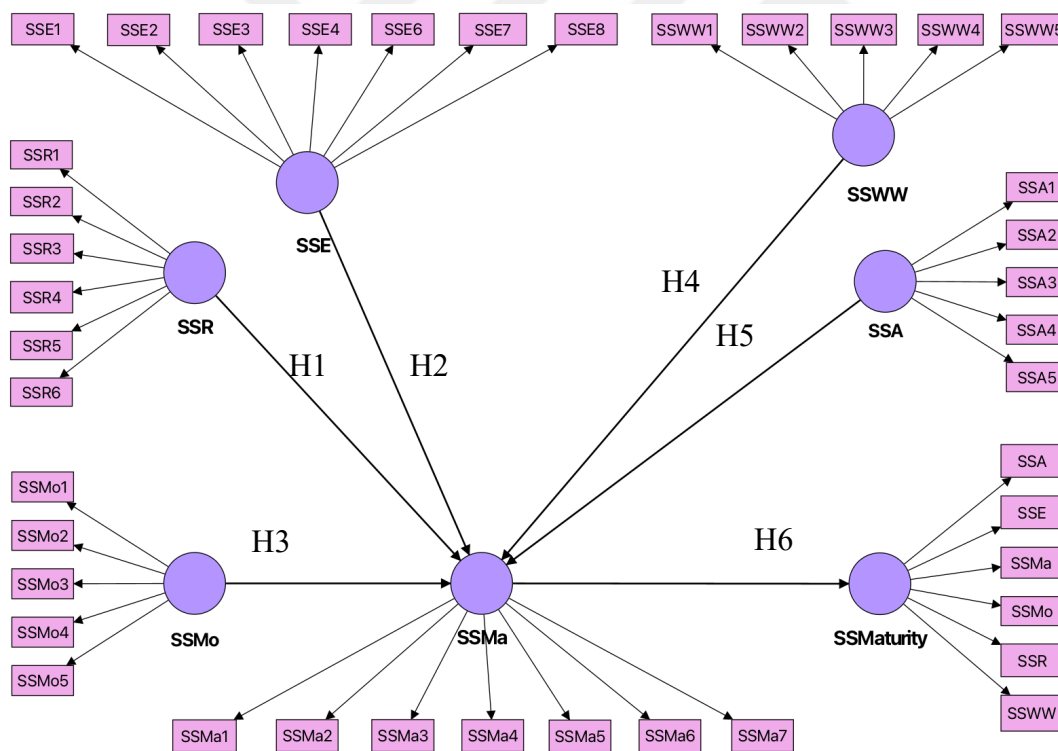


Figure 3.5 : Conceptual partial least square structural equation modeling.

4. FINDINGS AND ANALYSIS

4.1 BIM/GIS and SSB-CIEM Maturity in Turkish Construction Sector

4.1.1 Overview of the participants (demographic informations)

The research aims to evaluate the perceptions and experiences of construction professionals and academics working in the public and private sectors in Türkiye regarding the use of integrated BIM-GIS in sustainability and smart building applications. The target demographic consisted of professionals actively engaged in various roles within the construction industry. The participants were carefully selected to ensure a diverse representation of the construction sector, including architects, engineers, sustainability consultants, construction managers, and other relevant professionals. The survey was sent directly to 350 people via WhatsApp and LinkedIn network. Additionally, the survey was shared in WhatsApp groups and on the LinkedIn network flow. The total number of professionals who answered the survey was 224 people. After excluding nine responses five from professionals based outside Türkiye and four from those not meeting the defined professional criteria the final analysis was based on 215 completed surveys. These professionals have extensive experience and involvement in critical areas of the construction process, encompassing design, construction, green, sustainable, and smart building certification, as well as regulatory oversight. As seen in Table 4.1, the survey sought to gather demographic information, including gender, age, education level, professional background, institutional affiliation, and work experience, in addition to participants' engagement with sustainable project initiatives and their familiarity with Building Information Modeling (BIM) and Geographic Information Systems (GIS). The reliability of the data collection tool and the statistical analyses performed were anchored on this cohort of professionals, ensuring that the findings represent informed insights from the construction field.

Table 4.1 : Sample demographic.

Demographic variable	Category	Frequency	Percentage
Gender	Male	119	55.3%
	Female	96	44.7%
Age	18-28	33	15.3%
	29-39	116	54.0%
	40-50	45	20.9%
	51 or above	21	9.8%
City	Ankara	97	45.1%
	Istanbul	55	25.6%
	Other	63	29.3%
Education	Undergraduate	3	1.4%
	Bachelor	94	43.7%
	Master	84	39.1%
	Ph.D. or above	34	15.8%
Occupation	Architect	108	50.2%
	Urban planner	14	6.5%
	Civil engineer	33	15.3%
	Geomatic engineer	14	6.5%
	Mechanical engineer	9	4.2%
	Electrical-electronics engineer	8	3.7%
	Other engineering (topography, environment, software) and related occupations	29	13.5%
Experience	1-5 years	48	22.3%
	5-10 years	65	30.2%
	10-15 years	45	20.9%
	>15 years	57	26.5%
Institution	Private Sector	123	57.2%
	Public Sector (Municipality, ministry, etc.)	62	28.8%
	University	30	14.0%
Project type	Sustainable/green/smart	70	32.6%
	Other	145	67.4%
BIM Familiarity	Yes	150	69.8%
	No	65	30.2%
GIS Familiarity	Yes	148	68.8%
	No	67	31.2%

4.1.2 Construct reliability of SSB-CIEM scales

Cronbach's alpha coefficient was utilized to assess the structural validity and reliability of the measurement tool. In the initial stage, it was anticipated that the Cronbach Alpha would be 0.708 for the Reflective indicator loadings (J. F. Hair et al., 2018). However, the reliability analysis conducted using SPSS within the SSB-CIEM revealed a Cronbach Alpha value of 0.98. Since the values of Cronbach's Alpha fall between

0.708 and 1, and are notably close to 1, these results indicate that the measurement tool is highly reliable.

4.1.3 General perception of smart sustainable integration readiness

4.1.3.1 Distribution patterns across SSB-CIEM areas and indicators

In the statistical analysis of the data collected for the thesis study, the first step was to examine whether the data exhibited a normal distribution. The normal distribution, often referred to as the bell curve, is a probability distribution that suggests the collected data are randomly distributed within a population (Limpert et al., 2001). Several methods are employed to evaluate whether a data set follows a normal distribution (Ospina and Marmolejo-Ramos, 2019; Krithikadatta, 2014). By integrating these approaches, researchers can obtain a more comprehensive understanding of the data's distribution and assess the suitability of using parametric statistical methods. It is crucial to consider all available evidence when evaluating normality to ensure robust and reliable interpretations of the results, such as:

- 1) Bell curve shape of the histogram graph,
- 2) Calculating the coefficient of variation (CoV) less than 0.30,
- 3) Calculating the skewness/std value in the range of $-1.96 < x < 1.96$
- 4) Normality test result ($n > 50$, Kolmogorov-Smirnov) is greater than 0.05.

Bell curve shape of the histogram graphs

As seen in Figure 4.1, in the evaluations conducted by participants regarding the Smart Sustainable Building-City Integration areas, it is evident that their responses are primarily concentrated at levels 3 and 4. This observation indicates that the data is not normally distributed.

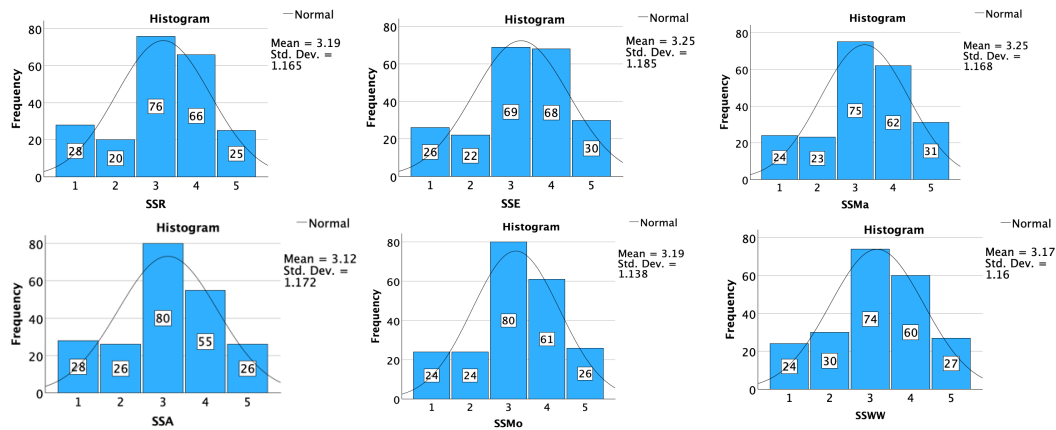


Figure 4.1 : Bell curve shape of the histogram graphs for SSR, SSE, SSMA, SSA, SSMo, and SSWW.

In statistical analysis, the relationship between the mode, median, and arithmetic mean can provide insights into the distribution of data. Specifically, when the mode, representing the most frequently occurring value, is less than both the median and arithmetic mean, it indicates a leftward concentration of data points on the graph. This scenario reflects a right-skewed distribution, characterized by the arrangement where $\text{Mode} < \text{Median} < \text{Arithmetic Mean}$. In the context of smart sustainable building-city integration indicators, participants' responses predominantly cluster around levels 1 and 2 on the evaluation scale. This clustering results in the visual representation of the data in histogram formats, as depicted in Figures 4.2 through 4.7, all of which confirm the presence of a right-skewed distribution.

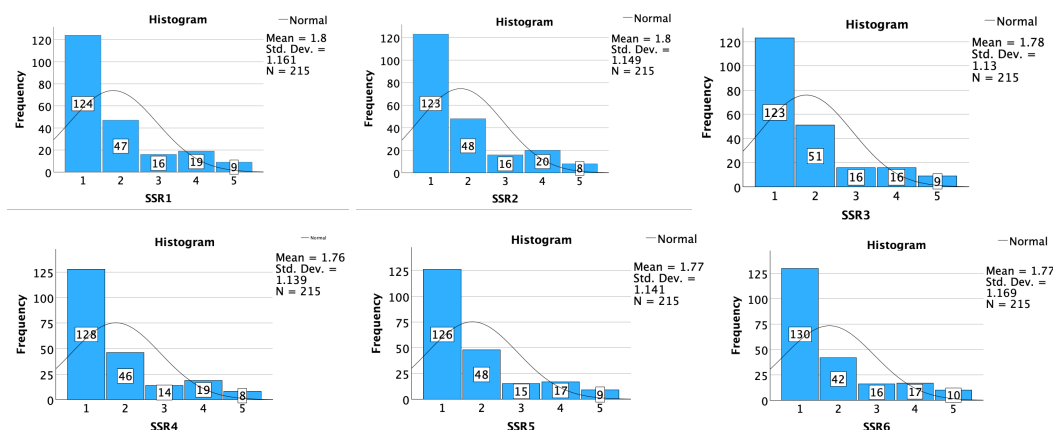


Figure 4.2 : Bell curve shape of the histogram graphs for SSR1, SSR2, SSR3, SSR4, SSR5, and SSR6.

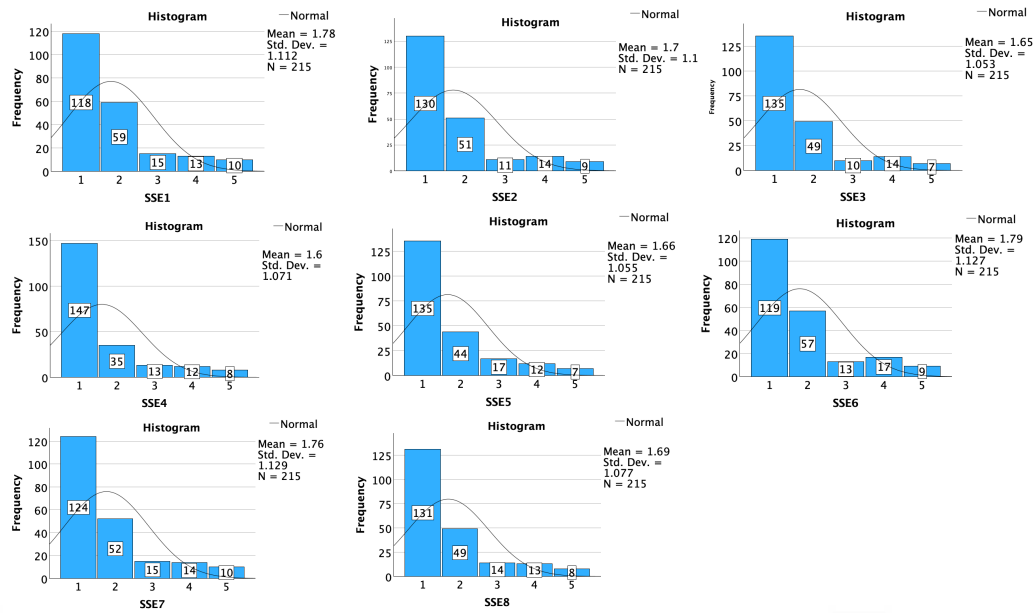


Figure 4.3 : Bell curve shape of the histogram graphs for SSE1, SSE2, SSE3, SSE4, SSE5, SSE6, SSE7, and SSE8.

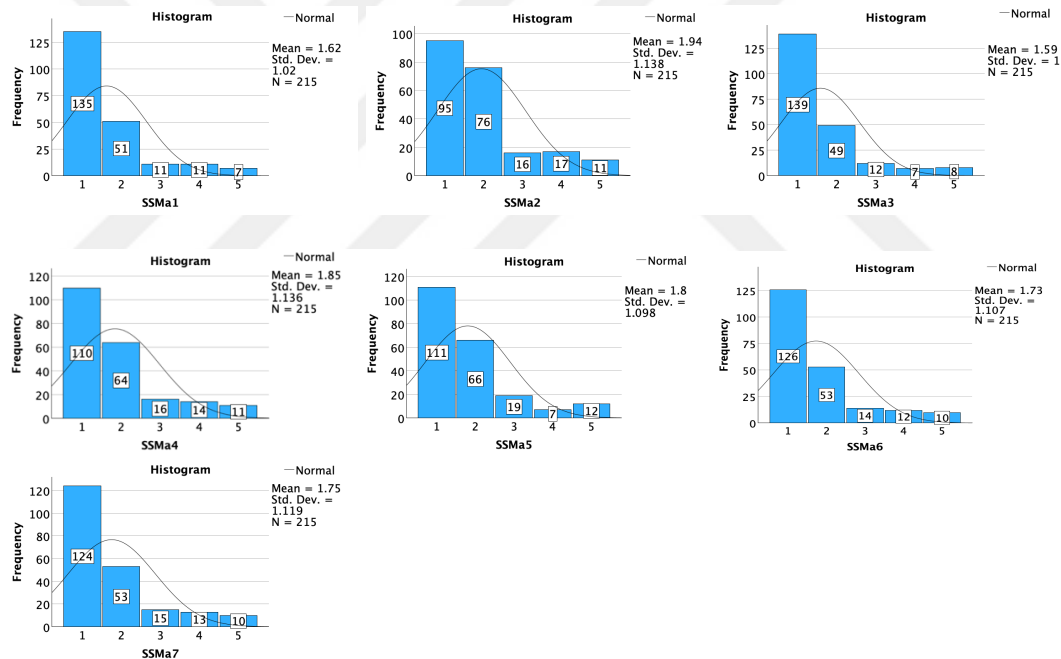


Figure 4.4 : Bell curve shape of the histogram graphs for SSMA1, SSMA2, SSMA3, SSMA4, SSMA5, SSMA6, and SSMA7.

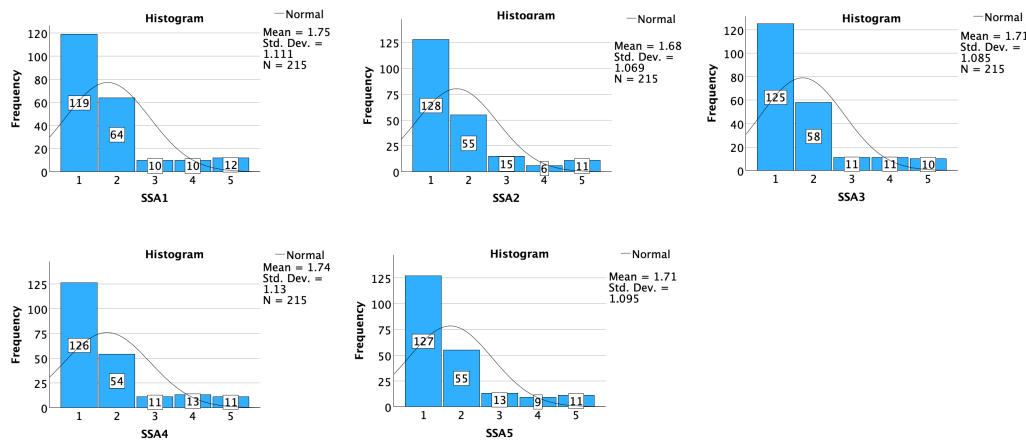


Figure 4.5 : Bell curve shape of the histogram graphs for SSA1, SSA2, SSA3, SSA4, and SSA5.

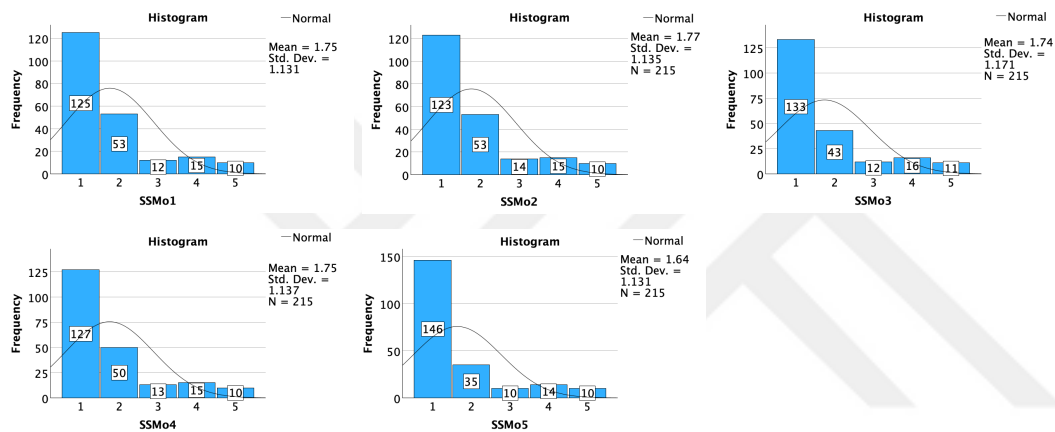


Figure 4.6 : Bell curve shape of the histogram graphs for SSMo1, SSMo2, SSMo3, SSMo4, and SSMo5.

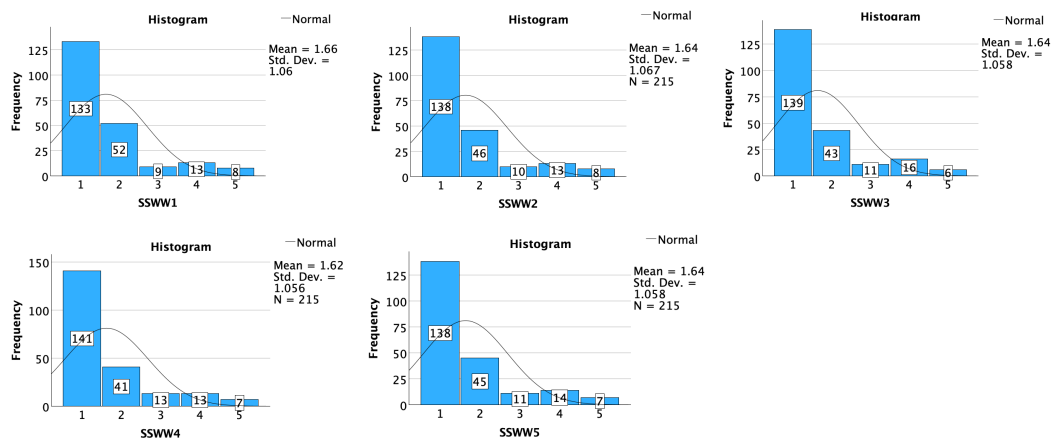


Figure 4.7 : Bell curve shape of the histogram graphs for SSWW1, SSWW2, SSWW3, SSWW4, and SSWW5.

Such distributions are significant as they suggest that while a majority of respondents may rate the indicators at lower levels, there exists a tail of higher ratings, which can influence overall averages and analyses. The observation of a right-skewed graph suggests that the distribution of the data may not adhere to the characteristics of a normal distribution. To substantiate the findings, it is essential to employ additional statistical measures of normality mentioned above.

Normality tests, calculating the skewness/std. deviation value and mean/std. deviation value the coefficient of variation (CoV)

Different values and graphs are analyzed to determine if the data follows a normal distribution. The primary method for assessing normality is through normality tests. Two commonly used tests for this purpose are the Kolmogorov-Smirnov test and the Shapiro-Wilk test. In the analysis of the data collected, the normality test was conducted using the Kolmogorov-Smirnov test due to the sample size exceeding 50 (Shapiro&Wilk, 1965). The null hypothesis for these statistical tests posits that the data follows a normal distribution. If the p-value obtained from the test is less than or equal to the predetermined level of significance, set at $p = 0.05$, the null hypothesis will be rejected. This rejection indicates that there is sufficient evidence to conclude that the data does not adhere to a normal distribution. The results yielded a p-value of less than 0.001, indicating that the data significantly deviates from a normal distribution, as the p-value does not exceed the threshold of 0.05.

Further examination of the coefficient of variation (CoV) across all fields and indicators revealed values greater than 0.30, reinforcing the conclusion that the data are not normally distributed. Conversely, the skewness divided by standard deviation values for all fields and indicators (except for SSMA3) fell within the range of -1.96 to 1.96. This outcome might suggest a normal distribution according to this specific criterion.

Mean Values:

The average responses for the maturity indicators examined within the SSB-CIEM framework, specifically SSR, SSE, SSMA, SSA, SSMo, and SSWW, yield mean values ranging from 3.12 to 3.25. This distribution indicates a medium-level trend on a 5-point evaluation scale. In contrast, the means for individual indicators such as SSR1 through SSR6 and SSE1 through SSE8 are significantly lower, fluctuating

between 1.59 and 1.94. This discrepancy suggests a lower level of agreement or density concerning the individual indicators as opposed to the broader areas assessed.

Skewness:

The skewness of the responses associated with the maturity indicators reveals negative values, ranging from -0.263 to -0.430 . These values imply that response distributions are concentrated toward higher values, resulting in a slightly left-skewed graph. Conversely, the indicators (for example, SSR1–SSR6 and SSE1–SSE8) display positive skewness, with values between 0.280 and 2.008 . This indicates a concentration of responses at lower values, thus rendering the distribution right-skewed. Notably, SSMa3 exhibits the most pronounced right skewness with a skewness value of 2.008 .

Standard deviation:

The standard deviation across all indicators varies between 1.000 (notably for SSMa3) and 1.185 (for SSE), suggesting a medium level of variability within the responses. This range signifies a modest dispersion of data points around the mean.

Skewness/Standard Deviation Ratio:

This calculated ratio shows the degree of skewness according to variability. Negative rates (-0.22 to -0.36) are seen in the maturity indicators, and positive rates (0.24 – 2.01) are seen in the other indicators. It can be said, SSMa3 has the most significant skewness with the highest ratio (2.01).

Coefficient of variation (CoV):

The Coefficient of Variation (CoV), defined as the ratio of the mean to the standard deviation, serves as a measure of relative variability and is essential for assessing the normality of data distribution. The maturity indicators exhibit higher CoV values ranging from 2.66 to 2.80 , indicating less relative variability. In contrast, lower CoV values from 1.45 to 1.70 are noted for other indicators, suggesting greater relative variability within those measures.

This statistical analysis underscores the varying degrees of agreement and variability among maturity indicators and their individual counterparts. The insights gathered from the mean values, skewness, standard deviation, skewness/standard deviation ratio, and CoV elucidate the nuanced dynamics at play within the SSB-CIEM

assessment framework, highlighting areas that may require further exploration and potential enhancement.

Table 4.2 : Normality evaluation of data.

Area/ Indicator	Mean	Sig. (Kolmogorov- Smirnov)	Skewness	Std. Deviation	Skewness/ std deviation	CoV (Mean/std.deviation)
SSR	3.19	<.001	-.422	1.165	-0,36	2,74
SSE	3.25	<.001	-.430	1.185	-0,36	2,74
SSMa	3.25	<.001	-.367	1.168	-0,31	2,78
SSA	3.12	<.001	-.263	1.172	-0,22	2,66
SSMo	3.19	<.001	-.343	1.138	-0,30	2,80
SSWW	3.17	<.001	-.277	1.160	-0,23	2,73
SSR1	1.80	<.001	1.392	1.161	1,20	1,55
SSR2	1.80	<.001	1.370	1.149	1,19	1,57
SSR3	1.78	<.001	1.469	1.130	1,30	1,58
SSR4	1.76	<.001	1.465	1.139	1,29	1,55
SSR5	1.77	<.001	1.478	1.141	1,30	1,55
SSR6	1.77	<.001	1.473	1.169	1,26	1,51
SSE1	1.78	<.001	1.532	1.112	1,38	1,60
SSE2	1.70	<.001	1.676	1.100	1,52	1,55
SSE3	1.65	<.001	1.767	1.053	1,68	1,57
SSE4	1.60	<.001	1.866	1.071	1,74	1,49
SSE5	1.66	<.001	1.679	1.055	1,59	1,57
SSE6	1.79	<.001	1.470	1.127	1,30	1,59
SSE7	1.76	<.001	1.540	1.129	1,36	1,56
SSE8	1.69	<.001	1.668	1.077	1,55	1,57
SSMa1	1.62	<.001	1.851	1.020	1,81	1,59
SSMa2	1.94	<.001	1.280	1.138	1,12	1,70
SSMa3	1.59	<.001	2.008	1.000	2,01	1,59
SSMa4	1.85	<.001	1.427	1.136	1,26	1,63
SSMa5	1.80	<.001	1.572	1.098	1,43	1,64
SSMa6	1.73	<.001	1.635	1.107	1,48	1,56
SSMa7	1.75	<.001	1.570	1.119	1,40	1,56
SSA1	1.75	<.001	1.699	1.111	1,53	1,58
SSA2	1.68	<.001	1.818	1.069	1,70	1,57
SSA3	1.71	<.001	1.724	1.085	1,59	1,58
SSA4	1.74	<.001	1.644	1.130	1,45	1,54
SSA5	1.71	<.001	1.746	1.095	1,59	1,56
SSMo1	1.75	<.001	1.572	1.131	1,39	1,55
SSMo2	1.77	<.001	1.522	1.135	1,34	1,56
SSMo3	1.74	<.001	1.578	1.171	1,35	1,49
SSMo4	1.75	<.001	1.567	1.137	1,38	1,54
SSMo5	1.64	<.001	1.807	1.131	1,60	1,45
SSWW1	1.66	<.001	1.794	1.060	1,69	1,57
SSWW2	1.64	<.001	1.815	1.067	1,70	1,54
SSWW3	1.64	<.001	1.723	1.058	1,63	1,55
SSWW4	1.62	<.001	1.788	1.056	1,69	1,53
SSWW5	1.64	<.001	1.771	1.058	1,67	1,55

Upon reviewing Table 4.2 and the corresponding histogram graphs (Figure 4.1-Figure 4.7), it was observed that the scales used in the survey met only one of the necessary criteria for normal distribution, specifically the skewness to standard deviation criterion. Consequently, in light of the evidence suggesting non-normality, non-parametric statistical methods were employed for further analysis, including the One Sample Wilcoxon Signed Rank Test, Kruskal-Wallis One-Way ANOVA, and Mann-Whitney U test.

4.1.4 Gap between expected and actual integration maturity levels

This doctoral thesis implemented the non-parametric One-Sample Wilcoxon Rank Test to evaluate the responses of 215 participants from the Turkish construction sector against a predetermined norm value. Given the assessed non-normal distribution of the dataset, this methodology was deemed appropriate for the analysis. Initially, the null hypothesis (H0) was established: the responses to 42 questions spanning six areas and 36 indicators do not significantly differ from the norm value of 4, which posits that BIM and GIS data are utilized in a partially integrated manner. To test H0, the observed medians of the collected data in comparison to the hypothesized median value were examined. The outcomes revealed a rejection of H0, indicating a statistically significant difference from the assumed median. Specifically, while the hypothetical median across all areas and indicators was 4, the observed median was notably lower, recorded at 3 for the all areas (SSR, SSE, SSMA, SSMo, SSA, and SSWW) and 2 for the indicator SSMA2 (indicating either BIM or GIS data utilization) and 1 for all other indicators (suggesting non-utilization of data).

Table 4.3 : One-Sample Wilcoxon Signed Rank Test.

Null hypothesis	Test	Sig. ^{a,b}	Decision
The median of all areas and indicators equals 4. Total N: 215	One-Sample Wilcoxon Signed Rank Test	<.001	Reject the null hypothesis.
a. The significance level is .050.			
b. Asymptotic significance is displayed.			

As seen in Table 4.3, since the One-Sample Wilcoxon Signed Rank Test result is sig. <.001, the H0 hypothesis is rejected. This suggests a substantial deficiency in the integration and application of data within the sector.

4.1.5 Comparative analysis of public, private and university responses

In this doctoral thesis, a comparative analysis was conducted on the responses of professionals from public, private, and university construction sectors regarding the areas and indicators of SSB-CIEM. The study aimed to identify differences in perspectives and practices among these groups, shedding light on how their backgrounds and roles influence their understanding and application of SSB-CIEM indicators. This research contributes to a deeper understanding of the construction industry's approach to sustainable practices and the factors affecting it across different sectors.

The Kruskal-Wallis one-way ANOVA test compares data from three or more groups when the data do not follow a normal distribution. According to the results derived from the Kruskal-Wallis One-way ANOVA test presented in Table 4.4, the decision to accept or reject the null hypothesis (H0), which posits that the group medians are equal, was made based on the Asymptotic Significance (Asymp. Sig.) values, with a significance level set at 0.05.

Table 4.4 : Kruskal Wallis One-way ANOVA test.

Area/Indicator	Asymp. Sig.	H0	Area/Indicator	Asymp. Sig.	H0	Area/Indicator	Asymp. Sig.	H0
SSR	.162	A	SSE3	.163	A	SSA2	.618	A
SSE	.328	A	SSE4	.051	A	SSA3	.644	A
SSMa	.121	A	SSE5	.160	A	SSA4	.499	A
SSA	.135	A	SSE6	.792	A	SSA5	.080	A
SSMo	.730	A	SSE7	.356	A	SSMo1	.036	R
SSWW	.501	A	SSE8	.086	A	SSMo2	.101	A
SSR1	.013	R	SSMa1	.317	A	SSMo3	.071	A
SSR2	.025	R	SSMa2	.643	A	SSMo4	.116	A
SSR3	.021	R	SSMa3	.099	A	SSMo5	.031	R
SSR4	.006	R	SSMa4	.083	A	SSWW1	.012	R
SSR5	.036	R	SSMa5	.071	A	SSWW2	.175	A
SSR6	.011	R	SSMa6	.037	R	SSWW3	.018	R
SSE1	.377	A	SSMa7	.174	A	SSWW4	.209	A
SSE2	.666	A	SSA1	.138	A	SSWW5	.086	A

A: Accepted, R: Rejected.

When the results are evaluated for areas, the Asymp. Sig. values for various areas SSR (0.162), SSE (0.328), SSMa (0.121), SSA (0.135), SSMo (0.730), and SSWW (0.501) are all greater than the 0.05 threshold. Consequently, the null hypothesis is accepted. This outcome indicates that the assumption of equality among the medians in these areas is upheld.

When the results are evaluated for areas indicators, H0 Accepted (Sig. > 0.05): for indicators including SSE3 (0.163), SSE4 (0.051), SSE5 (0.160), SSE6 (0.792), SSE7 (0.356), SSE8 (0.086), SSMa1 (0.317), SSMa2 (0.643), SSMa3 (0.099), SSMa4 (0.083), SSMa5 (0.071), SSMa6 (0.037), SSMa7 (0.174), and SSA1 (0.138), the significance values are either above 0.05 or borderline (except for SSMa6, which, while below 0.05, can be accepted based on contextual considerations). Thus, the null hypothesis is accepted, suggesting no statistically significant median differences among these indicators. It is worth noting that although the value of 0.037 for SSMa6 is below 0.05, its acceptance may vary depending on the interpretation context.

Conversely, H_0 Rejected (Sig. < 0.05) for indicators such as SSR1 (0.013), SSR2 (0.025), SSR3 (0.021), SSR4 (0.006), SSR5 (0.036), SSR6 (0.011), SSMo1 (0.036), SSMo5 (0.031), SSWW1 (0.012), SSWW3 (0.018), and certain values from SSWW2 (0.175) and SSWW4 (0.209), where significance falls below 0.05, the null hypothesis is rejected. This outcome signifies the presence of statistically significant differences among these indicators, indicating that their medians are not equal. The values for SSWW2 (0.175) and SSWW4 (0.209), though slightly above 0.05, are marked for contextual evaluation in the determination of significance.

At the area level, the null hypothesis is broadly accepted, suggesting that differences in medians between the areas lack significance. However, when examining the indicator level, the null hypothesis is rejected for several indicators associated with SSR, SSMo, and SSWW (notably SSR1 through SSR6, SSMo1, SSMo5, SSWW1, and SSWW3), which reveals that the medians for these specific indicators display significant variation. This variation may suggest distinctive behaviors among these indicators when compared to others within the analysis framework. Should a significant difference be identified among more than two groups through the Kruskal-Wallis test, all possible pairs of groups will subsequently be analyzed using the Mann-Whitney U test. Thus, the analysis will proceed with the application of the Mann-Whitney U test.

4.1.6 Public-private BIM/GIS readiness for smart sustainable integration

The Mann-Whitney U test is a nonparametric statistical method utilized to assess whether two independent samples originate from the same population distribution (Hollander et al., 2015). It is particularly valuable when the assumption of normality is not met, making it a robust alternative to parametric tests. This test is commonly applied in various fields, including social sciences and biomedical research, to compare medians between groups when data are ordinal or continuous but do not adhere to a normal distribution.

In this doctoral thesis, a comparative analysis was conducted on the medians of responses from professionals in the construction sector between two categories: public and private sector. The analysis focused on six primary areas and thirty-six specific indicators regarding the implementation of BIM-GIS data usage in building-city projects. Initially, a normality test was executed to assess the distribution of data.

Given that the sample sizes exceeded 50 for all sectors, the Kolmogorov-Smirnov test was employed. Results indicated that the significance values (p value) for all variables were less than .001 and .05, prompting the rejection of the null hypothesis and suggesting that the data did not follow a normal distribution. The sample sizes were 123 for the private sector and 62 for the public sector. The hypotheses for the Mann-Whitney U test were formulated as follows: Null Hypothesis (H0): There is no significant difference in the evaluation of projects by public and private sector employees concerning “BIM-GIS data usage in smart sustainable building-city areas and indicators”. Alternative Hypothesis (H1): There is a significant difference in the evaluation of projects by public and private sector employees regarding “BIM-GIS data usage in smart sustainable building-city areas and indicators”, indicating that the institution of employment influences the adoption of the smart sustainable building-city integration approach.

As seen in Table 4.5, upon analyzing the mean ranks, the findings revealed that private sector construction professionals perceived themselves as more prepared to utilize BIM-GIS across the six identified areas (SSR, SSE, SSMA, SSA, SSMo, and SSWW) compared to their public sector counterparts. Although the observed differences in mean ranks were marginal, the analysis indicated that the public sector consistently reported higher mean ranks for all thirty-six indicators (e.g., SSR1, SSR2). This trend suggests that public sector professionals consider themselves more inclined toward adopting an integrated BIM-GIS approach for smart sustainable building-city integration initiatives in the context of SSB-CIEM indicators.

Table 4.5 : Mann-Whitney U test (mean ranks).

Area/ Indicator	Sector	Mean rank	Sum of ranks	Area/ Indicator	Mean Rank	Sum of ranks
SSR	Private	96.27	11841.50	SSMa2	91.57	11263.00
	Public	86.51	5363.50		95.84	5942.00
SSE	Private	96.54	11875.00	SSMa3	90.29	11106.00
	Public	85.97	5330.00		98.37	6099.00
SSMa	Private	96.67	11890.00	SSMa4	88.07	10832.00
	Public	85.73	5315.00		102.79	6373.00
SSA	Private	96.38	11855.00	SSMa5	92.15	11334.50
	Public	86.29	5350.00		94.69	5870.50
SSMo	Private	93.28	11473.00	SSMa6	88.21	10849.50
	Public	92.45	5732.00		102.51	6355.50
SSWW	Private	93.77	11534.00	SSMa7	89.00	10947.50
	Public	91.47	5671.00		100.93	6257.50
SSR1	Private	87.07	10709.50	SSA1	91.12	11208.00
	Public	104.77	6495.50		96.73	5997.00

Table 4.5 (continued) : Mann-Whitney U test (mean ranks).

Area/ Indicator	Sector	Mean rank	Sum of ranks	Area/ Indicator	Mean Rank	Sum of ranks
SSR2	Private	86.75	10670.50	SSA2	91.16	11212.50
	Public	105.40	6534.50		96.65	5992.50
SSR3	Private	87.04	10705.50	SSA3	90.70	11156.00
	Public	104.83	6499.50		97.56	6049.00
SSR4	Private	85.78	10551.00	SSA4	90.56	11139.00
	Public	107.32	6654.00		97.84	6066.00
SSR5	Private	86.97	10697.00	SSA5	89.74	11038.50
	Public	104.97	6508.00		99.46	6166.50
SSR6	Private	86.25	10609.00	SSMo1	87.41	10751.00
	Public	106.39	6596.00		104.10	6454.00
SSE1	Private	89.73	11037.00	SSMo2	88.62	10900.00
	Public	99.48	6168.00		101.69	6305.00
SSE2	Private	92.42	11367.50	SSMo3	88.04	10829.50
	Public	94.15	5837.50		102.83	6375.50
SSE3	Private	88.48	10883.50	SSMo4	88.22	10851.00
	Public	101.96	6321.50		102.48	6354.00
SSE4	Private	87.43	10754.00	SSMo5	87.62	10777.00
	Public	104.05	6451.00		103.68	6428.00
SSE5	Private	90.05	11076.00	SSWW1	87.26	10733.50
	Public	98.85	6129.00		104.38	6471.50
SSE6	Private	91.52	11257.50	SSWW2	88.90	10934.50
	Public	95.93	5947.50		101.14	6270.50
SSE7	Private	90.26	11102.50	SSWW3	86.33	10618.00
	Public	98.43	6102.50		106.24	6587.00
SSE8	Private	88.16	10844.00	SSWW4	88.92	10937.50
	Public	102.60	6361.00		101.09	6267.50
SSMa1	Private	89.74	11037.50	SSWW5	88.10	10836.00
	Public	99.48	6167.50		102.73	6369.00

Table 4.6 presents the results of the Mann-Whitney U test (Asymp. Sig., 2-tailed) for the hypothesis evaluation (H0) across various areas and indicators. The analysis yielded significant findings regarding the use of integrated BIM/GIS in the context of smart sustainable building and city integration. The null hypothesis is accepted (A) if Sig. > 0.05 and rejected (R) if Sig. ≤ 0.05.

In this thesis study, areas (SSR (0.222), SSE (0.188), SSMa (0.173), SSA (0.209), SSMo (0.918), SSWW (0.774)) all have Sig. > 0.05, so H0 is accepted, indicating no significant difference between the public and private sectors.

On the other hand, following indicators: SSE3 (0.061), SSE5 (0.227), SSE6 (0.558), SSE7 (0.275), SSMa1 (0.177), SSMa2 (0.584), SSMa3 (0.262), SSMa4 (0.055), SSMa5 (0.742), SSMa6 (0.056), SSMa7 (0.111), SSA1 (0.459), SSA2 (0.455), SSA3 (0.352), SSA4 (0.326), SSA5 (0.192), SSMo2 (0.082), SSMo4 (0.054), SSWW4 (0.084) have Sig. > 0.05, accepting H0, suggesting no significant difference between public and private sectors. Conversely, SSE4 (0.015), SSE8 (0.049), SSR1 (0.019),

SSR2 (0.013), SSR3 (0.018), SSR4 (0.004), SSR5 (0.015), SSR6 (0.006), SSMo1 (0.025), SSMo3 (0.043), SSMo5 (0.021), SSWW1 (0.020), SSWW3 (0.005), SSWW5 (0.041) have Sig. ≤ 0.05 , rejecting H0, indicating a significant difference between the public and private sectors.

Table 4.6 : Mann-Whitney U test for the hypothesis (H0) evaluation.

Area/Indicator	Asymp. Sig. (2- tailed)	H0	Area/Indicator	Asymp. Sig. (2- tailed)	H0	Area/Indicator	Asymp. Sig. (2- tailed)	H0
SSR	.222	A	SSE3	.061	A	SSA2	.455	A
SSE	.188	A	SSE4	.015	R	SSA3	.352	A
SSMa	.173	A	SSE5	.227	A	SSA4	.326	A
SSA	.209	A	SSE6	.558	A	SSA5	.192	A
SSMo	.918	A	SSE7	.275	A	SSMo1	.025	R
SSWW	.774	A	SSE8	.049	R	SSMo2	.082	A
SSR1	.019	R	SSMa1	.177	A	SSMo3	.043	R
SSR2	.013	R	SSMa2	.584	A	SSMo4	.054	A
SSR3	.018	R	SSMa3	.262	A	SSMo5	.021	R
SSR4	.004	R	SSMa4	.055	A	SSWW1	.020	R
SSR5	.015	R	SSMa5	.742	A	SSWW2	.087	A
SSR6	.006	R	SSMa6	.056	A	SSWW3	.005	R
SSE1	.196	A	SSMa7	.111	A	SSWW4	.084	A
SSE2	.813	A	SSA1	.459	A	SSWW5	.041	R

A: Accepted, R: Rejected.

Findings highlight the need for focused exploration of these indicators to further understand the dynamics influencing the implementation of integrated BIM/GIS across different sectors. Most areas show no significant differences (H0 accepted), while several indicators, particularly within SSR, SSMo, and SSWW, show significant differences (H0 rejected), suggesting variability in those specific categories. Such insights could be pivotal in shaping future strategies for the better integration of BIM and GIS methodologies.

4.2 Structural Relationships Among Smart Sustainable Integration Factors

In this doctoral thesis, the variance-based partial least squares structural equation modeling (PLS-SEM) approach has been identified as the most suitable method to address the research objectives effectively. As seen in the Figure 4.8, the PLS-SEM method centers on examining the effects of independent variables, including SSE, SSR, SSWW, SSMo, and SSA, on the dependent variable SSMa, as well as the influence of SSMa on SSMaturity to evaluate the SSB-CIEM.

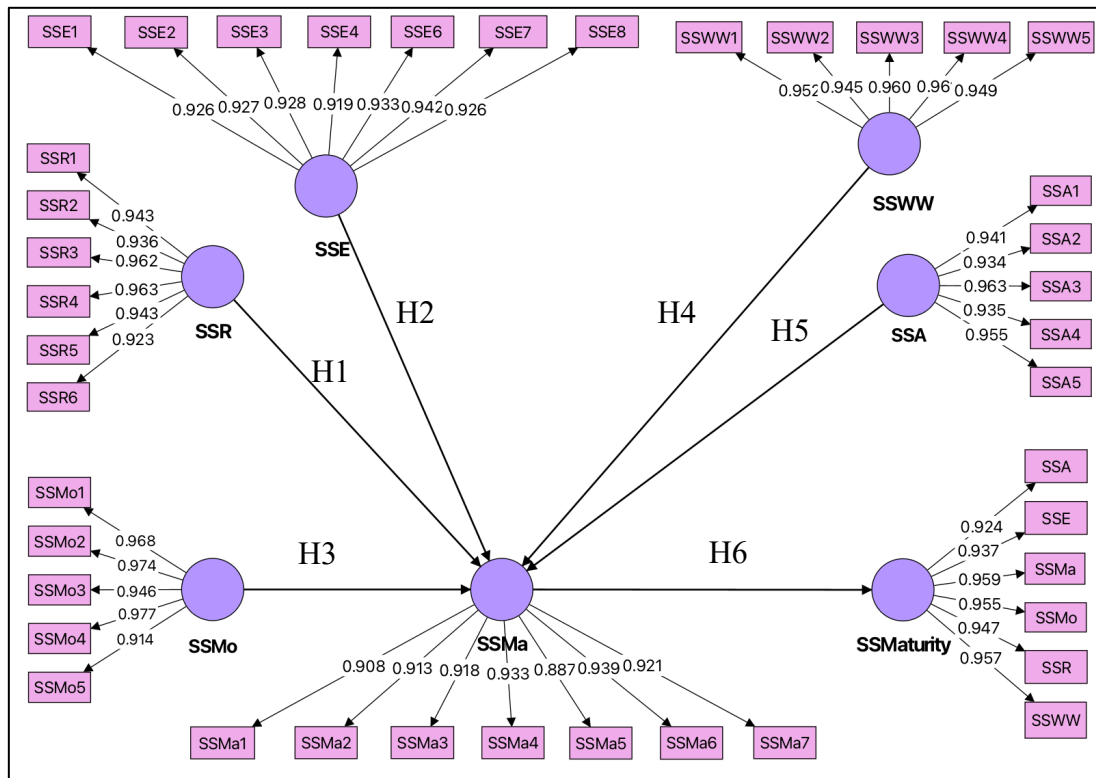


Figure 4.8 : Outer loadings for indicators in SSB-CIEM.

The analysis begins with the application of the PLS-SEM algorithm to optimize the parameters of the measurement model. Following this, the path coefficients within the structural model are estimated in accordance with the methodologies outlined by Sarstedt et al. (2014). To ensure the robustness of the model, parameters are adjusted after assessing threshold values, and subsequent analyses are conducted.

While the initial draft model presents threshold values related to outer loadings, internal indicator reliability, and convergent validity, modifications are made to enhance the model by including threshold values for collinearity checks and the HTMT (Heterotrait-Monotrait ratio) tests. Furthermore, the structures SSWW, SSMo, and SSA are integrated into a cohesive framework for refined analysis.

The SSB-CIEM has undergone modifications to incorporate the threshold values associated with the PLS-SEM method as outlined in existing literature. Consequently, the six hypotheses derived from the findings in the preceding chapter have been restructured into four foundational hypotheses. These core hypotheses will be examined in greater depth in this chapter. The details regarding these hypotheses are presented below:

Hypothesis 1 (H1) posits that the use of BIM-GIS technologies in the smart sustainable resilience (SSR) among Turkish construction professionals positively influences the integration maturity of smart sustainable management (SSMa).

Hypothesis 2 (H2) asserts that the application of BIM-GIS technologies in the smart sustainable environment (SSE) among Turkish construction professionals positively impacts the integration maturity of smart sustainable management (SSMa).

Hypothesis 3 (H3) suggests that the utilization of BIM-GIS technologies across the areas of smart sustainable welfare-wellbeing, mobility, and aesthetics (SSWW-SSMo-SSA) among Turkish construction professionals enhances the integration maturity of smart sustainable management (SSMa).

Hypothesis 4 (H4) contends that employ BIM-GIS technologies in the smart sustainable management (SSMa) positively influence the integration maturity of smart sustainable maturity (SSMaturity).

After establishing threshold values for the acceptable features of the measurement models, the results from PLS-SEM are compared with existing literature for interpretation, as outlined by Hair et al. 2011). In the PLS-SEM framework, it is essential to first validate and establish the reliability of the measurement models. Nenavath (2025) as well as Hair JR. et al. (2013) define validity and reliability in the following ways:

Validity pertains to the extent to which a concept is accurately represented by its measures, while reliability refers to the consistency of the measures. Specifically, reliable measures will yield consistent values across multiple assessments. This distinction emphasizes that validity focuses on what is being measured, whereas reliability concerns how it is measured.

4.2.1 Assessment of reflective measurement models

To assess the adequacy of the relationship models between latent and observed variables in a structural equation model, several analyses are conducted, including:

- Individual indicator reliability analysis
- Convergent validity assessment of individual latent variable measures (Cook & Campbell, 1979)

- Discriminant validity analysis of research items (Campbell & Fiske, 1959).

4.2.1.1 SSB-CIEM indicators reliability

During the evaluation of the reflective measurement model, the indicator loadings are examined first. Research indicates that 82% of scholars assess item loading values in reflective measurement models (Russo & Stol, 2021). The outer loadings represent the standardized regression coefficients for each indicator (observed variable) associated with its corresponding latent variable. According to Fornell & Larcker (1981) and Hair et al. (2020) an outer loading greater than 0.708 is considered highly satisfactory. However, Hulland (1999) posits that for exploratory or explanatory studies developing new scales and dimensions, a threshold of >0.5 or even >0.4 may be acceptable to assure indicator reliability. In this study, it was determined through the SmartPLS v.4.1.1.2 output that all constructs exceeded the 0.7 threshold, indicating strong reliability. Consequently, the external loadings for all indicators in the reflective constructs signify satisfactory individual indicator reliability, and all loadings achieved statistical significance.

4.2.1.2 Internal consistency reliability for SSB-CIEM areas/constructs

In Partial Least Squares Structural Equation Modeling (PLS-SEM), various criteria are employed to assess internal consistency reliability, such as Cronbach's alpha, Dijkstra-Henseler's rho (ρ_A), and composite reliability Oyewobi et al. (2023). Russo & Stol (2021) highlight that every PLS-SEM study utilized at least one measure of internal consistency reliability, with the majority employing both Cronbach's alpha and composite reliability assessments. The Cronbach's alpha coefficient, introduced by Cronbach in 1951, serves to evaluate the reliability or consistency of a set of variables intended to measure a single-dimensional latent construct (Cronbach, 1951). It is crucial to note that Cronbach's alpha tends to produce lower values when the underlying data exhibit a multidimensional structure (Aibinu & Al-Lawati, 2010).

Further analysis of the PLS-SEM literature reveals that Jöreskog (1971)'s composite reliability coefficient is frequently utilized. While both Cronbach's alpha and composite reliability share similar threshold values, the former generally yields lower estimates. Standard threshold values for Cronbach's alpha and composite reliability include: 0.70 (satisfactory) to 0.90 (good), 0.60-0.70 deemed acceptable for

exploratory research, and values above 0.95 categorized as problematic (Cronbach, 1951; K. G. Jöreskog, 1971).

As illustrated in Table 4.7, the internal consistency reliability tests confirm that all reliability criteria values meet or exceed 0.70, thereby affirming the internal reliability of the constructs involved. The measurement indicators are deemed appropriate for their respective latent variables within the PLS-SEM framework of SSB-CIEM.

Table 4.7 : Internal consistency reliability-validity result matrix.

	Cronbach's alpha	Composite reliability (rho_a)	Composite reliability (rho_c)	Average variance extracted (AVE)
SSE	0.960	0.961	0.969	0.864
SSMa	0.961	0.962	0.970	0.866
SSMaturity	0.943	0.964	0.963	0.897
SSR	0.957	0.961	0.969	0.886
SSWW- SSMo-SSA	0.962	0.962	0.968	0.814

It is noteworthy that the Cronbach alpha values are marginally above the threshold of 0.95 for the latent variables SSMaturity, SSMa, and SSWW-SSMo-SSA, indicating a strong internal consistency. However, this also raises the possibility of redundancy among closely related scale items. In alignment with the findings from the analysis studies conducted by Aldoghiher et al.'s (2025), this research emphasizes the importance of maintaining the integrity of the model. To achieve this, results were obtained that met the threshold values, especially for assessing discriminant validity through the HTMT ratio and for assessing linearity through the VIF values. In this context, further variable removal was intentionally avoided, as all constructs demonstrated their theoretical distinctiveness. This approach underscores a commitment to preserving the model's robustness while ensuring that each construct remains clearly defined and distinct from the others.

4.2.1.3 Convergent validity for SSB-CIEM areas/constructs

In Partial Least Squares Structural Equation Modeling (PLS-SEM), the assessment of more than one observed variable for latent construct measurement necessitates a consideration of both the reliability of the measurement items and the extent of convergent validity as highlighted by (Hulland, 1999). According to Russo & Stol (2021) convergent validity is an essential aspect of all PLS-SEM studies, typically

evaluated through the Average Variance Extracted (AVE) metric. Fornell & Larcker (1981) assert that an AVE value should exceed 0.5, indicating that at least 50% of the variance in measurements is accounted for by the latent variables (J. F. Hair et al., 2020). As demonstrated in Table 4.7, every component of the model complied with this criterion, with the AVE estimates derived from SmartPLS v.4.1.1.2 surpassing the 50% threshold for all latent variables in the PLS-SEM analysis of the SSB-CIEM.

4.2.1.4 Discriminant validity for SSB-CIEM areas/constructs

Discriminant validity, which signifies the distinctiveness of one construct from another, can be evaluated through two primary methods in PLS-SEM: the Fornell-Larcker criterion and the Heterotrait-Monotrait Ratio. The Fornell-Larcker criterion stipulates that the square root of the AVE for a latent variable must be greater than its correlations with other latent variables. The results for the Fornell-Larcker analysis pertaining to PLS-SEM analysis of the SSB-CIEM are illustrated in Table 4.8. The initial values in each column correspond to the square roots of the AVE, while the remaining figures represent the correlation coefficients among constructs. As outlined in Table 4.8, the square roots of the AVEs for all constructs exceed their respective correlation coefficients, thereby satisfying the conditions for discriminant validity.

Table 4.8 : Fornell-Larcker analysis result matrix.

	SSE	SSMa	SSMaturity	SSR	SSWW-SSMo-SSA
SSE	0.929				
SSMa	0.846	0.930			
SSMaturity	0.297	0.312	0.947		
SSR	0.719	0.733	0.228	0.942	
SSWW-SSMo-SSA	0.855	0.855	0.299	0.759	0.902

The use of the Heterotrait-Monotrait (HTMT) criterion, as proposed by Henseler et al. (2015), is increasingly being recognized in academic research as a robust method for assessing discriminant validity, especially in the context of Partial Least Squares Structural Equation Modeling (PLS-SEM). This is in contrast to the traditional Fornell-Larcker criterion, which has dominated the landscape of validity testing but may not capture nuanced relationships between constructs.

In the current study of the SSB-CIEM framework, the HTMT criterion serves as a secondary validity assessment tool. The HTMT measure is defined by the average of item correlations across different constructs (heterotrait-heteromethod correlations) compared to the geometric mean of item correlations within the same construct

(monotrait-heteromethod correlations). The cross-loadings, representing heterotrait-heteromethod correlations, involve relationships between different reflective or single-item constructs with their lower-order components, while the monotrait-heteromethod correlations reflect the correlations found between those lower-order components themselves (Sarstedt et al., 2019).

For constructs that are conceptually similar such as various developer skills like decomposition and abstraction a higher cut-off value of 0.90 is recommended for HTMT assessment. Conversely, a more conservative threshold of 0.85 applies in broader scenarios (Henseler et al., 2015).

In relation to the SSB-CIEM scale, the identified constructs converge around the concept of utilizing integrated Building Information Modeling (BIM) and Geographical Information Systems (GIS) within distinct phases of a building's construction life cycle encompassing pre-construction, construction, and post-construction management activities. Consequently, adhering to a cut-off value of 0.90 was deemed appropriate for ensuring discriminant validity within this context. The analytical outcomes, as illustrated in Table 4.9, affirm that all latent variables maintain thresholds below 0.90, thereby confirming the achievement of discriminant validity in the proposed model.

Table 4.9 : Heterotrait-Monotrait Ratio analysis result matrix.

	SSE	SSMa	SSMaturity	SSR	SSWW-SSMo-SSA
SSE					
SSMa	0.879				
SSMaturity	0.307	0.324			
SSR	0.748	0.761	0.235		
SSWW-SSMo-SSA	0.889	0.888	0.311	0.792	

Both the Fornell-Larcker and HTMT assessments validate that the factors within the model are distinct, with no excessive correlations, thereby reinforcing the integrity of the construct validity.

4.2.1.5 SSB-CIEM indicators' variance interrelation degree (collinearity)

The Variance Inflation Factor (VIF) serves as an indicator of how much variance of a particular variable is accounted for by other variables within the same construct. According to Sarstedt et al. (2014, 2019) there is no necessity to assess multicollinearity in reflective measurement models (outer models). However, initial

HTMT analysis revealed values nearing the upper limits, prompting a review of the involved variables. Prioritizing the removal of variables exhibiting high VIF values can enhance model integrity as it restructures the framework effectively. Lowering the VIF values to acceptable thresholds may also positively influence HTMT values. Nevertheless, it is crucial to maintain a balanced approach in this process. In the context of a Partial Least Squares Structural Equation Modeling (PLS-SEM) framework, the measurement elements derived from experimental testing should ideally conform to statistical properties that align with the threshold values established in theoretical literature.

For instance, discarding indicators solely to meet reliability or multicollinearity reduction targets within a reflective or formative index, respectively, is a counterproductive approach concerning the validity of a literature-supported measurement model. There are no standardized guidelines detailing the equilibrium between content adequacy and statistical evaluation; thus, an exclusive focus on statistical measures may not yield a robust measurement outcome (Diamantopoulos & Siguaw, 2006).

Becker et al. (2015) and Hair et al. (2011) advocate for more conservative thresholds, such as $VIF < 5$ or $VIF < 3.3$, which enhance model explanatory power. However, Kline, (2011), Hair JR. et al. (2013), and Kutner et al. (2005) suggest that a VIF threshold below 10 is tolerable for multicollinearity. Given the extensive dataset utilized for the PLS-SEM of the SSB-CIEM and the diverse nature of the variables, it can be anticipated that inter-variable correlations will not critically impact the model results. Therefore, to maintain the intended structure of the literature-supported model, a threshold value of < 10 was established, resulting in a judicious reduction of the number of variables. Adopting a VIF threshold of < 10 mitigated multicollinearity issues and necessitated minor model adjustments. Based on the VIF values presented in Table 4.10, no multicollinearity concerns are evident for the PLS-SEM analysis of the SSB-CIEM. Furthermore, Urbach & Ahlemann (2010) have indicated that a threshold value of 10 does not induce multicollinearity, citing Gujarati & Porter (2003). According to Gujarati & Porter (2003) multicollinearity is not significantly detrimental if the objective is merely estimation. In developing the SSB-CIEM scale, an initial set of 42 indicators across 7 (SSR, SSE, SSMA, SSMo, SSA, SSWW, SSMaturity), constructs were established for the formulation of reflective measurement models. The identification of high levels of multicollinearity among

observed variables within the measurement model raises potential issues, as it complicates the clear attribution of effects to each indicator on the latent structure; thus, multicollinearity among items was assessed first.

The developed hypotheses were tested with the PLS-SEM approach. The initially developed model consisted of a total of six hypotheses. The model was modified in an effort to improve the fit indices. Hypotheses H3, H4 and H5 were combined and established as a single hypothesis. The modified model seen in Figure 4.9 was re-analyzed.

The SSB-CIEM developed in this thesis is the result of exploratory research, representing the initial estimates of a novel modeling approach. A threshold value of 10 was selected, as it allows for the Fornell-Larcker criterion of discriminant validity to be met, even when values exceed 10. To enhance measurement sensitivity using the HTMT ratio criterion, several observed variables were excluded from the model, specifically SSA3, SSA5, SSE3, SSE5, SSE7, SSMA1, SSMA3, SSMo1, SSMo2, SSMo4, SSR3, SSR4, SSWW2, SSWW4, SSWW5, as well as SSWW, SSMA, and SSMo latent variables, which were merged to strengthen the HTMT ratio discriminant validity. Consequently, achieving optimal values for both the inner and outer models in PLS-SEM, such as model fit and discriminant validity, enabled the creation of a robust structural model. The final model incorporates four latent variables (constructs) and 24 observed/manifest variables (indicators). In the final PLS-SEM, VIF values for all variables are <7.06. This value, which is below the threshold value for VIF in the literature (<10), was decided to be reasonable for an exploratory model.

Table 4.10 : VIF for multicollinearity assessment.

Observed variable	VIF	Observed variable	VIF
SSA	3.763	SSMa5	3.464
SSA1	5.476	SSMa6	6.141
SSA2	4.962	SSMa7	5.654
SSA4	4.293	SSMo3	5.486
SSE	4.930	SSMo5	4.894
SSE1	7.068	SSR	6.621
SSE2	6.588	SSR1	6.038
SSE4	4.720	SSR2	6.272
SSE6	5.137	SSR5	5.650
SSE8	5.081	SSR6	4.314
SSMa2	5.971	SSWW1	5.552
SSMa4	7.056	SSWW3	6.035

In the context of Partial Least Squares Structural Equation Modeling (PLS-SEM) applied to SSB-CIEM, the assessment of indicator loadings, composite reliability (CR), and average variance extracted (AVE) indicates that all criteria are satisfactory, confirming the validity and reliability of the measurement models. Following the positive outcomes from the discriminant validity tests, which ensure the effective differentiation of constructs, the model's structural validity has been established.

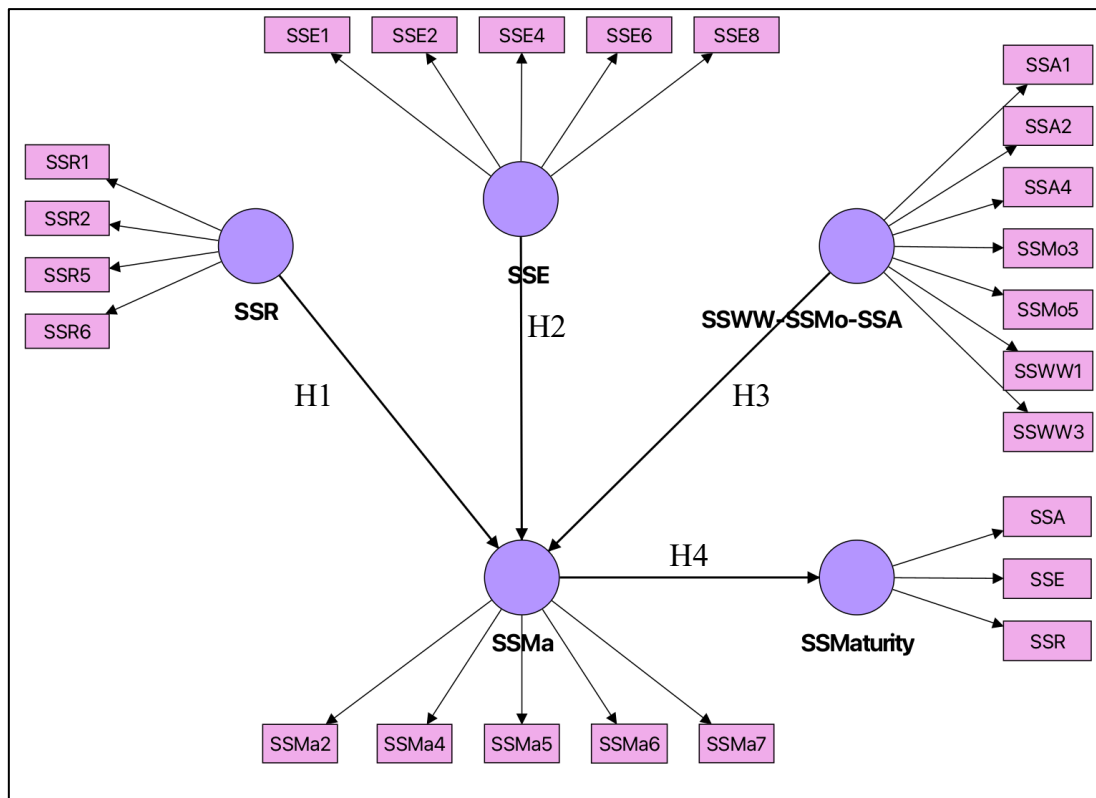


Figure 4.9 : Modified conceptual PLS-SEM.

In accordance with the modified conceptual structural equation model presented in the Figure 4.9, the following hypotheses were developed:

Hypothesis 1 (H1): The usage of BIM-GIS technologies in the area of smart sustainable resilience (SSR) among Turkish construction professionals positively impacts the integration maturity of smart sustainable management (SSMa).

Hypothesis 2 (H2): The usage of BIM-GIS technologies in the area of smart sustainable environment (SSE) among Turkish construction professionals positively impacts the integration maturity of smart sustainable management (SSMa).

Hypothesis 3 (H3): The usage of BIM-GIS technologies in the area of smart sustainable welfare-wellbeing, smart sustainable mobility, smart sustainable aesthetics

(SSWW-SSMo-SSA) among Turkish construction professionals positively impacts the integration maturity of smart sustainable management (SSMa).

Hypothesis 4 (H4): The usage of BIM-GIS technologies in the area of smart sustainable management (SSMa) among Turkish construction professionals positively impacts the general maturity to usage of BIM-GIS technologies in the area of smart sustainable maturity (SSMaturity).

4.2.2 Assessment of structural PLS-SEM for SSB-CIEM

Once the measurement model's validity and reliability have been confirmed and aligned with reference values, the next step involves evaluating the structural model. This assessment utilizes several key metrics, including the coefficient of determination (R^2), effect size (f^2), path coefficients, t-values, and validity estimates of the Q^2 values (Sakarya et al., 2023). Additionally, model fit is gauged using the Standardized Root Mean Square Residual (SRMR), Squared Euclidean Distance (d_ULS), Geodesic Distance (d_G), Chi-Square, and Normed Fit Index (NFI) values as outlined by (Sakarya et al., 2023).

4.2.2.1 Model fit values for SSB-CIEM

Unlike covariance-based structural equation modeling (CB-SEM), PLS-SEM does not necessitate a goodness-of-fit criterion for model evaluation (Sarstedt et al., 2017). Presently, there is no universally accepted standard for PLS-SEM model fit criteria. Instead, researchers predominantly consider metrics such as SRMR and NFI, rather than conventional goodness-of-fit indices like Chi-square or RMSEA (Demirel et al., 2025). Notably, the bootstrapping resampling method is often employed for enhanced reliability in results.

The SRMR quantifies the discrepancy between the observed correlation and the model's predicted correlation matrix. Henseler et al. (2014) suggest that SRMR serves as a viable goodness-of-fit criterion that aids in identifying model errors within PLS-SEM frameworks. Another relevant model fit measure is the Bentler-Bonett Index or NFI (Bentler & Bonett, 1980), which has been advocated for use alongside PLS path modeling by Lohmöller (1989). Optimal model fit is indicated by an SRMR value below the cutoff of 0.08 (Hu & Bentler, 1999) with values closer to 0 denoting better

fit. Similarly, an NFI value approaching 1 reflects superior model fit (Bentler & Bonett, 1980; Hu & Bentler, 1999).

As seen in Table 4.11, within the analysis conducted via SmartPLS for SSB-CIEM, the resultant SRMR was calculated as 0.041 and the NFI as 0.840.

Table 4.11 : Model fit results.

	Saturated model	Estimated model
SRMR	0.040	0.041
d_ULS	0.474	0.497
d_G	1.020	1.021
Chi-square	1198.339	1199.752
NFI	0.841	0.840

According to Table 4.11, the model fit metrics are not only within acceptable thresholds but also demonstrate a robust model fit, confirming the structural soundness of the evaluated model.

4.2.2.2 SSB-CIEM areas' variance interrelation degree

In a PLS-SEM model, the evaluation of relationships between observed and latent variables is critical in both the measurement models (outer models) and the structural models (inner models). The presence of multiple interrelationships among latent variables can be assessed using the Variance Inflation Factor (VIF), which indicates the extent to which the variance of a latent construct is explained by other constructs, demonstrating potential redundancy. An ideal VIF threshold is set below 5, suggesting that multicollinearity between variables is not an issue (Becker et al., 2015; J. F. Hair et al., 2011). It is important to note that VIF values may change based on the specific structure of the model and the characteristics of the data. In this study, as seen in Table 4.12, the VIF values obtained from SmartPLS 3.0 demonstrate that all values are under the threshold of 5, confirming the absence of multicollinearity among the latent variables.

Table 4.12 : Inner model multicollinearity test results.

Latent variable	VIF
SSE -> SSMa	3.873
SSMa -> SSMaturity	1.000
SSR -> SSMa	2.465
SSWW-SSMo-SSA -> SSMa	4.422

4.2.2.3 The explanatory power of the SSB-CIEM

The examination of the structural model necessitates the calculation of R^2 values for endogenous constructs, which provide insight into the model's explanatory power and predictive accuracy (Nenavath, 2025). R^2 reflects the proportion of variance in dependent variables explained by the model, with higher values indicating greater explanatory strength. According to Hair et al. (2011), R^2 values of 0.75, 0.50, and 0.25 are considered substantial, moderate, and weak, respectively.

As seen in Figure 4.10, the R^2 value for SSMa is determined to be 0.78, indicating that 78% of the variation influencing the adoption of the smart sustainable building-city integration approach by construction professionals in Türkiye using BIM/GIS technologies within the realm of smart sustainable management can be accounted for by the three latent variables (SSR, SSE, SSWW-SSMo-SSA). On the other hand, the R^2 value for SSMaturity is determined to be 0.09, indicating that 9% of the variation in SSMaturity can be accounted for by the SSMa.

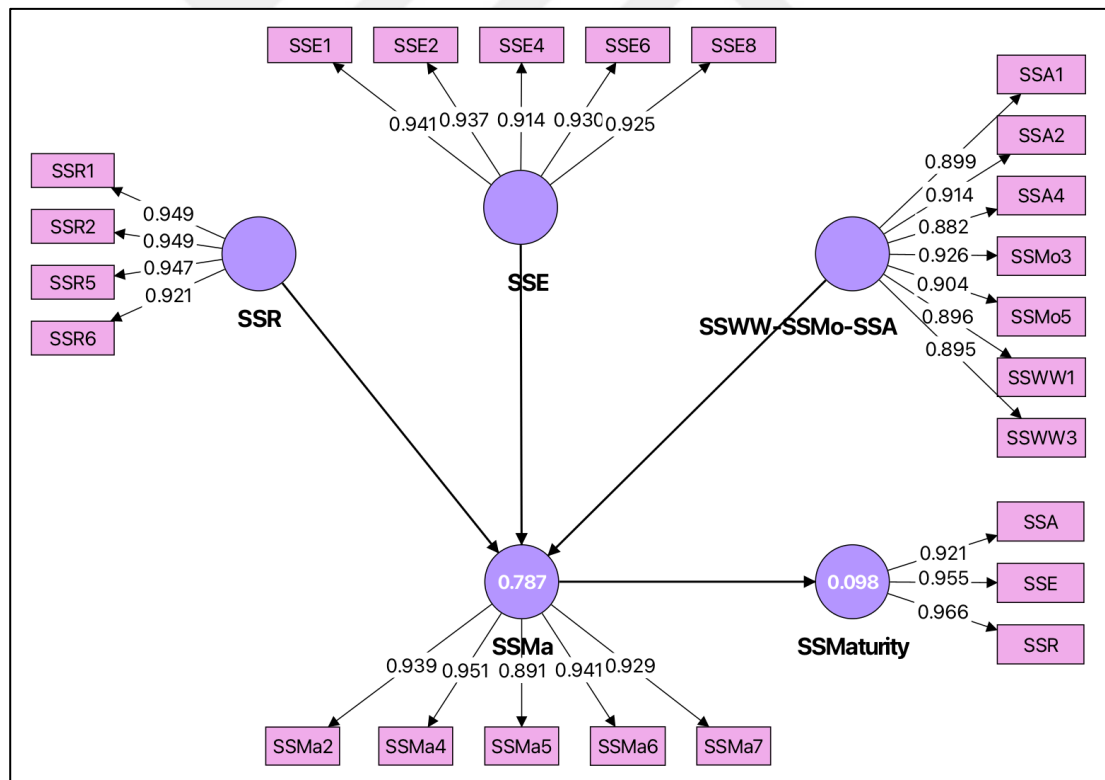


Figure 4.10 : R^2 value for structural model

4.2.2.4 Construct' effect sizes (f^2) and relevance (Q^2) in SSB-CIEM

In addition to assessing R^2 values, the f^2 (effect size) is evaluated to determine the impact of removing a particular exogenous latent variable on the R^2 of endogenous latent variables (Sakarya et al., 2023). The f^2 effect size threshold values categorize the predictive effect of a latent variable as weak ($0.02 < f^2 < 0.14$), medium ($0.15 < f^2 < 0.34$), or high ($f^2 > 0.34$) at the structural level (Cohen, 1988). This comprehensive evaluation aids in understanding the dynamics of the latent constructs and their interrelationships within the PLS-SEM framework.

The analysis reveals the following (f^2) effects for SSMA and SSMaturity as an exogenous variable:

- The effect of SSR on SSMA is very small (0.03). This implies that SSR has a minimal role in explaining the variance in SSMA, almost negligible.
- The effect of SSE on SSMA is small (0.18, slightly above 0.15). This suggests that SSE has a limited but meaningful contribution to the variance.
- The effect of SSWW-SSMo-SSA on SSMA is small (0.18). This indicates that this variable has a contribution to SSMA's variance similar to SSE, remaining within the small effect category.
- The effect of SSMA on SSMaturity is small (0.10). This indicates that SSMA contributes to SSMaturity's variance, though its impact is slightly less than that of SSE, still within the small effect range.

SSE → SSMA (0.18) and SSWW-SSMo-SSA → SSMA (0.18) have the highest f^2 values, suggesting they have a slightly greater impact on SSMA compared to the SSR.

Similarly, the Q^2 value assesses the predictive accuracy of the structural model, with values greater than 0 signifying meaningful predictive relevance. The Q^2 (predict values) values for the endogenous constructs exceed 0, confirming the model's strong predictive capability (Shmueli et al., 2016). This indicates that the model not only explains the relationships among constructs effectively but also maintains a high degree of predictive accuracy, reinforcing its robustness and reliability. According to the analysis results for SSMA ($Q^2_{\text{predict}}: 0.770 > 0$), RMSE= 0.488, and MAE=0.294; and for SSMaturity ($Q^2_{\text{predict}}: 0.086 > 0$), RMSE= 0.965, and MAE=0.741). The findings from the PLS Predict Latent Variables analysis for SSMA in the Q^2 predict

assessment are indicative of the model's strong predictive capability. The Q^2 both of two latent variables, especially for SSMA, which signifies robust predictive relevance, as values greater than 0 support the assertion that the model possesses predictive power. The validity of the model has been ensured. That is, the model predicts the latent variables (SSMA and SSMaturity) well.

Additionally, the model's performance metrics for SSMA are as follows: the Root Mean Square Error (RMSE) is recorded at 0.488, which offers insights into the average magnitude of errors in the predicted outcomes. The Mean Absolute Error (MAE) is calculated at 0.294, reflecting the average absolute discrepancies between the predicted and actual values.

Collectively, these metrics highlight that the model demonstrates commendable predictive accuracy for SSMA, characterized by a high Q^2 predict score alongside relatively low error rates. Such outcomes emphasize the model's reliability and efficacy in forecasting.

4.2.2.5 Test of SSB-CIEM hypotheses and path coefficients

In the context of Partial Least Squares Structural Equation Modeling (PLS-SEM), path analysis is vital for examining hypotheses established within the structural model framework. According to Sakarya et al. (2023), it is advisable to employ Bootstrap confidence intervals at a 95% significance level to assess the significance of path coefficients. Additionally, p-values obtained from Bootstrap analysis using the SmartPLS program serve as a reliable means to validate the path coefficients (Avkiran & Ringle, 2018).

The values obtained from the path analysis performed using the SmartPLS program are presented in detail in Table 4.13 and visually in Figure 4.11. According to Table 4.13, hypotheses 1, 2, 3 and 4 are accepted.

Table 4.13 : Standardized estimates and hypothesis testing results.

	SSE	SSMa	SSMaturity	SSR	SSWW-SSMo-SSA
SSE		0.394			
SSMa			0.312		
SSMaturity					
SSR		0.133			
SSWW-SSMo-SSA		0.417			

The results gleaned from Figure 4.11 can be summarized as follows:

Hypothesis 1 (H1): A unit increase in smart sustainable resilience (SSR) is associated with a 0.13 unit increase in integration maturity regarding smart sustainable management (SSMa). (Supported)

Hypothesis 2 (H2): A unit increase in smart sustainable environment (SSE) correlates with a 0.39 unit increase in integration maturity in smart sustainable management (SSMa). (Supported)

Hypothesis 3 (H3): A unit increase in smart sustainable welfare-wellbeing (SSWW), smart sustainable mobility (SSMo), and smart sustainable aesthetics (SSA) results in a 0.41 unit increase in integration maturity in smart sustainable management (SSMa). (Supported)

Hypothesis 4 (H4): A unit increase in smart sustainable management (SSMa) leads to only a 0.31 unit increase in integration maturity of smart sustainable maturity (SSMaturity) (for smart sustainable environment, smart sustainable aesthetics, and smart sustainable resilience). (Supported)

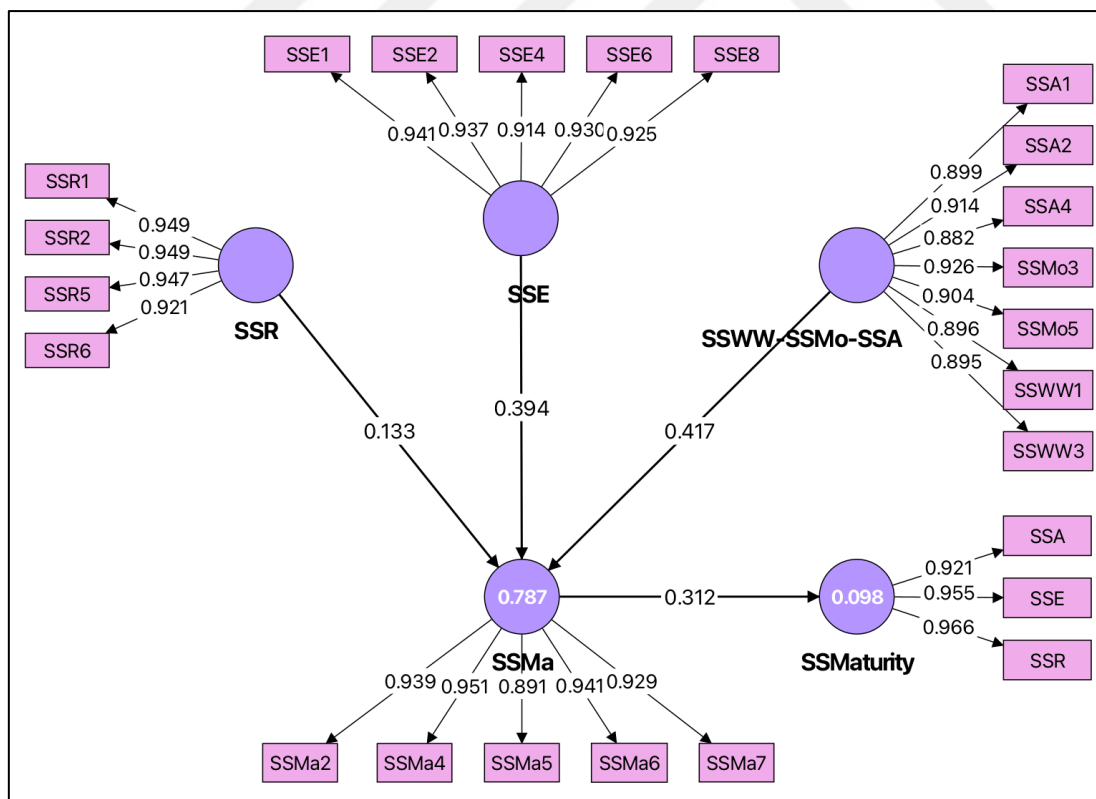


Figure 4.11 : Final PLS-SEM structural model for SSB-CIEM.

4.2.2.6 Empirical validation of smart sustainability's influence

To complete the SSB-CIEM analyses, Bootstrapping was finally performed to determine the significance of confidence intervals and PLS path modeling estimates. In the bootstrap process, random subsamples are drawn from the population (Sakarya et al., 2023). As in the studies of Sarstedt et al. (2021), Henseler et al. (2009), and, Demirel et al. (2025), 1,000 subsamples were selected. Conversely, 5,000 subsamples were selected as in the studies of Oyewobi et al.'s (2023) and Sakarya et al.'s (2023) that were considered sufficient for the main hypothesis testing.

Table 4.14 : Path coefficients for 1,000-5,000 subsamples.

Latent variable	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (O/STDEV)	P values (1000 re-samples)	P values (5000 re-samples)	Decision
SSR → SSMA	0.133	0.137	0.063	2.107	0.037	0.035	Supported
SSE → SSMA	0.394	0.375	0.133	2.959	0.003	0.003	Supported
SSWW-SSMo-SSA → SSMA	0.417	0.432	0.144	2.890	0.003	0.004	Supported
SSMA → SSMAaturity	0.312	0.313	0.054	5.746	0.000	0.000	Supported
Two tailed test, significance level: 0.05.							

In Table 4.14, the original T values, P values, and standard deviations for the path coefficients based on bootstrap analysis is evaluated:

- SSR → SSMA: The original sample has a coefficient of 0.133, with a sample mean of 0.137, a standard deviation of 0.063, a T statistic of 2.107, and a p-value of 0.035. This demonstrates a moderate and statistically significant effect of durability (SSR) on management.
- SSE → SSMA: The original sample shows a coefficient of 0.394, with a sample mean of 0.375, a standard deviation of 0.133, a T statistic of 2.959, and a p-value of 0.003. This indicates that the effect of the smart sustainable environment (SSE) on management (SSMA) is statistically significant ($p < 0.05$)
- SSWW, SSMo, SSA → SSMA: The original sample shows a coefficient of 0.417, with a sample mean of 0.432, a standard deviation of 0.144, a T statistic of 2.890, and a p-value of 0.004. This indicates that the combined effect of

well-being, mobility, and aesthetics (SSWW, SSMo, SSA) on management is significant.

- SSMA → SSMaturity: The original sample indicates a coefficient of 0.312, with a sample mean of 0.313, a standard deviation of 0.054, a T statistic of 5.746, and a p-value of 0.000. This relationship is strong and significant, evidenced by the high T statistic of 5.746.

The final bootstrapping analysis of the SSB-CIEM provides robust empirical support for the hypothesized structural relationships between smart sustainability constructs and their influence on smart sustainable management (SSMa) and integration maturity (SSMaturity). All four hypotheses were statistically supported across both 1,000 and 5,000 resampling iterations, indicating the internal stability and reliability of the model's core pathways.

These hypotheses provide critical insights into the role of BIM-GIS technologies in enhancing the integration maturity of smart sustainable management practices within the Turkish construction sector. The findings underscore the nuanced dynamics of technological adoption across diverse smart sustainability areas and their implications for holistic, data-driven urban and infrastructure planning.

Additionally, literature suggests Bootstrapping algorithm for HTMT. When HTMT Ratio is calculated with Bootstrapping, the values in Table 4.15 are obtained. Bootstrapped confidence interval of HTMT should not contain 1.0. The results once again confirm that discriminant validity is achieved.

Table 4.15 : HTMT ratio (bootstrapping).

	Original sample (O)	Sample mean (M)	2.5%	97.5%
SSMa <-> SSE	0.879	0.878	0.808	0.935
SSMaturity <-> SSE	0.307	0.306	0.183	0.419
SSMaturity <-> SSMa	0.324	0.323	0.202	0.432
SSR <-> SSE	0.748	0.748	0.624	0.852
SSR <-> SSMa	0.761	0.761	0.650	0.856
SSR <-> SSMaturity	0.235	0.236	0.094	0.366
SSWW-SSMo-SSA <-> SSE	0.889	0.888	0.804	0.948
SSWW-SSMo-SSA <-> SSMa	0.888	0.888	0.800	0.951
SSWW-SSMo-SSA <-> SSMaturity	0.311	0.310	0.187	0.417
SSWW-SSMo-SSA <-> SSR	0.792	0.793	0.690	0.880

4.3 Critical Discussion of Findings

The findings align with the BSI (2014) definition of a smart city, which emphasizes the effective integration of physical, digital, and human systems within the built environment to foster a sustainable, prosperous, and inclusive future for citizens. However, this research advances the concept by placing a stronger emphasis on the 'building' aspects of these systems within the integration process. This additional focus highlights the critical role that the architectural and infrastructural components play in achieving the overarching goals of smart city development. By prioritizing this dimension, it becomes possible to not only enhance the efficiency of urban ecosystems but also to ensure they are adaptable, resilient, and capable of addressing the diverse needs of their inhabitants.

SSR as a weak predictor (Hypothesis 1):

The findings indicate that while the SSR construct ranks as the least robust among the three evaluated constructs, it nevertheless attains statistical significance ($\beta = 0.133$). This outcome implies that, despite an established theoretical framework acknowledging the importance of resilience, its practical application within existing Building Information Modeling (BIM) and Geographic Information Systems (GIS) practices in Türkiye is still limited. Such a discrepancy may point to notable institutional or infrastructural challenges in converting the principles of resilience into effective digital workflows within this context. The indicators included in the SSR structure in the final SSB-CIEM and references to existing literature on this subject are as follows:

- Compatibility of building projects with city-specific natural disaster (fire, earthquake, flood, landslide, etc.) plans (SSR1) (Lyu et al., 2016),
- Selection of safe land/site for building location (in disaster risk areas) (SSR2) (Isikdag et al., 2008; Kumar & Bansal, 2016)
- Disaster (fire, earthquake, flood, landslide, etc.) response and emergency evacuation planning for buildings (SSR5) (Isikdag et al., 2007; Jiang et al., 2022; L. Liu et al., 2021; Rašković et al., 2020; Teo & Cho, 2016)
- Seismic vulnerability/ structural assessments of historical structures/settlements, improvement strategies, restoration or reconstruction

Works (SSR6) (Arayici, 2008; Cardinali et al., 2022; Caroti et al., 2021; Gigliarelli & Pontrandolfi, 2020; Qian & Leng, 2021; Tsilimantou et al., 2020; Yaagoubi et al., 2019).

Türkiye has faced a range of disasters in recent years, prompting both central and local governments to develop resilience plans and implement new measures. However, as demonstrated in this thesis, there is a pressing need for a more comprehensive approach to resilience planning, particularly through the integration of BIM and GIS. The detailed content analysis presented in this doctoral thesis highlights the significance of the integrated BIM/GIS applications, which are illustrated in Figure 2.15 of the literature review and outlined in Table 3.4 of the methodology chapter. It is essential to thoroughly examine these applications and undertake the necessary infrastructure developments to facilitate their implementation across Türkiye. This integrated approach can significantly enhance the nation's capacity to withstand and recover from future disasters.

SSE as a strong predictor (Hypothesis 2):

In the concluding analysis of the SSB-CIEM framework, the influence of the SSE structure is noteworthy, exhibiting a significant effect with a coefficient (β) of 0.394. The findings from the SSB-CIEM underscore the critical role of various factors in promoting smart sustainable management integration. These include the emphasis on renewable energy sources, the use of certified eco-friendly and low-carbon emission materials, the implementation of local climate-appropriate construction practices, effective management of construction and demolition waste, and robust energy management strategies. Collectively, these elements serve as essential drivers for advancing sustainability initiatives within the field. The indicators included in the SSE structure in the final SSB-CIEM and references to existing literature on this subject are as follows:

- Use of energy (electricity) produced from renewable sources (sun, wind, water, etc.) in buildings (SSE1) (Revelo Cáceres et al., 2023),
- Smart or sustainability certified (life cycle assessment has been made, low carbon emission), local (regional/micro-climate appropriate) materials in buildings (SSE2) (Bansal, 2021),

- Construction and demolition waste management (recycling or reuse) (SSE4) (Akinade et al., 2016; Mair et al., 2023; Rašković et al., 2020; Rigillo et al., 2023; Sepasgozar et al., 2021; S. Su et al., 2021),
- Management of energy required for heating, cooling, ventilation (HVAC) systems and lighting (demand management, supply, distribution, consumption, monitoring, control, etc.) (SSE6) (Göçer et al., 2015; Piras et al., 2024; H. Wang et al., 2019).

The increasing awareness and sensitivity toward the creation of smart, sustainable environments in construction and urban design projects in Türkiye is noteworthy. Recent findings indicate that there are distinct applications at both building and city scales, which may be attributed to the limited integrated utilization of BIM and GIS. To address this issue, enhancing the maturity level of integrated BIM and GIS usage is not just beneficial but essential in the current technological landscape. This integration is crucial for embedding smart and sustainable features within buildings and urban environments, as well as for establishing an effective management approach that promotes sustainability. To facilitate this transition, a comprehensive examination of existing literature on integrated BIM/GIS applications in environmental studies is necessary. Additionally, it is imperative to develop the requisite digital and physical infrastructure to support the implementation of these innovative approaches in various projects. This foundational work can significantly contribute to advancing smart sustainable management practices in the construction sector.

SSWW-SSMo-SSA as a strongest predictor (Hypothesis 3):

Among the hidden structures, the composite area encompassing Smart Sustainable Welfare-Well-being, Mobility and Aesthetics (SSWW-SSMo-SSA) showed the highest impact on management practices ($\beta = 0.417$, $p < 0.01$). These findings highlight that the more human-centered, experiential dimensions of sustainability are perceived by professionals as central to achieving integrated management. These challenges the generally technology-centered approach and supports the broader urban sustainability literature that emphasizes liveability, social equity and cultural values as key dimensions of smart integration; integrating human-centered dimensions.

The evaluation tools for smart sustainable buildings-cities, detailed extensively in the literature review (Chapter 2) and illustrated through data in the methodology section (Table 3.1, Table 3.2, and Table 3.3), emphasize the deployment of smart technologies specifically in the domains of energy efficiency and environmental design. Additionally, these tools encompass critical areas of Welfare-Well-being, Mobility, and Aesthetics. A review of the literature on integrated BIM and GIS, as presented in Table 3.4, reveals a significant focus on these same areas. The final Smart Sustainable Building-City Integration Evaluation Model (SSB-CIEM) incorporates indicators from these areas, with corresponding references from the existing literature that address the application of integrated BIM/GIS for each indicator. The indicators included in the SSWW-SSMo-SSA structure in the final SSB-CIEM and references to existing literature on this subject are as follows:

- Enhancing the quality of views from buildings by considering the urban landscape, including building layout, facade, and interior design (SSA1) (Mignard & Nicolle, 2014),
- Preventing physical deterioration, such as staining of facade claddings due to humidity and condensation, by addressing local climate characteristics (SSA2) (Sestras et al., 2020; Song et al., 2017),
- Utilizing techniques like 3D modeling and photorealistic visualization to predict how new structures will harmonize with existing surroundings, particularly in historic building restorations (SSA4) (Caroti et al., 2021; Costantino et al., 2022; Tsilimantou et al., 2020; Yaagoubi et al., 2019),
- Installing electric vehicle charging stations close to the building (SSMo3) (Schlosser et al., 2022)
- Implementing secure bike-sharing services facilitated by IoT (Internet of Things) technology (SSMo5) (Schlosser et al., 2022),
- Information related to building and urban services, including health, education, and cultural activities (SSWW1) (Mignard & Nicolle, 2014),
- Sharing air pollution data between buildings and cities (SSWW3) (Daneshfar et al., 2022; Fernández-Alvarado & Fernández-Rodríguez, 2022; Sepasgozar et al., 2019).

The final iteration of the Smart Sustainable Building-City Integration Evaluation Model (SSB-CIEM) upholds the indicators related to welfare-wellbeing, mobility, and aesthetics corroborating findings present in existing literature. As construction professionals in Türkiye enhance their utilization of integrated BIM and GIS related to these indicators, aiming for a maturity level of 5 on a scale of 1 to 5, they are likely to bolster their capabilities in smart sustainable management.

Conversely, the omission of specific indicators namely SSA3, SSMo1, SSMo2, SSMo4, SSWW2, SSWW4, and SSWW5 suggests that Turkish construction experts can adopt smart sustainable practices as secondary initiatives, following the prioritization of the retained indicators within the model. The removal of these indicators stems from an analysis of the existing landscape of construction activities in Türkiye, indicating that evaluation results may vary by country. This variability suggests that distinct priority indicators may need to be established based on regional and urban contexts, thus allowing for nuanced explanations of smart sustainable management maturity across different locales. The findings support the existing literature by revealing that the issue of the necessity for local and regional specificity in assessment tools for buildings and cities, which was highlighted in the literature review section of this doctoral thesis, cannot be ignored in assessing the smart sustainability of integrated buildings and cities.

The findings of this doctoral thesis underline the interconnectedness of the indicators associated with welfare-wellbeing, mobility, and aesthetics, which are essential components of effective smart sustainable city management. Their inclusion in the SSB-CIEM with a unified approach possibly stems from their direct relevance to individual citizens, which may yield a more pronounced impact compared to indicators focused on resilience or environmental factors. The structure of the SSB-CIEM, shaped by responses from professionals in Türkiye regarding smart sustainable building-city integration, opens avenues for the development of alternative models when these indicators are applied in other national contexts.

SSMa to SSMaturity as a strong predictor (Hypothesis 4):

The relatively high and significant coefficient from SSMa to SSMaturity ($\beta = 0.312$, $t = 5.746$) confirms that effective management practices serve as precursors to broader integration maturity. The indicators included in the SSMa structure in the final SSB-CIEM and references to existing literature on this subject are as follows:

- Automated drawing creation, including 3D model generation and documentation (SSMa2) (Abd et al., 2020; Bartoněk, 2023)
- Consideration of surrounding environments and topography in site layout planning, including temporary facilities, conflict detection, and route planning (SSMa4) (Karimi et al., 2021)
- Construction cost estimation (SSMa5) (Park et al., 2014; Wei et al., 2021)
- Management of real-time information at both micro-scale (building level) and macro-scale (city level) (SSMa6) (D. M. Azevedo et al., 2021; Farooq et al., 2017; Mignard & Nicolle, 2014; Yang et al., 2022)
- Interoperability of data acquired through digital technologies in construction, including sensors, GPS, Light Detection and Ranging (LIDAR), and unmanned aerial vehicles (UAVs)/drones by utilizing sensor data for monitoring and control processes (SSMa7) (Barazzetti et al., 2020; Celeste et al., 2022; Chen et al., 2022; Piras et al., 2024)

These findings reinforce theories of organizational learning and digital capability accumulation: as teams improve management within smart sustainability projects, they become more capable of adopting systemic, mature digital strategies.

Bootstrapped HTMT confidence intervals – validating discriminant validity:

The HTMT bootstrap results further reinforce the distinctiveness of the model's constructs. All 95% confidence intervals remained well below the threshold of 1.0, satisfying rigorous discriminant validity criteria. This lends credence to the structural clarity of the latent variables and confirms the model's conceptual soundness. Despite these promising results, several critical issues emerge.

Low R² for SSMaturity (0.09):

The low variance explained in SSMaturity suggests that while SSMA is influential, it alone is insufficient to account for maturity levels. Factors such as policy environment, organizational culture, or regulatory mandates may also significantly influence maturity but lie outside the current model's scope. This limitation invites future research to integrate macro-level institutional variables or internal organizational readiness metrics.

Multicollinearity concerns and variable reduction trade-offs:

The need to exclude certain indicators (e.g., SSA3, SSMo2, SSMA1) to satisfy discriminant validity and VIF thresholds raises questions about content representativeness. While statistical integrity was preserved, the model may have sacrificed some of its theoretical richness, particularly in constructs like aesthetics or resilience. This points to a broader challenge in balancing empirical precision with conceptual inclusiveness especially when dealing with emergent, interdisciplinary constructs like smart sustainability.

Context- specific validity (Türkiye):

While the findings are robust within the Turkish construction sector, their generalizability to other geographic or institutional contexts remains uncertain. Particularly, the relative impact of SSR might differ in countries with stronger disaster-preparedness frameworks or centralized sustainability policies.

Theoretically, the model bridges sustainability theory with digital integration practices, offering an operationalizable framework for smart sustainable transformation in the built environment.

Practically, the findings can inform capacity-building strategies in BIM-GIS adoption, emphasizing the need for not just technical training but also greater focus on human-centered design values and environmental policy compliance. Strategically, the identification of weak maturity links suggests a need for sector-wide benchmarking and incentives (e.g., public project requirements or maturity audits) to scale integrated practices beyond isolated project successes.

Model reliability and validity

As mentioned in the literature review chapter of this doctoral thesis, the reliability of smart city evaluation tools, especially those developed through multi-criteria decision-making methods, is a subject of concern. To enhance their validity, these tools must undergo comprehensive testing and validation using complementary techniques. In this context, employing the SSB-CIEM with a cohort of 215 construction professionals in Türkiye and conducting validity and reliability assessments through both basic statistical methods and Partial Least Squares Structural Equation Modeling (PLS-SEM) is significant for advancing the scholarly discourse in this field



5. CONCLUSION

Literature review

The literature on smart sustainable buildings and cities strongly supports practices that improve human well-being while tackling climate change, in line with global policies and research efforts. In recent decades, sustainability certification systems have been established for buildings, and national strategies have increasingly emphasized city-wide smart initiatives. As Stieninger (2016) argues, a building is not truly “smart” just because it includes advanced technologies; instead, it must be designed through an integrative approach that connects it with broader urban systems. This perspective underscores the critical role of integration in aligning smart buildings with the development of smart cities.

The existing literature, spanning approximately the last thirty years, has focused on evaluating and comparing sustainability and impact performance across urban environments utilizing widely recognized assessment tools. Through a thorough review of the literature, it has become evident that the potential advantages of systematically integrating smart sustainable buildings and cities have been largely understudied. However, early contributions, such as those by Conte and Monno (2012), proposed a conceptual model for a cross-scale assessment approach that promotes integration and synergy between buildings and urban systems. This model enables the assessment of a building’s performance at different scales, ranging from individual components to the whole structure.

Central to this framework is the idea of building sustainability as dynamic entities akin to living organisms within a continuously evolving urban landscape (Conte & Monno, 2012). Research by Apanaviciene et al. (2020) examines how buildings can utilize the capabilities provided by smart cities to enhance functionalities across various domains, including smart energy, smart mobility, smart living, and smart environments. Their detailed case study of nine office projects that employed smart materials and services

ultimately resulted in the proposal of smart construction features that consider the interlinked systems surrounding them.

Bi & Little (2022) advocate for a holistic, multi-scale systems-of-systems approach that marries building and urban scales to optimize performance. Despite these studies in the literature, this Ph.D. thesis identifies a model gap that emphasizes data integration through the application of digital technologies, focusing on the interaction between smart sustainable buildings and urban infrastructure throughout the building life cycle. The model proposed in this thesis differentiates itself by holistically evaluating buildings and cities rather than treating them as independent entities. This integrated evaluation model leverages Building Information Modeling (BIM) technology on a micro scale for buildings and Geographic Information Systems (GIS) technology on a macro scale for cities. A single platform that combines BIM and GIS geometric and semantic data stands out as a digital environment where the “smart sustainable management” approach can be applied for the integration of smart, sustainable building and city systems.

Methodology

This Ph.D. thesis developed a comprehensive model for evaluating smart sustainable building-city integration was developed using a mixed-methods approach (qualitative and quantitative) to achieve the determined sub-objectives. Initially, a systematic literature review (1) was conducted, incorporating both bibliometric and content analyses, with a focus on smart sustainable buildings and cities (thesis goals 1, 2). This review facilitated the identification of key intersection/integration areas and indicators essential for the Smart Sustainable Building-City Integration Evaluation Model (SSB-CIEM) (thesis goal 3). Building on this literature base, a conceptual model was articulated to elucidate the principles of smart sustainable building-city integration, detailing a systematic approach for achieving this integration across the identified areas. Additionally, a systematic literature review (2) was conducted to explore the state-of-the-art digital technologies within the construction sector, with a particular emphasis on the role of integrated BIM and GIS. This analysis also involved bibliometric and content evaluations to uncover the strengths, weaknesses, opportunities, and threats associated with the use of integrated BIM/GIS. Based on the insights gleaned from both literature reviews, specific evaluation areas and indicators tailored to the model were determined, emphasizing the potential applications of

BIM/GIS within the context of smart sustainable building-city integration. Moreover, after the second systematic literature review, a five-level integration scale was decided (thesis goal 4): 1. Data is not utilized, 2. Either BIM data or GIS data is utilized; 3. BIM data and GIS data are used separately; 4. BIM data and GIS data are used in a partially integrated manner; 5. BIM data and GIS data are fully integrated.

The literature review led to the development of the draft SSB-CIEM, which includes six distinct areas, thirty-six evaluation indicators, and a five-level integration scale (thesis goal 5) to evaluate integration effectiveness. SSB-CIEM was evaluated by 13 experts from the Ministry of Environment, Urbanization, and Climate Change, specifically from the Department of Smart City Planning, using a 5-point Likert scale. The mean scores for various areas ranged from 4.00 to 4.77, while the scores for indicators varied from 4.15 to 4.85, and the integration scale scores ranged from 4.23 to 4.77. These results indicate a consensus among the experts. Additionally, all significance values were less than 0.05, demonstrating a statistically significant agreement among the experts. Consequently, all areas and indicators derived from the literature were retained in the evaluation.

The data required for the reliability and validity analysis of SSB-CIEM was collected from professionals in the construction industry in Türkiye (thesis goal 6). A total of 215 participants from the public, private and university sectors in Türkiye focused on the use of integrated BIM/GIS in six specified areas and thirty-six indicators. Firstly, this doctoral thesis employed first generation statistical analysis techniques. The reliability analysis conducted using SPSS within the SSB-CIEM revealed a Cronbach Alpha value of 0.98. Partial Least Squares Structural Equation Modeling (PLS-SEM) was used as a secondary method to analyze the draft model. PLS-SEM was preferred for analyzing the fields and indicators in SSB-CIEM using a second-generation variance-based statistical analysis method. The reason for the preference for SSB-CIEM is that variance-based PLS-SEM works with fewer samples than covariance-based structural equation models and is a "softer" model, providing more explanatory and accurate results in exploratory studies. The objective is to identify specific factors influencing the integration of smart, sustainable buildings within smart, sustainable cities. The study particularly focuses on evaluating how integrated BIM-GIS applications in the areas of Smart Sustainable Resilience (SSR), Smart Sustainable Environment (SSE), Smart Sustainable Welfare-Wellbeing (SSWW), Smart

Sustainable Mobility (SSMo), and Smart Sustainable Aesthetics (SSA) affect integrated BIM-GIS application in Smart Sustainable Management (SSMa) and how SSMa subsequently affects Smart Sustainable Maturity (SSMaturity).

Results of the model

SSB-CIEM aims to support the decision-making processes of senior managers in public institutions responsible for managing the built environment in cities. For an integrated smart sustainable management approach to be fully embraced in urban settings, smart sustainable applications should develop in six key areas identified in this thesis, which lie at the intersection of buildings and cities: resilience, environment, management, mobility, aesthetics, welfare, and well-being.

This model stands out from other evaluation tools by focusing on the integration of buildings and urban systems through the collaborative use of BIM and GIS technologies. Tested by construction professionals in Türkiye, the model has proven applicable within the local context. However, as the maturity of integrated BIM-GIS applications and holistic smart sustainable practices improves, the model will offer even more precise and reliable measurements.

Results of findings and analysis

The first analysis in this doctoral thesis employed the first-generation statistical analysis techniques. As indicated by normality tests, since it is assumed that the collected data are not normally distributed, the data were analyzed using the One-Sample Wilcoxon Signed-Rank Test via SPSS. While the hypothetical median across all areas and indicators was set at 4, the observed median was significantly lower, recorded at 2 for the indicator SSMa2 (indicating the utilization of either BIM or GIS data) and 1 for all other areas and indicators, suggesting a lack of data utilization. The result of the One-Sample Wilcoxon Signed Rank Test was significant at $p < .001$, leading to the rejection of the null hypothesis. This indicates a substantial deficiency in the integration and application of BIM/GIS data within the sector.

Kruskal-Wallis One-Way ANOVA test was used to evaluate the responses of professionals in the public, private, and university sectors of the construction industry to the SSB-CIEM. The results indicated that for the overall maturity assessments across the six main areas (SSR, SSE, SSMa, SSA, SSMo, and SSWW), the sigma value exceeded the 0.05 significance threshold, leading to the acceptance of the null

hypothesis. This outcome suggests that there are no significant differences in maturity status among the three sub-sectors at the aggregate level.

A nuanced examination at the indicator level revealed the rejection of the null hypothesis for specific indicators linked to SSR, SSMo, and SSWW (particularly SSR1 through SSR6, SSMo1, SSMo5, SSWW1, and SSWW3). This finding highlights notable variations in median scores for these indicators, thus illustrating disparities in readiness assessments among professionals in the six areas compared to their evaluations at a more granular indicator level. According to the SSB-CIEM data, construction sector professionals in Türkiye tend to rate their overall maturity on a 5-point Likert scale with a median score of 3 at the area level. This assessment is more favorable than at the indicator level, indicating a discrepancy between perceived readiness and actual conditions observed in practical applications as posited by the model.

The Mann-Whitney U Test was employed to evaluate the differences in perceptions between construction sector professionals in the public and private sectors regarding their readiness to implement BIM-GIS technologies. Areas (SSR (0.222), SSE (0.188), SSMa (0.173), SSA (0.209), SSMo (0.918), SSWW (0.774)) all have Sig. > 0.05, so H₀ is accepted, indicating no significant difference between the public and private sectors at area level (maturity). In the indicator level analysis, while the disparities in mean ranks were slight, the findings consistently showed that public sector professionals reported higher mean ranks across all thirty-six evaluated indicators.

On the other hand, following indicators: SSE3 (0.061), SSE5 (0.227), SSE6 (0.558), SSE7 (0.275), SSMa1 (0.177), SSMa2 (0.584), SSMa3 (0.262), SSMa4 (0.055), SSMa5 (0.742), SSMa6 (0.056), SSMa7 (0.111), SSA1 (0.459), SSA2 (0.455), SSA3 (0.352), SSA4 (0.326), SSA5 (0.192), SSMo2 (0.082), SSMo4 (0.054), SSWW4 (0.084) have Sig. > 0.05, accepting H₀, suggesting no significant difference between public and private sectors. Conversely, SSE4 (0.015), SSE8 (0.049), SSR1 (0.019), SSR2 (0.013), SSR3 (0.018), SSR4 (0.004), SSR5 (0.015), SSR6 (0.006), SSMo1 (0.025), SSMo3 (0.043), SSMo5 (0.021), SSWW1 (0.020), SSWW3 (0.005), SSWW5 (0.041) have Sig. ≤ 0.05, rejecting H₀, indicating a significant difference between the public and private sectors.

The analysis indicated that professionals in the public sector perceived themselves as more ready at utilizing these technologies across thirty-six key indicators when compared to their private sector colleagues. This inclination towards greater readiness suggests that practitioners in the public sector are more favorably disposed to embrace an integrated BIM-GIS approach, particularly in the context of initiatives aimed at fostering smart sustainable building-city integration.

The second analysis in this doctoral thesis employed the PLS-SEM method to develop the theoretical model. In PLS-SEM, latent variables were combined to prepare a model suitable for the threshold values in the literature and to increase the clarity and efficiency of SSB-CIEM. The constructs related to Smart Sustainable Welfare and Well-being (SSWW), Smart Sustainable Aesthetics (SSA), and Smart Sustainable Mobility (SSMo) were integrated into a single construct. The necessity of this aggregation arose from the fact that the data collected for these areas yielded similar results despite their independent indicators. The final structural model comprises three independent variables, SSR, SSE, and the combined SSWW-SSA-SSMo, as well as two dependent variables, SSMA and SSMaturity. As a result, the revised model focuses on the factors that affect and explain managerial maturity in smart sustainable cities by evaluating the use of integrated BIM and GIS by construction industry professionals in Türkiye. In terms of observed variables, no more indicators were removed; the HTMT value fell below the specified threshold of 0.90. The final SSB-CIEM is a comprehensive model comprising 24 indicators, manifest variables, and observed variables, covering five separate latent variables/constructs. In this model, all indicators exhibit strong outer loading values and thus effectively capture the underlying constructs to which they are associated. The six initially proposed hypotheses were modified and reduced to four hypotheses by removing observed variables and combining latent variables. Hypotheses H3, H4, and H5 were combined and established as a single hypothesis, and the modified model was reanalyzed. The model built on modified H1, H2, H3, and H4 was reanalyzed. In the final model, the hypotheses are as follows: Hypothesis 1 (H1): The usage of BIM-GIS technologies in the area of smart sustainable resilience (SSR) among Turkish construction professionals positively impacts the integration maturity of smart sustainable management (SSMA). Hypothesis 2 (H2): The usage of BIM-GIS technologies in the area of smart sustainable environment (SSE) among Turkish construction

professionals positively impacts the integration maturity of smart sustainable management (SSMa). Hypothesis 3 (H3): The usage of BIM-GIS technologies in the area of smart sustainable welfare-wellbeing, smart sustainable mobility, smart sustainable aesthetics (SSWW-SSMo-SSA) among Turkish construction professionals positively impacts the integration maturity of smart sustainable management (SSMa). Hypothesis 4 (H4): The usage of BIM-GIS technologies in the area of smart sustainable management (SSMa) among Turkish construction professionals positively impacts the general maturity to usage of BIM-GIS technologies in the area of smart sustainable maturity (SSMaturity).

SSB-CIEM, which has been evaluated for reliability and validity using the PLS-SEM model, provides insights into the level of integration between smart sustainable buildings and cities in Türkiye based on data. In the model, all Cronbach's alpha values (0.96, 0.96, 0.94, 0.95, and 0.96) exceed 0.70, and all AVE values (0.86, 0.86, 0.89, 0.88, and 0.81) exceed 0.50. Moreover, the model has a perfect fit, with an SRMR value of 0.04 and an NFI value of 0.84.

The findings support the hypotheses (H1, H2, and H3) that the external latent variables (SSR, SSE, SSWW-SSA-SSMo) obtained through the PLS-SEM method affect SSMa and that SSMa, in turn, has an impact on SSMaturity. Among the external variables, SSMa is most strongly influenced by SSWW-SSA-SSMo (H3), which has the highest path coefficient of 0.41 compared to the other variables. This indicates that integrating aspects of smart sustainable welfare-wellbeing, smart sustainable mobility, and smart sustainable aesthetics into administrative processes is critical for Türkiye.

The combined SSWW-SSMo-SSA dimension emerges as a pivotal construct in shaping management practices, emphasizing the critical need to prioritize user well-being, inclusive mobility, and environmental aesthetics in the context of urban digital transformation. This dimension underlines that the implementation of BIM-GIS technologies extends beyond mere technical efficiency; it necessitates a deep alignment with the lived experiences, comfort, and social equity of urban populations. By embedding these human-centered dimensions into the framework, the model advocates for a comprehensive and socially responsive approach to sustainability within the built environment, ultimately fostering urban spaces that are equitable and attuned to the needs of their communities.

The effect of SSMA on SSMaturity is also notable (H4), with a medium-level path coefficient of 0.31. However, analyses conducted using the one-sample rank test show that respondents rated maturity higher than the average of their answers to the indicators, which may have diminished the explanatory power despite the strong effect of SSMA on SSMaturity. The low R^2 value of maturity (0.09) suggests that other factors may also influence maturity.

The Smart Sustainable Environment (SSE) has an indirect but strong impact on Smart Sustainable Maturity, with a high path coefficient of 0.39. It also contributes to Smart Sustainable Management with a moderate effect. In comparison, Smart Sustainable Resilience (SSR) has the weakest relationship with Smart Sustainable Management, showing a much lower path coefficient of 0.13. However, the analysis still confirms that SSR has a statistically significant effect.

In examining the relationship between management, as indicated by SSMA, and maturity (SSMaturity), the analysis reveals a theoretical weakness, evidenced by a coefficient of 0.09. However, the empirical findings from the bootstrap results, which show a value of 0.31 with a T-statistic of 5.74, suggest a stronger relational dynamic than initially indicated. This indicates a complex interplay in which theoretical constructs may not fully capture the strength of empirical relationships within the studied context. This finding is expected, especially in countries with a low maturity level in integrated BIM-GIS use. Additionally, (H2) the influence of environmental factors (SSE) and (H3) multidimensional factors (including SSWW, SSMo, and SSA) reinforces the foundational dynamics of the system, highlighting their significant role in shaping management outcomes. Nevertheless, since the p-values of the path coefficients for all exogenous latent variables were less than 0.05, the structural relationships of the model were deemed reliable, and all four established hypotheses were supported. Hypothesis 1 (H1): A unit increase in smart sustainable resilience is associated with a 0.13 unit increase in integration maturity regarding smart sustainable management (Supported); Hypothesis 2 (H2): A unit increase in smart sustainable environment correlates with a 0.39 unit increase in integration maturity in smart sustainable management (Supported); Hypothesis 3 (H3): A unit increase in smart sustainable welfare-wellbeing, smart sustainable mobility, and smart sustainable aesthetics results in a 0.41 unit increase in integration maturity in smart sustainable management (Supported); Hypothesis 4 (H4): A unit increase in smart sustainable

management leads to a 0.31 unit increase in integration maturity of smart sustainable maturity (for smart sustainable environment, smart sustainable aesthetics, and smart sustainable resilience) (Supported).

These findings not only validate the structural soundness of the SSB-CIEM but also reveal the nuanced dynamics between management practices and maturity in smart sustainable integration. While theoretical expectations may initially underestimate these relationships, empirical evidence underscores the transformative role of multidimensional factors particularly in environments where BIM-GIS adoption is still evolving. These insights reinforce the importance of context-aware modeling and highlight the need for continued empirical validation to guide strategic decision-making and policy development in smart sustainable urban frameworks.

Integration of BIM and GIS offers a transformative strategy for smart cities and effective construction management. When the use of integrated BIM-GIS within the relationships defined in PLS-SEM is examined, it is evident that the effectiveness of the indicators in the SSMA framework, shaped by the exogenous latent variables, is significantly increased. The final PLS-SEM identifies several Smart Sustainable Environment (SSE) indicators: the use of renewable energy (SSE1), the use of smart or sustainable certified materials (SSE2), waste management (SSE4), energy efficiency (SSE6), and wastewater management (SSE8). Integrated BIM-GIS enhances the SSMA framework by providing building energy simulations and optimizing geographic-based renewable resources to support these SSE indicators. For example, BIM can model energy consumption throughout a building's life cycle or facilitate building-based waste management planning. GIS can consolidate city electrical infrastructure data with semantic and geometric information on a single platform or improve waste management plans using geographic data. To illustrate further, BIM enables the integration of electrical data from building systems with broader city management systems, while GIS enhances data visualization, performance analysis, and strategic site selection using a bottom-up management approach with smart microgrids. This integration ultimately supports sustainable environmental management coherently and efficiently.

SSWW (Smart Sustainable Wellbeing), SSMo (Smart Sustainable Mobility), and SSA (Smart Sustainable Aesthetics) are key indicators used in urban planning and development. These include building design (SSA1), preventing physical deterioration

(SSA2), and utilizing 3D modeling and photorealistic visualization for restoration (SSA4). For mobility, this involves electric vehicle charging stations (SSMo3), bike-sharing services (SSMo5), and urban services information (SSW1) for welfare and wellbeing. Additionally, it includes sharing air pollution data (SSW3).

BIM-GIS integrates these indicators within building design and spatial data analysis. For instance, while GIS can create city air quality maps (SSW3), BIM offers design recommendations for enhancing mobility infrastructure (SSMo3) and aesthetic improvements (SSA4). This integration supports smart sustainable management (SSMa) through a user-centric and multi-dimensional approach.

The indicators of SSMa can be summarized as follows: automated drawing creation, 3D model generation, and documentation (SSMa2); incorporating the surrounding environment and topography in site layout planning (SSMa4); cost estimation (SSMa5); and providing real-time information at both building and city levels (SSMa6). Additionally, SSMa emphasizes the interoperability of data and sensor data for monitoring and control processes (SSMa7). To fulfill the criteria of the smart sustainable management approach (SSMa) in local governments (municipalities), a transition to a common and integrated BIM/GIS platform is necessary.

To illustrate the impact of the SSWW-SSMo-SSA structure on SSMa, the use of integrated BIM/GIS in air pollution data sharing, which positively increases the maturity of real-time information sharing, can be given as an example (SSMa6). Similarly, integrating BIM/GIS for establishing electric vehicle charging stations near buildings (SSMo3) benefits the interoperability of data, sensor data monitoring, and control processes (SSMa7), as well as cost estimation (SSMa5), thereby contributing to effective smart sustainable management.

The Smart Sustainable Resilience (SSR) indicators cover key resilience-focused aspects such as aligning building projects with city plans (SSR1), selecting safe sites (SSR2), planning for disaster response and emergency evacuation (SSR5), and assessing the seismic vulnerability of historic structures (SSR6). While integrated BIM-GIS technologies have the potential to support these strategies through disaster risk mapping and seismic simulations, the very low path coefficient in the PLS-SEM analysis (0.133) indicates that their current impact on Smart Sustainable Management (SSMa) is limited. A municipality can enhance resilience by integrating BIM and GIS

to map seismic risks, assess building safety, and plan safe evacuation routes aligned with urban development policies.

SSMaturity is primarily influenced by SSMA, an endogenous latent variable. SSMA has a strong effect on SSMaturity (0.312), highlighting the potential of BIM-GIS to enhance managerial processes. However, the relatively low impact of SSR (0.133) suggests that resilience strategies should be more thoroughly integrated with BIM-GIS. These findings indicate that BIM-GIS can serve as a strategic tool to enhance systemic maturity in smart cities, ultimately leading to the development of more sustainable urban systems by optimizing the indicators that support SSMA.

The significant path coefficient from SSMA to SSMaturity (0.312, $T = 5.746$, $p < 0.001$) highlights the potential of BIM-GIS to improve real-time data management (SSMA6) and real-time logistics monitoring and simulation in supply chain management (SSMA3) within construction workflows. This integration enables the development of 3D models and documentation (Ma2) by utilizing BIM, while GIS provides the spatial context necessary for site layout planning and resilience strategies, including disaster-specific plans (SSR1) and seismic improvements (SSR6).

Additionally, the strong influence of SSE on SSMA (0.394, $T = 2.959$, $p = 0.003$) emphasizes the role of BIM-GIS in enhancing energy efficiency and waste management through the integration of spatial and lifecycle data. Moreover, the contribution of SSWW-SSMo-SSA to SSMA (0.417, $T = 2.890$, $p = 0.004$) suggests that BIM-GIS can support in facade design, improve mobility infrastructure, and facilitate welfare-wellbeing data sharing, promoting a comprehensive approach to smart construction and urban development.

Furthermore, the significant impact of SSE on SSMA underscores the need to incorporate environmental sustainability measures, including the use of renewable energy (SSE1) and smart building certifications (SSE2), into urban governance frameworks. Improvements in (SSWW), (SSMo), and (SSA) have a positive impact on SSMA, indicating that managers should utilize BIM-GIS to implement mobility solutions (e.g., SSMo3) and welfare-wellbeing enhancing initiatives (e.g., SSW1) to improve system maturity.

While the influence of SSR on SSMA is relatively weak, it highlights the importance of strengthening resilience strategies. These strategies should include the compatibility

of disaster plans (SSR1), safe land selection (SSR2), disaster response systems (SSR5), and the restoration or reconstruction of historical structures, all of which can be enhanced through BIM-GIS applications to ensure comprehensive urban resilience.

Given that Türkiye is prone to significant earthquakes due to its numerous fault lines, it is essential to establish smart sustainable resilience (SSR) criteria using integrated BIM/GIS. Improving SSR positively impacts SSMA while increasing resilience from the building level to the urban scale.

Theoretically, the divergence between the graphical SSMA $\rightarrow$ SSMA maturity coefficient (0.09) and the empirical estimate (0.31, $T = 5.74$, $p = 0.000$) suggests a need to refine existing theoretical models of smart city maturity, particularly by accounting for the dynamic interplay of management practices facilitated by BIM-GIS. This study extends the theoretical framework by validating the interconnected effects of SSE (0.39), SSWW-SSMo-SSA (0.41), and SSR (0.133) on SSMA, providing a basis for future research into the scalability of BIM-GIS applications. In practice, the results argue that the widespread adoption of integrated BIM-GIS tools in the areas of energy efficiency and use of waste management (recycling and reuse), renewable energy, certified materials, wastewater management (SSE1, SSE2, SSE 4, SSE6, SSE8) and aesthetic integration (SSA1, SSA2 and SSA4) is particularly effective in increasing the maturity of real-time monitoring (SSMA6). The moderate SSR influence (0.13) implies that practitioners should conduct regular resilience assessments using integrated BIM-GIS to align with theoretical expectations.

The research revealed that although a large number of professionals claimed familiarity with BIM and GIS technologies, actual usage particularly their integration for smart and sustainable urban planning remains very limited. This gap between familiarity and real-world application points to a major weakness in digital maturity. When comparing the public, private, and academic sectors, the study found no significant differences in overall maturity scores across these groups. However, deeper analysis at the indicator level showed meaningful differences in specific areas. Notably, public sector professionals consistently reported higher levels of readiness across all indicators, suggesting that they are more prepared and willing to adopt integrated BIM-GIS solutions than their counterparts in the private sector.

Among the different factors evaluated, environmental sustainability and mobility-related indicators had the strongest positive influence on smart sustainable management. Elements like renewable energy use, waste management, air quality monitoring, and electric mobility stood out as key drivers of maturity. In contrast, resilience-related indicators such as disaster planning and seismic safety had the weakest influence, indicating that current BIM-GIS applications are not yet effectively supporting disaster risk management. Importantly, the study confirmed that effective smart management practices enabled by BIM-GIS integration directly contribute to higher levels of maturity. Overall, the findings highlight that Türkiye's construction sector is still at an early stage of BIM-GIS adoption, and to move forward, municipalities and industry leaders must invest in training, technological infrastructure, and policy frameworks that support integrated digital solutions.

Limitations

SSB-CIEM emphasizes the use of the latest information and communication technologies currently applied in developed countries throughout the project lifecycle, including planning, construction, operation, and demolition, while being sensitive to environmental considerations and prioritizing human welfare. The digital technologies examined in this thesis evolve rapidly, and researchers and industry leaders continuously introduce new innovations particularly in artificial intelligence (AI) that expand and redefine the capabilities of those highlighted in the model.

The study focused on construction professionals only in Türkiye who are knowledgeable about smart sustainable building and city concepts, as well as BIM-GIS technologies. However, both smart sustainable building-city projects and the application of integrated BIM-GIS digital technologies remain underdeveloped in Türkiye, as is the case in many other countries. Although approximately 70% of participants reported familiarity with BIM (69.8%) and GIS (68.8%), this indicates a significant gap in digital competency, as nearly one-third of professionals remain unfamiliar with these foundational technologies highlighting a critical weakness in the sector's readiness for smart sustainable integration. The lack of maturity in BIM/GIS utilization has hindered the effective evaluation of smart sustainable building-city integration. There are a limited number of professionals who can implement these concepts and technologies at an intermediate or advanced level, and the absence of a

comprehensive database of these experts restricts the applicability of the study's findings to the broader group of construction professionals in Türkiye.

Future studies

For universities, it is crucial to organize training sessions, conferences, and similar events to promote the adoption of BIM and GIS. Additionally, practical courses on the integrated use of BIM and GIS should take part in the curriculum. To governments, regulations and standards, along with their usage, should be made mandatory. Training and certification programs, as well as national standards, are crucial for effective BIM/GIS utilization. Furthermore, financial incentives play a crucial role in the adoption of these technologies. Likewise, credit supports and other facilitative state-supported approaches, such as those incorporating smart and sustainable criteria, can take integration to higher levels. To the firms (private sector), companies should regularly provide training to their employees on the use of integrated BIM/GIS. Investors should consider investing in the adoption of digital construction technologies in offices and construction sites. Administrations in municipalities should add articles regarding the use of integrated BIM/GIS in the technical specifications of construction projects. Architects, engineers, and urban planners in municipalities receive training on the integrated use of BIM/GIS. Additionally, municipalities can enhance their BIM/GIS infrastructures. Establishing common digital standard work environments across both public and private sectors in BIM/GIS use supports a smart and sustainable management approach.

Further studies can compare the situation in Türkiye with that of other countries by applying the prepared model to nations that are relatively more advanced and pioneering in smart city applications and the integrated use of BIM-GIS technologies. This comparison can help identify the areas and indicators that require development for effective integrated smart sustainable building-city integration in cities. Examples of advanced digital and physical infrastructures in buildings and cities can serve as benchmarks for achieving higher maturity levels in the areas and indicators outlined in the SSB-CIEM. By analyzing these examples, it will be possible to determine the necessary steps and priorities for improvement.

This underscores that the indicators established for smart sustainable building-city integration are currently at low maturity levels for Türkiye. The low average of the

responses indicated that the different indicators measure similar structures, which led to the removal of numerous indicators from the model. In future studies, the indicators can be tailored to reflect local characteristics relevant to the specific context of the evaluated city.

The strong influence of SS_{Ma} on SS_{Maturity}, despite a lower theoretical estimate, suggests that city managers should prioritize the implementation of integrated BIM/GIS to enhance smart sustainable management practices for smart sustainable cities. The PLS-SEM analysis results of SSB-CIEM offer crucial insights for managing smart sustainable cities. Moreover, the findings of this doctoral thesis open the door for future research to explore additional parameters in determining the impact of construction professionals in Türkiye's use of integrated BIM/GIS technologies in five key areas (smart sustainable resilience, smart sustainable environment, smart sustainable aesthetics, smart sustainable mobility, and smart sustainable welfare and wellbeing) of smart sustainable management. The SSB-CIEM framework actively bridges the gap between academic models and real-world applications by integrating cross-scale, data-driven insights and artificial intelligence. This approach accelerates the maturity of smart and sustainable urban systems via better organizations by enabling adaptive, predictive, and scalable solutions across building and city infrastructure.



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APPENDICES

APPENDIX A: Ethics committee approval

Istanbul Technical University Social and Human Sciences Scientific Research and Publication Ethics Committee, evaluation result (project no: 565, dated November 4, 2024).

İSTANBUL TEKNİK ÜNİVERSİTESİ
SOSYAL VE BEŞERİ BİLİMLER BİLİMSSEL ARAŞTIRMA VE YAYIN ETİĞİ KURULU
DEĞERLENDİRME SONUCU

PROJE NUMARASI: 565

TARİH: 04/11/2024

1	Projenin Adı ve Yürütücüsü: Türkiye’de İnşaat Profesyonellerinin Yapı Bilgi Modellemesi (YBM/BIM) ve Coğrafi Bilgi Sistemi (CBS/GIS) Teknolojilerini Kabullerinin ve Kullanımlarının Ölçülmesi; Akıllı Sürdürülebilir Bina-Şehir Bütünleşmesine Hazırlıklarının Değerlendirilmesi Prof. Hüsnü Murat Günaydın Fatma Handan Sarıgül
2.	Projenin Amacı (azami 100 kelime) : Amaç 1: Araştırma ile, Türkiye’de inşaat profesyonellerinin (kamu, özel, akademi) ve bu alandaki öğrencilerin Yapı Bilgi Modellemesi (YBM/BIM) teknolojisini kabullerinin ve kullanımlarının ölçülmesi amaçlanmaktadır. Bunun yanı sıra, katılımcılardan YBM ile ilgili mevcut bilgi düzeyleri ve YBM’nin sunduğu fırsatlardan hangi ölçüde yararlandıklarını değerlendirmeleri beklenir. Sorulara verilen cevaplar bilimsel çalışma (doktora tezi ve doktora tezinden üretilen makale) için kullanılacaktır. Amaç 2: Araştırma ile, Türkiye’de inşaat profesyonellerinin (kamu, özel, akademi) ve bu alandaki öğrencilerin Coğrafi Bilgi Sistemi (CBS/GIS) teknolojisini kabullerinin ve kullanımlarının ölçülmesi amaçlanmaktadır. Bunun yanı sıra, katılımcılardan CBS ile ilgili mevcut bilgi düzeyleri ve CBS’nin sunduğu fırsatlardan hangi ölçüde yararlandıklarını değerlendirmeleri beklenir. Sorulara verilen cevaplar bilimsel çalışma (doktora tezi ve doktora tezinden üretilen makale) için kullanılacaktır. Amaç 3: Araştırma ile, Türkiye’de inşaat profesyonellerinin Akıllı Sürdürülebilir Bina-Şehir Bütünleşmesine Hazırlıklarının Değerlendirilmesi amaçlanmaktadır. Sorular, Akıllı Sürdürülebilir Bina-Şehir Bütünleşmesine psikolojik hazırlık, şehirde ve çalışma ortamında fiziksel altyapı ve dijital altyapının var olması bağlamlarındaki değerlendirmeleri kapsamaktadır. Araştırmada dijital altyapı/ teknolojiler, bütünleşmede öne çıkan iki temel teknoloji YBM (yapı bilgi modellemesi) ve CBS (coğrafi bilgi sistemi) odağında, inşaatta kullanılan dijital teknolojiler göz önünde bulundurulacak şekilde sınırlandırılmıştır. Sorulara verilen cevaplar bilimsel çalışma (doktora tezi ve doktora tezinden üretilen makale) için kullanılacaktır.
3.	Projenin Yöntemi (azami 100 kelime) : Yöntem 1: Araştırma yöntemini, Birleşik Teknolojinin Kabulü ve Kullanımı Teorisi, (The Unified Theory of Acceptance and Usage of Technology 2/UTAUT 2)’den uyarlanan ve içerikleri YBM ile ilgili literatürden yararlanılarak hazırlanan anketin uygulanması oluşturur. Anket, Türkiye’de inşaat sektörü çalışanlarının ve öğrencilerin (kamu, özel, akademi) YBM teknolojisini kabullerini ve kullanımlarını ölçmek amacıyla bakanlıklar, il müdürlükleri, özel proje/inşaat ofisleri, belediyeler, üniversiteler ve diğer kamu kurum ve kuruluşlarının inşaat ile ilgili birimlerine uygulanacaktır. Sorulara verilecek cevapların türü çoktan seçmeli, onay kutuları ve kısa yanıtlardan oluşmaktadır. Yöntem 2: Araştırma yöntemini, Birleşik Teknolojinin Kabulü ve Kullanımı Teorisi, (The Unified Theory of Acceptance and Usage of Technology 2/UTAUT 2)’den uyarlanan ve içerikleri CBS ile ilgili literatürden yararlanılarak hazırlanan anketin uygulanması oluşturur. Anket, Türkiye’de inşaat sektörü çalışanlarının ve öğrencilerin (kamu, özel, akademi) CBS teknolojisini kabullerini ve kullanımlarını ölçmek amacıyla bakanlıklar, il müdürlükleri, özel proje/inşaat ofisleri, belediyeler, üniversiteler ve diğer kamu kurum ve kuruluşlarının inşaat ile ilgili birimlerine uygulanacaktır. Sorulara verilecek cevapların türü çoktan seçmeli, onay kutuları ve kısa yanıtlardan oluşmaktadır. Yöntem 3: Araştırma yöntemini, literatürün gözden geçirilmesi ile belirlenen, akıllı sürdürülebilir bina- şehir bütünleşme alanlarına ve göstergelerine ait sorulardan oluşan anketin, Türkiye’deki inşaat profesyonellerine uygulanması oluşturur. Anket kapsamında, Birleşik Teknolojinin Kabulü ve Kullanımı Teorisi, (The Unified Theory of Acceptance and Usage of Technology 2/UTAUT 2)’den uyarlanarak hazırlanmış anket soruları ile inşaat profesyonellerinin, Akıllı Sürdürülebilir Bina-Şehir Bütünleşmesi için gerekli olan, inşaatta kullanılan dijital teknolojileri kabul ve kullanımlarının ölçülmesi bölümü de yer alır.

Figure A.1: Ethics committee approval.

APPENDIX A (continued) : Ethics committee approval

xProje değerlendirilmiş ve etik açıdan uygun BULUNMUŞTUR.

☐Proje değerlendirilmiş ve etik açıdan uygun BULUNMAMIŞTIR.

☐Proje değerlendirilmiş ve etik kurul belgesine GEREK DUYULMAMIŞTIR.

Projenin Adı ve Yürütücüsü:

TARİH: 04/11/2024

Türkiye'de İnşaat Profesyonellerinin Yapı Bilgi Modellemesi (YBM/BIM) ve Coğrafi Bilgi Sistemi (CBS/GIS) Teknolojilerini Kabullerinin ve Kullanımlarının Ölçülmesi; Akıllı Sürdürülebilir Bina-Şehir Bütünleşmesine Hazırlıklarının Değerlendirilmesi
Prof. Hüsnü Murat Günaydın
Fatma Handan Sarıgül

Figure A.1 (continued) : Ethics committee approval.



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PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:

- **Sarigul, F. H., & Gunaydin, H. M.** 2025. Integrated BIM, GIS and interoperable digital technologies in lifecycle management of building construction projects: Systematic literature review. *Smart and Sustainable Built Environment, Ahead of Print* (Ahead of Print). <https://doi.org/10.1108/SASBE-08-2024-0312>.
- **Sarıgül, F. H., & Günaydın, H. M.** 2025. A systematic evaluation approach for integrating smart sustainable buildings and cities. *AIZ ITU Journal of the Faculty of the Architecture*, 22(2), 465–491. <https://doi.org/10.58278/0.2025.96>.
- **Sarigul, F. H., Gunaydin, H. M.** (2022). Evaluation of Smart Sustainable Building-City Integration Level: An Analysis for Criteria in Building-City Intersection. *7th International Project and Construction Management Conference (IPCMC2022)*, Yıldız Technical University, İstanbul, Türkiye, 20-22 October.

OTHER PUBLICATIONS, PRESENTATIONS AND PATENTS:

- **Sarigul, F. H., & Arslan Selcuk, S.** 2019. Certification for Sustainability: An Assessment on Design and Construction Process of Via Green Office Building, 4. International Sustainable Buildings Symposium (ISBS 2019) Dallas/USA. (Author and oral presentation)

- **Sarıgöl, F. H., & Arslan Selçuk, S.** 2016. Kentsel Dönüşüm Projeleri ve Sertifika Sistemleri: Kuzey Ankara Girişi Kentsel Dönüşüm Projesi Üzerine Bir Değerlendirme. 1.Ulusal Kent Estetiği Sempozyumu, 25-27 Mayıs 2016/Samsun, Samsun Büyükşehir Belediyesi Kültür Yayınları No:29, 255-278. (Author and oral presentation)

