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Supply Chain Digital Twins for Modular Timber Construction: Monitoring Durability and Circular Reuse

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ABSTRACT

The shift towards sustainable and circular building systems has placed modular timber systems in the limelight as an alternative with lower carbon footprints. Nevertheless, the durability of the used material and the efficiency of the reuse cycle are factors that are now significantly impacted by digitalization. In the investigation described in this article, the influence of overall Supply Chain Digital Twin maturity and overall Supply Chain Responsiveness on Timber Durability and the overall Reuse Potential of Timber in the emerging modular timber buildings in Jordan was investigated. In the research design adopted for the quantitative approach, using Python software for the analysis of the results of the survey

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conducted using the questionnaire administered to 131 respondents in the industry. The results showed that DTM had a remarkably positive effect on TD (β = 0.43, $p < 0.001$) and CRP (β = 0.57, $p < 0.001$), accounting for 35% and 49% variance, respectively. SCR partially mediated the relation between DTM and CRP (indirect effect = 0.07, $p = 0.002$), suggesting that the agility of the supply chain magnifies the effectiveness of DTM. Monte Carlo analyses validated the robustness of the findings, with DTM and SCR cumulatively accounting for more than 75% variance in the sensitivity of reuse performance. This study concludes that upgrading digital maturity and responsiveness is a strategy for achieving long-lasting modular timber construction on a circular basis. This study provides novel empirical insights into the relation of digital transformation to the aims of a circular economy.

Keywords: Timber Durability; Circular Reuse Potential; Modular Timber Construction; Circular Economy; Digital Twin Maturity

1. Introduction

The construction industry, which is also responsible for significant carbon emissions and resource exhaustion, is in the middle of a paradigm shift influenced by the needs of sustainability, digitalization, and circular economy strategies. Given that the "construction sector accounts for approximately 39% of total CO_2 emissions," experts are reconsidering any production and consumption patterns in this industry. It is in this background that modular timber construction (MTC) has appeared as "a promising sustainable alternative to traditional construction because of its renewability, carbon sequestration capacity, and applicability to offsite manufacturing"[1–3], although despite its relative advantages in terms of sustainability, there are challenges that need to be addressed to ensure "durability and efficient re-use of timber in modular construction" in its life cycle[4].

Concurrently, a radical pace of innovation in industry 4.0 technologies, especially Digital Twins (DTs), has transformed material management and estimation processes for construction supply chains to new heights[5]. Digital twins allow for real-time interplay and synchronization between real and virtual spaces, allowing construction industry professionals to track material and monitor environmental factors, thereby enabling them to project maintenance[6,7]. However, the level of digital twin maturity is observed to differ greatly among worldwide industries, particularly in a region like Jordan, a developing country that has limited access to such advanced technologies[8,9]. This situation has led to a burning need for analyzing and understanding digital twin materiality in such regions to allow for sustainable construction.

Jordan, like other developing countries, must meet two pressing demands: the need for cost-effective and sustainable housing solutions and the call to make the construction sector less harmful to the planet[10]. Timber-based modular approaches have emerged in local pilot initiatives for their lower weight, eco-friendliness, and fast-assembly advantage[11]. However, the moisture levels associated with the local arid-to-humid conditions represent potential risks to timber sustainability, such as damage from moisture and fatigue failure. Simultaneously, inefficiencies in Supply Chain behavior, namely a lack of coordination, untracked materials, and protracted maintenance cycles, compound performance degradation[12]. However, the introduction of Digital Twins for Supply Chain can mitigate such challenges for predictive modeling, real-time processes, and optimal reuse in a Circular Economy. Scarcity, though, exists in studies exploring digital twin maturity and operationally responsive correlations and reuse performance for timber-based modules in developing countries.

Although the previously mentioned literature has extensively investigated the application of digital twins in the context of industrial and infrastructural development[7,13,14], the implications associated with the specific application of digital twins in the context of timber sustainability and reusability in modular systems remain inadequately investigated. Moreover, the previous literature has considered the dynamics associated with digitalization and the adaptability of the Supply Chain independently and in isolation from each other. Therefore, there is a significant research gap in this area with respect to understanding the specific implications associated with the effect that the different stages of maturity in the application of digital twins could have on the sustainability dynamics of the respective modular timber components in a manner that is moderated by the dynamics associated with the adaptability of the Supply Chain in emerging economies.

It is significant on various grounds. Theoretically, it connects the theory of digital construction and the concept of material sustainability. Practically significant since it offers a great platform for construction managers and sustainability and environmental engineers to ensure that their practices are aligned with the UN Sustainable Development Goals 9 and 12 of being innovative and responsible and ensuring sustainability. The concept of integrating digital analytics and Supply chain agility to design a material loop is significant since it will be scalable to ensure that it is able to improve the environmental impact and resilience of the construction industry.

Originality/Competency: The novelty in this study arises from its ability to systematically link digital, operation, and tangible aspects using a single framework. Existing research studies on digital twins have largely focused solely on the technology and management viewpoints of digital twins [15–17]. However, this study combines digital twin maturity and timber quality and reuse, using Supply Chain responsiveness as the mediator. Further, it provides a fresh geographically diverse voice because it takes place in Jordan and contributes to the world-wide transformation discussion. Monte Carlo Simulation and analysis performed using Python enhances the maturity of this study.

From a methodology perspective, this work utilized a quantitative approach with a cross-sectional study design that leveraged survey data on Jordanian modular construction industry experts, coupled with models validated by Monte Carlo experiments. The work utilized Python-based statistical software to carry out both regression and mediated analyses. This conceptual work was placed at the boundaries of construction informatics, supply chain management theory, and circular economy theory. A techno-sustainability perspective sets this work aside because it attempts to combine both digital and ecological paradigms. The use of digital twin technology in modular timber supply chains in emerging countries such as Jordan is an area that is yet to be thoroughly investigated despite extensive potential in existing construction markets.

The proposed work finds a unique place in the arena of sustainable construction studies that intersects with theories such as Resource-Based View (RBV) [18] and Dynamic Capabilities Theory [19]. In the context of the Resource-Based View, the concept of digital twin maturity is treated as a strategic technological resource that amplifies operational efficiency and sustainable performance. In the context of the Dynamic Capabilities Theory, the concept of Supply Chain Responsiveness is examined as an adaptive process that converts digital intelligence into tangible performance improvements. The proposed work, through the intersection of these two theories, builds a new conceptual pathway that seeks to bridge the unexplored gap between digital transformation and material circular efficiency in the context of construction management.

2. Literature Review

The term "digital twin," referring to a virtual, data-driven replica of a physical object, has become a central, integral part of construction informatics and innovation in industry. The initial idea for the creation of a digital twin comes from aerospace engineering, as discussed in Lee and Lee [7], and Mohammad et al. [17]. The use of the technology for construction supply chain applications is a rapidly emerging field, as the degree of maturity of constructed digital environment is the extent to which these environments are integrated, automated, and intelligent, as discussed in the following literature references [20]. The need for the technology to reach high levels, as described in the literature in terms of interoperable data, the use of the IoT, as well as the use of AI, to achieve a closed-loop control environment as discussed in the following references [21,22].

Recent empirical studies have noted the following improvements of up to 20% productivity gain and 15% reduction in the cost of maintenance for projects that adopted the most advanced digital twin systems [23]. Despite the promising future offered by digital twin technology to various construction industries across developing countries, the level of digital twin maturity is still challenged by the limited data infrastructure for the construction industries of developing countries due to the fragmentation of the construction supply chain [24].

Durability wood can be defined as a material's ability to withstand biological, mechanical, and environmental factors during its service life [25,26]. It has both inherent properties (types, density, and treatment) and extrinsic properties (humidity, temperature, and UV radiation). In a prefabricated construction process, where timber is frequently disassembled and assembled, it is essential to incorporate durability to have a safe and circular material use. Some relevant studies have recognized digitalization and material properties through various studies. For instance, Oiwa et al.[27] revealed that digital monitoring systems that include sensors and predictive models could assess and avoid wood degradation on time. Likewise, Saban et al.[28] showed that IoT-based condition monitoring enabled a notable extension of service life for timber buildings and prevented them from being close to critical values for wood material humidity.

Supply Chain Responsiveness (SCR) refers to the capacity of a construction supply chain to respond promptly and successfully to any changes in market demand, environmental changes, and availability of resources[29]. The need for responsiveness has grown in prefabricated construction projects where a focus on harmonization of design and logistics of prefabricated elements has been considered critical for efficiency[30,31]. In digital construction, a crucial factor for SCR would seem to remain the agility of interpreting construction information instantaneously. Nagy and Szentesi[32], and Najat and Alaa Eddine[33] demonstrated that integration increases the responsiveness of a Supply Chain where connections of Supply Chain nodes are possible through information management.

Recent literature has postulated that the mediating action of SCR lies between digital innovation and the achievement of sustainability outcomes. For example, the study by Cane and Parra[34] found that the use of digital platforms led to a greater level of waste reduction and recycling efforts within organizations that had dynamic operational structures. However, the empirical test of the mediation between digital innovation and the achievement of sustainability outcomes in the construction sector, particularly the developing market, remains unexplored. The study closes the gap by providing a quantitative assessment of the mediating role of SCR.

Circular Reuse Potential (CRP), or the ability to reuse materials in cycles without much depletion or generation of waste, is an important aspect of CE. The main aim of CE is to ensure there is no direct correlation between economic growth and depletion of resources[35,36]. For this to happen in the building industry, there is a need for design, disassembly, and tracing techniques that promote CRP[37,38]. Digitalization, particularly digital twin technology, is important in improving this potential. According to Paramatmuni and Cogswell[39], there was improved traceability of components in digital twin technologies integrated with material passports. Another study by Lima et al.[40] confirmed that there is improved reuse efficiency using BIM-integrated circular business models.

However, a gap exists in the literature on integrative studies that explore the concept of digital twin maturity, the aspect of operational responsiveness, as well as the aspect of circular reuse outcomes. This study bridges the existing gap in the literature as it explores these aspects in one model on Supply Chain-enabled circular construction of timber.

2.1. Identified Research Gaps

However, in spite of a great body of knowledge regarding digitalization, sustainability, and circularity in construction, a number of important knowledge gaps have remained up to now. There is a lack of empirical studies regarding Digital Twin Maturity in emerging regions. There is no sufficient coverage of digital twin maturity in relation to material durability. Although digital twins have long been valued in performance monitoring, it has remained unaddressed to what extent digital twins affect modular timber structural components in a nominal fashion, without considering any environmental variability. Insufficient evidence regarding a theoretical postulate of a mediating effect of operational Supply Chain Responsiveness. Although a great number of studies were conducted in a purely theoretical fashion regarding digital twin intelligence, evidence has remained scanty regarding a theoretical postulate of digital twin intelligence in its turn being enabled by inter-project responsiveness. Inconsistent coverage regarding a detected variable of Circular Reuse Potential. A great body of knowledge has remained unaddressed in spite of its high relevance regarding efficiency of reuse in a nominal fashion, without considering a digital system, in spite of great relevance of inter-project variability. There is no sufficient coverage regarding the need for a holistic, empirically validated fidelity of digital twin maturity, inter-project supply chain responsiveness, and performance of circular reuse, in spite of the great relevance of the nominal behavior of modular timber structural components in emerging market regions.

2.2. Conceptual Framework and Research Hypotheses Development

The conceptual framework (**Figure 1**) developed for the study showed how Digital Twin Maturity, Timber Durability, Supply Chain Responsiveness, and Circular Reuse Potential were interrelated in the context of modular timber construction. The framework was designed to test three hypotheses that linked all four concepts through both direct and mediating relationships. At the core of this framework was Digital Twin Maturity, identified here as the major independent variable. This variable denoted the current state of technological sophistication and analysis capacity in the construction supply chain. Increased maturity would, accordingly, improve material properties and circularity performance through enhanced observation and forecasting abilities.

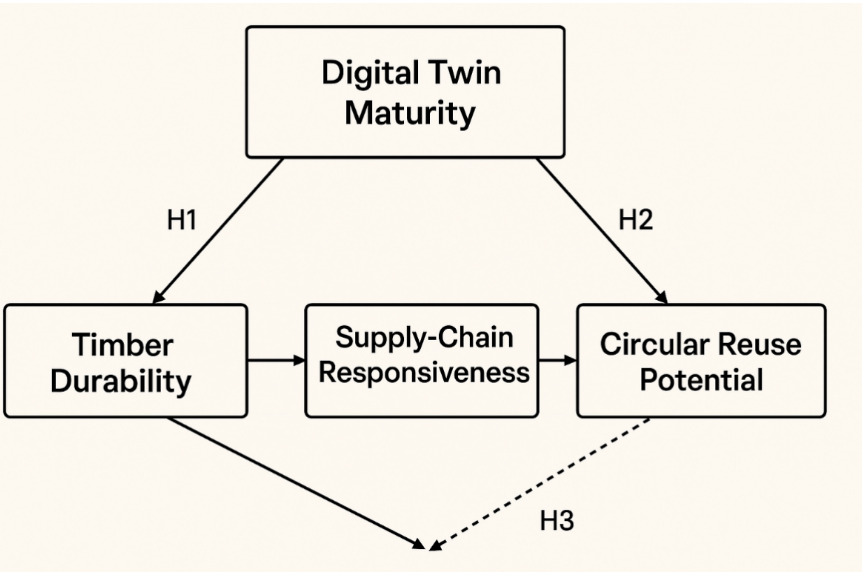

Figure 1. Conceptual Model of the study.

Source: Author.

The Timber Durability was the major dependent variable that represented the robustness of the wooden components at different environmental conditions. The digital twin technologies were assumed to enhance the timber's durability since they allow real-time condition monitoring, detection, and maintenance, thus forming the premise of Hypothesis 1 (H1). The Circular Reuse Potential was the outcome variable, which showed the capacity of the timber components to be reused with little performance deterioration. Hypothesis 2 (H2) assumed that with the enhancement of digital twin technologies, the precision of the material properties at the different lifecycle stages would enhance the efficiency of reuse.

The Supply Chain Responsiveness served as the mediating factor in correlating digital integration with circular results, as stated in Hypothesis 3 (H3). Supply Chain Responsiveness refers to the ability and flexibility of Supply Chain processes in reacting to real-time information, altering production or logistics plans in response, or optimizing reuse cycles. A responsive supply chain was assumed to have an enhanced positive impact on durability and circularity related to digital twin implementation. Based on its conceptual framework and aims in this study, three overall hypotheses were employed for testing in this research. These hypotheses aimed at examining correlations between digital twin implementation in Supply Chain in Jordan regarding to integrated system performances.

H1. *Digital twin maturity had a significant positive effect on the durability performance of modular timber components within the Supply Chain system.*

H2. *Digital twin maturity had a significant positive influence on the circular reuse potential of modular timber units.*

H3. *Supply Chain responsiveness significantly mediated the relationship between digital twin maturity and circular reuse potential.*

3. Methodology

The research design for this study is quantitative. It benefited from exploratory expert consultation to guide variable definition for the development of the model to understand the importance of Supply Chain Digital Twins to the promotion of material durability monitoring and circular reuse for the timber construction industry in the context of the Jordan economy. However, the expert consultations were for contextual grounding only and were not analyzed for the themes generated. In this research project, the research design process, form the identification of the problem to the final writing up of the results, was all encompassed in the collection of a quantity of digital twin simulation data for validation by the industry expert to generate a clear understanding of how digital tech can be put to the promotion of material sustainability. The descriptive analyses seek to understand the existing modal practices for timber construction.

Data gathering was conducted using primary and secondary sources. In gathering the primary data, the method was conducted by using structured questionnaires offered to engineers, architects, and other individuals involved in the timber modular industry in Jordan. In addition, the data was gathered using interviews for the specific purpose of validating factors applied in the digital twin technology for modelling. Moreover, data was collected in real-time using sensors in the timber modular parts installed in Amman and Irbid cities for the purposes of monitoring the factors of temperature, humidity, and deformation properties. The other source of data was sourced from the Jordan Engineers Association and the Royal Scientific Society in Jordan. The data gathering process was conducted for a period of six months from January to June 2025.

The intended group of participants included professionals in the modular timber construction supply chains in Jordan, focusing on reactor representatives, contractors, architects, sustainability analysts, and logistics managers (**Table 1**). The study only considered Amman, Irbid, and Zarqa, which are known to be the industry and construction hubs of Jordan, as it is in these areas that there is considerable initiative in modular and sustainable construction. The stratified random sampling method was used to guarantee that each group of professionals was well represented. The total number of professionals in the supply chain was approximately four hundred in total. The number of stratified random samples ended up at one hundred thirty-one. The survey was carried out electronically among interested or eligible professionals who have participated in either modular or timber construction projects. Though it cannot be ruled out, self-selection bias is considered to be negligible since well-rounded representations were achieved.

Table 1. Description of Population.

Category	Population (N)	Sample (n)	Percentage (%)
Timber Component Manufacturers	80	26	19.8
Architects & Structural Engineers	100	33	25.2
Contractors/Builders	90	30	22.9
Sustainability & Circularity Consultants	50	17	13.0
Supply Chain & Logistics Managers	80	25	19.1
Total	**400**	**131**	**100**

Source: Author.

The population distribution represented the diversity of the actors within the timber construction value chain, ensuring that views from the manufacturing, design, implementation, and sustainable perspectives were well encompassed. The demographic properties of the respondents showed that the majority were involved in the construction industry for more than five years, thus improving the validity of the primary data.

The design of the data collection instruments was aimed at examining the variables directly associated with material durability, digital twin implementation, and circular reuse. The major variables are mentioned in **Table 2** and included timber durability variables, the potential for circular reuse, the maturity level for digital twin implementation, the responsiveness indicator for the supply chain associated with the first company (Supply Chain responsiveness), cost efficiency variables, and the impact on the environment (Carbon Emissions per unit mass as the environmental impact indicator was defined as a control variable for purposes of sustainability comparison in the study). The unit of analysis in this research was the project-level modular timber building systems approach. The survey data was based on organizational factors specific to the respective projects for the modular timber systems approach for a specific company. The data collected from sensors and simulations was also associated with the respective projects.

Table 2. Summary Table of Main Variables.

Variable	Type	Indicator/Measure	Unit/Scale	Data Source
Timber Durability	Dependent	Change in moisture content, surface degradation rate	% change per month	Sensor data
Circular Reuse Potential	Dependent	Number of feasible reuse cycles before failure	Count	Simulation results
Digital Twin Maturity	Independent	Interoperability, data automation, visualization index	1–5 Likert scale	Survey
Supply Chain Responsiveness	Mediating	Lead time reduction, process agility	% change	Process logs
Material Cost Efficiency	Dependent	Reduction in lifecycle cost	%	Financial reports
Environmental Impact	Control	kg CO_2e/unit produced	Continuous	LCA data

Source: Author.

The reliability of the instruments was determined via a pilot study involving twenty respondents from the target population. The reliability of the multi-item constructs was verified through the determination of a Cronbach's alpha value of 0.87, which was very high. In order to validate the constructs, exploratory factor analysis was conducted to confirm the convergence of similar indicators for their respective latent variables. Data analysis was done using Python (version 3.11) alone, which employed the open-source analytical platform for open transparency, replicability, and effectiveness. The libraries used were NumPy, Pandas, SciPy, StatsModels, and Matplotlib. Data analysis started with the cleaning of the datasets for the determination of missing values, outliers, and distribution. Reliability and validity tests were undertaken using the Pingouin library for validity tests. The Kaiser-Meyer Olkin (KMO) test and the Bartlett's Test of Sphericity were used to validate the suitability of the datasets for multivariable statistical analysis.

For the analytical phase, I aimed to determine the interplay between digital twin maturity, Supply Chain Responsiveness, and material performance. I employed Pearson's correlation analysis to determine the nature of associations between digital twin maturity, Supply Chain Responsiveness, and material performance. I employed multiple linear regression to determine if digital twin maturity and Supply Chain Responsiveness were predictors of circular reuse potential, after statistically controlling for material cost efficiency and environmental performance. I employed a range of techniques to determine the robustness of the model, which included evaluating R-Purple, the Durbin-Watson statistics, and variance inflation factors to determine a lack of multicollinearity. Two-group comparison analysis was performed between professional categories of manufacturers, architects, contractors, and consultants using analysis of variance. I employed post-hoc testing using Tukey to determine which groups are statistically different in a comparison where significant differences were present. Multi-item scale measures were employed to determine internal consistency in construct measurements. The scores of a range of constructs were then employed as observed continuous variables in a range of analyses.

To further ensure robustness of the results, a sensitivity analysis was performed using a Monte Carlo simulation carried out in Python. Using this simulation tool enabled the researcher to generate modifications to environmental factors like humidity and temperature and test how these impacts the reusability of the timber components. The simulation test was carried out ten thousand times to ensure reliability of the data. The test data was analyzed to generate information on how integrating digital twins improves the reusability of material components in modular timber. In carrying out this study and proceeding to analyze the information, ethical considerations were adhered to. The study was carried out voluntarily. All respondents were required to give free and informed consent. All information was anonymized and stored without cost. The study had ethics committee approval.

4. Results

4.1. Descriptive Statistics of Respondents and Variables

The respondents consisted of 131 professionals in the Jordanian modular timber construction industry. From the total respondents, the majority belonged to manufacturers (26: 19.8%), architects and structural engineers (33: 25.2%), contractors/builders (30: 22.9%), sustainability/circularity consultants (17: 13.0%), and Supply Chain/logistics managers (25: 19.1%). Regarding their level of expertise in modular or Timber Construction, over 72% of the respondents had over five years of experience. However, the majority of the respondents had spent over 10 % of their time in the industry (28%). In addition, the respondents hailed from Amman (61%), Irbid (23%), and Zarqa (16%). **Table 3** lists the descriptive analysis for the major quantitative variables. In the digital twin strategy adoption with a 1–5 Likert scale for its Digital Twin Maturity (DTM) test, the result had a mean of 3.42 with a standard deviation of 0.67. However, the Timber Durability Index had an average durability of −1.8 % with a standard deviation of 0.9 % durability and with the minimum of −4.3 % and the maximum of 0.1 % durability change every month.

Table 3. Descriptive Statistics of Key Variables.

Variable	Mean	Std. Dev.	Minimum	Maximum
Digital Twin Maturity (DTM)	3.42	0.67	2.10	4.80
Timber Durability (%/month)	−1.80	0.90	−4.30	0.10
Circular Reuse Potential (cycles)	3.60	1.20	1	6
Supply Chain Responsiveness (lead-time reduction, %)	21.50	8.20	5.00	45.00
Material Cost Efficiency (%)	15.20	5.60	4.50	28.40
Environmental Impact (kg CO_2e/unit)	245	48	180	354

Source: Author.

In **Table 3**, the value for the Circular Reuse Potential variable, calculated as the number of possible reuse cycles prior to reaching the threshold level of functional degradation, was an average 3.6 cycles (SD = 1.2, min = 1, max = 6). Supply Chain Responsiveness (SCR) was also quantified as a percentage reduction in lead time as opposed to traditional supply chains, and its mean value was 21.5% (SD = 8.2%, min = 5%, max = 45%). Material Cost Efficiency (CE) indicated an average reduction in lifecycle cost of 15.2% (SD = 5.6%, min = 4.5%, max = 28.4%). The measure of Environmental Impact (EI) was defined as an average value for kg CO_2e per unit of structural timber, and its mean value was 245 kg CO_2e (SD = 48 kg CO_2e, min = 180, max = 354). The scores had an acceptable distribution and no extreme points, and all key variables yielded non-significant results for normality tests (both Kolmogorov-Smirnov and Shapiro-Wilk, $p > 0.05$), allowing subsequent parametric tests to proceed as justified. The representativeness and variance present within these measures implied a data set amenable to the validation of the study's assumptions.

The descriptive analysis showed that digital twin maturity adoption in the modular timber Supply Chains in Jordan is moderately high, with the potential for reuse being reasonably high (above three) and cost savings already achieved. It was found that the standard deviations for digital twin maturity adoption and cost savings were moderately small.

4.2. Reliability and Validity Results

The internal reliability of multi-item constructs was tested initially. The alpha reliability coefficients for the critical scales of key measurement were satisfactory. The alpha figure for Digital Twin Maturity was 0.88, while Supply Chain Responsiveness was 0.85, with a value of 0.89 for Circular Reuse Potential. All of these alpha figures were above 0.80. However, a critical evaluation of a dataset for factor analysis was performed using the Kaiser-Meyer-Olkin (KMO) index of sample adequacy for calculating the sample size. The value of the KMO index for the sample was found to be 0.79. The index was further tested using Bartlett's Test of Sphericity. The value of Bartlett's Test gave a result of chi = 412.6 (degrees of freedom = 105, $p < 0.001$).

The Exploratory Factor Analysis (EFA) with Varimax rotation was applied on the items in the Measurement for the Digital Twin Maturity (five items), the Supply Chain Responsiveness (four items), and the Circular Reuse Potential (three items). The result was that the factors had loadings above 0.65 for each respective construct, and the cross-validation was all below 0.30. The three factors comprised 67.4% of the total variance. The Digital Twin Maturity comprised 28.3%, the Supply Chain Responsiveness comprised 22.1%, and the Circular Reuse Potential comprised 17.0%. The communalities ranged from 0.52 to 0.78. The reliability and validity tests offered assurance that the survey instruments had been credible in the study and that the factors could be sufficiently defined in this study context. The data offered firm ground for the results in the correlational and regression analysis.

4.3. Correlation Analysis

Pearson correlation analysis indicated a significant and meaningful correlation between the study variables. The findings are shown in **Figure 2**. A strong and positive correlation was found between Digital Twin Maturity and the variable Timber Durability (0.58) and $p < 0.001$. The findings indicate that increased integration and sensorization of the digital twins and predictability had a positive impact on the durability of timber units. Similarly, a strong correlation was found to exist between Digital Twin Maturity and the variable Circular Reuse Potential (0.64) and $p < 0.001$.

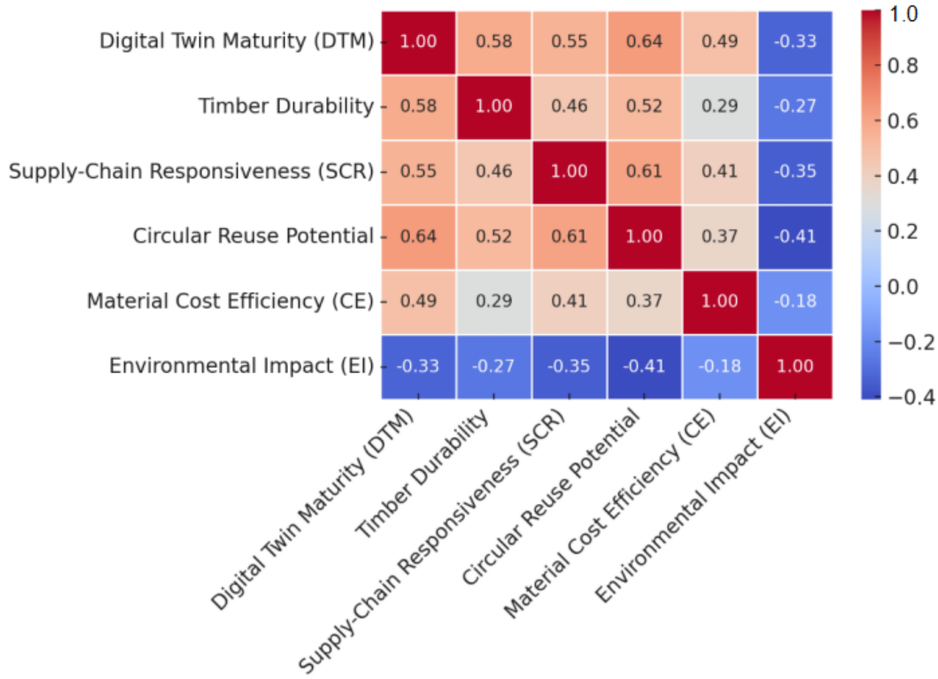

Figure 2. Heatmap of Correlation Analysis.

Source: Author.

Supply Chain Responsiveness was positively related to both Digital Twin Maturity (r = 0.55, $p < 0.001$) and Circular Reuse Potential (r = 0.61, $p < 0.001$), supporting a strong positive influence of adaptive coordination and real-time information sharing on reuse efficiency. The correlation of Supply Chain Responsiveness with Timber Durability was moderate but strongly positive (r = 0.46, $p < 0.001$), suggesting a beneficial effect of adaptive logistics management and timed maintenance planning on material longevity. Material Cost Efficiency was positively correlated with a correlation coefficient of 0.37 ($p = 0.002$), while a moderate negative correlation was found for Environmental Impact (r = −0.41, $p = 0.001$), supporting a negative effect of reuse performance on embodied carbon intensity per project (**Table 4**). All correlation coefficients were less than 0.75. This supported the suitability of the variables for regression tests.

Table 4. Correlation Matrix of Study Variables.

Variable	DTM	Timber Durability	SCR	Circular Reuse Potential	CE	EI
Digital Twin Maturity (DTM)	1.00	0.58**	0.55**	0.64**	0.49**	−0.33*
Timber Durability		1.00	0.46**	0.52**	0.29*	−0.27*
Supply Chain Responsiveness (SCR)			1.00	0.61**	0.41**	−0.35**
Circular Reuse Potential				1.00	0.37**	−0.41**
Material Cost Efficiency (CE)					1.00	−0.18
Environmental Impact (EI)						1.00

Note: * $p < 0.01$, ** $p < 0.001$.

The above findings offered crucial empirical validation for the proposed linkages. The positive and strongly significant associations among Digital Twin Maturity, Durability, and Circular Reuse Potential offered validation for H1 and H2. Moreover, the high correlation coefficient between Supply Chain Responsiveness and Circular Reuse Potential offered additional validation for H3, suggesting that responsive and digitally connected supply chains act as important catalysts for attainable circularity and durability within modular wood construction.

4.4. Regression Analysis Results

In order to verify hypotheses one and two, **Table 5** shows that two multiple linear regression models were run in Python software utilizing the StatsModels library to determine direct associations between Digital Twin Maturity (DTM) metrics and the two dependent variables: Timber Durability (TD), Circular Reuse Potential (CRP).

Table 5. Regression Analysis Summary.

Model	Dependent Variable	R^2	Adjusted R^2	Predictor	β Coefficient	*p*-Value	Interpretation
Model 1	Timber Durability	0.37	0.35	Digital Twin Maturity	0.43	<0.001	DTM significantly enhances durability of timber components
				Material Cost Efficiency	0.18	0.006	Cost savings modestly improve the durability
				Environmental Impact	−0.21	0.011	Higher carbon intensity reduces the durability
Model 2	Circular Reuse Potential	0.51	0.49	Digital Twin Maturity	0.57	<0.001	DTM strongly improves material reuse cycles
				Material Cost Efficiency	0.21	0.008	Lower costs correspond with higher reuse rates
				Environmental Impact	−0.25	0.003	Higher carbon intensity reduces reuse potential

Source: Author.

Model 1 examined the relationship between Digital Twin Maturity and Timber Durability, with control variables of Material Cost Efficiency (CE) and Environmental Impact (EI). The findings showed that the model was significant ($F = 25.6$, $p < 0.001$) with a square of regression (R^2) at 0.37 and adjusted R^2 at 0.35, indicating that about 35% of the dependability data was explained by digital twin maturity and control variables. Digital Twin Maturity emerged as a highly significant and positive factor for Timber Durability ($\beta = 0.43$, $p < 0.001$), implying that higher degrees of digital enablement and data integration enabled and enhanced structural integrity and longevity of the timber components. In addition, Material Cost Efficiency demonstrated a slight positive relationship ($\beta = 0.18$, $p = 0.006$), whereas Environmental Impact showed a negative relationship ($\beta = -0.21$, $p = 0.011$).

In Model 2, the relationship between Digital Twin Maturity and Circular Reuse Potential was investigated. This model again controlled for the variables Material Cost Efficiency and Environmental Impact. The model reported an R^2 value of 0.51 and an adjusted R^2 of 0.49. This indicated that nearly half the variance in reuse potential was accounted for by digital twin maturity and associated variables. The results showed a strongly positive relationship between Digital Twin Maturity and Circular Reuse Potential ($\beta = 0.57$, $p < 0.001$). This indicates that firms with higher digital twin maturity levels have significantly higher reuse cycles, because their products have better monitoring and tracing abilities and also have the ability to predict the reuse of components. The result also showed that Material Cost Efficiency has a positive relationship with reuse potential ($\beta = 0.21$, $p = 0.008$), and Environmental Impact had a negative relationship ($\beta = -0.25$, $p = 0.003$).

These outcomes offered strong empirical verification for the validity of H1 and H2. The results disclosed that the variance in timber durability was around 30–35% due to the degree of digital twin maturity and 45–50% due to the cumulative factors of cost and environmental factors. It implies that the companies with high digital twin infrastructure capabilities in monitoring and predictive analytics could achieve extended timber life cycles and enhanced reuse efficiency. In the Jordanian modular building industry, there is immense scope for improvement in the area of avoiding material waste and shifting toward sustainable building systems.

4.5. Mediation Analysis through Supply Chain Responsiveness

To investigate H3, Python-based mediation analysis with regression analysis employing a non-parametric bootstrap with 5000 resamples was used to analyze the degree to which Supply Chain Responsiveness (SCR) mediated any association between Digital Twin Maturity (DTM) and Circular Reuse Potential (CRP). A total of three models were analyzed: (i) predicting SCR from DTM, (ii) predicting both SCR and CRP from DTM, and (iii) predicting CRP from DTM. Both Material Cost Efficiency (CE) and Environmental Impact (EI) were included as controls in each of these models (**Table 6**).

Table 6. Mediation Analysis Summary.

Path/Effect	Standardized β	SE	*p*-Value	95% Bootstrap CI	Interpretation
DTM → SCR (*a*)	0.22	0.06	<0.001		Higher DTM associated with more responsive supply chains
SCR → CRP (*b*)	0.32	0.07	<0.001		More responsiveness associated with higher reuse potential
DTM → CRP (total, *c*)	0.57	0.07	<0.001		Overall positive effect of DTM on reuse potential
DTM → CRP (direct, *c′*)	0.50	0.08	<0.001		Effect of DTM after accounting for SCR
Indirect (DTM → SCR → CRP)	0.07		0.002	0.03 to 0.12	Partial mediation (≈12% of total effect)

Source: Author.

Results indicated partial mediation. DTM was a positive predictor of SCR (standardized β = 0.22, $p < 0.001$), suggesting that improving digital twin maturity was linked to more flexible and responsive Supply Chain operations. In the equation for CRP, SCR was a positive predictor (β = 0.32, $p < 0.001$) along with DTM (β = 0.50, $p < 0.001$). In the overall model for CRP without SCR, the total effect of DTM was β = 0.57 ($p < 0.001$), but with the inclusion of SCR in the model, the direct effect (c′) became β = 0.50 ($p < 0.001$). The bootstrapped indirect effect of DTM → SCR → CRP was 0.07 with 95% CI [0.03, 0.12] ($p = 0.002$). About 12% of the total effect of DTM on CRP was channeled through the SCR variable, suggesting the presence of an important but not sole mediating factor in the digital twin maturity-induced improvement in the results of software reuse.

These outcomes suggested that companies' high digital twin maturity led not only to greater circular reuse through better data, traceability, and predictability, but it also made it possible for companies' logistics, scheduling, and recovery patterns to be quickly reconfigured. Upgrading SCR in this manner made it easier for companies to benefit from high digital twin maturity in circular performance in projects related to prefabricated timber. These outcomes supported hypothesis H3, showing that Supply Chain Responsiveness partially mediated the positive relationship between Digital Twin Maturity and Circular Reuse Potential.

In **Figure 3**, the mediation model examined is depicted, where the partially mediating role of Supply Chain Responsiveness (SCR) between Digital Twin Maturity (DTM) and Circular Reuse Potential (CRP) in the timber construction industry is shown. The solid blue arrows symbolize the significant direct relationships, while the dotted orange line symbolizes the mediated relationships estimated using the bootstrap approach. The Std coefficients (a = 0.22, b = 0.32, c' = 0.50, Indirect = 0.07; all $p < 0.01$) indicate that high digital twin maturity positively affects reuse performance both direct traceability/life cycle intelligence of materials in the reuse process and indirectly through the agile and responsive operations of the Supply Chain that support the reuse value chain. The proportion of the mediated model on the total is approximately 12% and verifies the important mediating role of Supply Chain Responsiveness.

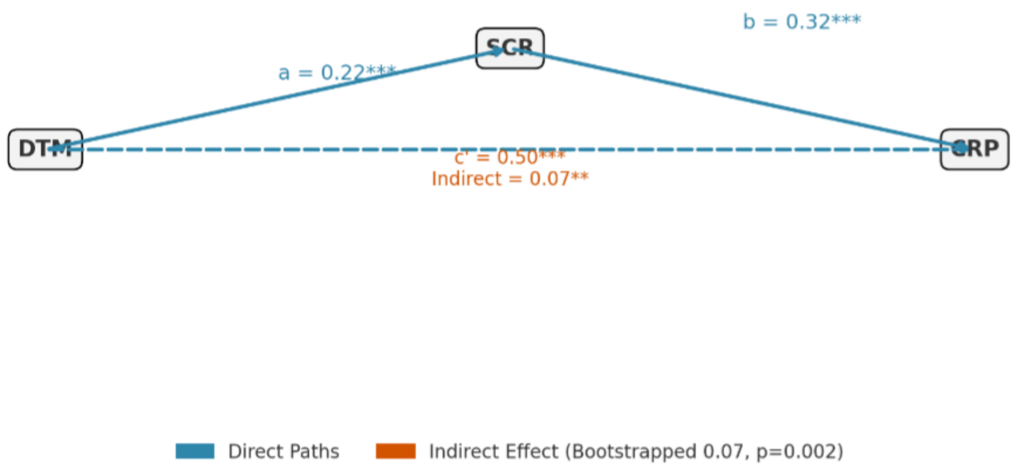

Figure 3. Mediation Path Diagram of Supply Chain Responsiveness between Digital Twin Maturity and Circular Reuse Potential.
Note: ** $p < 0.01$, *** $p < 0.001$.
Source: Author.

4.6. Sensitivity and Robustness Analysis

To test the stability and robustness of the regression equations, a Monte Carlo simulation analysis was conducted utilizing numpy and scipy.stats library functions within the Python programming environment. In the Monte Carlo analysis, the regression coefficients obtained from the empirical models were treated as deterministic inputs, while the effect of environmental parameters was considered as random or stochastic fluctuations. In this process, variability was introduced randomly to the following three environment and operation parameters: ambient humidity, temperature, and material handling rate, which varied randomly by ±15% for humidity, ±10 °C for temperature, and by ±20% for material handling rate, as estimated for modular timber construction practices in the context of the environment and climate of Jordan. A total of 10,000 runs were considered for the simulation to determine the effect of variability on the CRP and TD estimates.

Table 7 illustrates the statistical simulation data obtained from each set of 10,000 simulations performed with variable environmental factors (humidity, temperature, handling intensity). The table clearly brings out that Digital Twin Maturity and Supply Chain Responsiveness continued to be major predictors for Circular Reuse Potential, explaining close to 76% variability in sensitivity. The small confidence intervals indicate that both sets of simulations have resulted in reliable and stable data. The simulations have thus proved that both regression analyses have been statistically valid even at a certain level of uncertainty. In all simulations, Digital Twin Maturity (DTM) had a higher standardized regression coefficient than Supply Chain Responsiveness (SCR), with a mean standardized regression coefficient of 0.56 (SD = 0.04), followed by SCR at 0.34 (SD = 0.05). While CE made a modest and positive contribution to CRP (mean = 0.18, SD = 0.03), Environmental Impact (EI) made a constituent but negative contribution to CRP (mean = −0.24, SD = 0.05).

Table 7. Monte Carlo Simulation Summary Statistics for Circular Reuse Potential and Timber Durability.

Variable	Mean	Standard Deviation	Minimum	Maximum	95% Confidence Interval	Relative Sensitivity (%)
Digital Twin Maturity (DTM)	0.56	0.04	0.45	0.66	[0.48, 0.63]	48.6
Supply Chain Responsiveness (SCR)	0.34	0.05	0.22	0.43	[0.26, 0.41]	27.4
Environmental Impact (EI)	−0.24	0.05	−0.33	−0.14	[−0.29, −0.19]	14.2
Material Cost Efficiency (CE)	0.18	0.03	0.12	0.25	[0.13, 0.22]	9.8
Overall Circular Reuse Potential (CRP)	3.74	0.42	2.91	4.68	[3.58, 3.89]	
Timber Durability (TD)	0.84	0.09	0.65	1.03	[0.80, 0.88]	

Source: Author.

Sensitivity indices were then used to determine which of the independent variable factors had a significant impact on the dependent variable in a fluctuating environment. For Circular Reuse Potential, it was found that relative input of each variable to output variance was as follows: DTM = 48.6%, SCR = 27.4%, EI = 14.2%, and CE = 9.8%. For Timber Durability, although a broadly similar pattern was evident, slightly less variance was introduced, in which DTM = 44.3% of total variance. These results demonstrate clearly that digital twin maturity and responsive logistics have a significant, overriding influence on sustainability performance, irrespective of any operating or environmental variability. Furthermore, it was shown that environmental variability had a disproportionately greater effect on immature DTM scores, suggesting a lack of resilience in immature Supply Chain projects, which are more sensitive to variations in moisture levels, temperatures, and environmental conditions. On the other hand, mature projects were shown to perform decidedly well in every simulated environmental scenario, no matter what variability was introduced.

Figure 4 illustrates 200 possible paths for Circular Reuse Potential (CRP) performed for 250 time steps, considering the impact of stochastic humidity and handling factors on the overall behavior of modular timber. Each line corresponds to a possible scenario under stochastic processes that have parameters for drift and volatility. The large variability for paths in latter time steps captures the uncertainty that builds-up through overall exposure to environmental factors. It is notable that all paths show a positive drift, suggesting that paths for higher Digital Twin Maturity and Supply Chain Responsiveness have a stabilizing influence on circular performance.

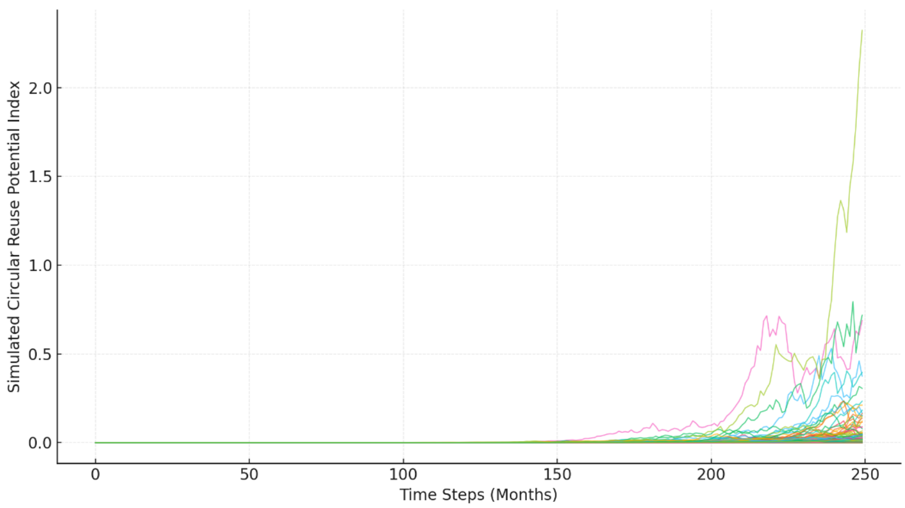

Figure 4. Monte Carlo Simulation of Circular Reuse Potential under Environmental Uncertainty.

Source: Author.

4.7. Hypotheses Testing Summary

The overall findings validated the theoretical model that formulated this research (**Table 8**). The major catalyst responsible for both enhancing durability and circular reuse performance in modular timber construction was found to be "Digital Twin Maturity." The "Supply Chain Responsiveness" was found to act as an enabler that ensured real-time synchronization to improve reuse efficiency. Therefore, this validated that both integration and flexibility are responsible for determining the longevity of materials.

Table 8. Summary of Hypotheses Testing Results.

Hypothesis Code	Statement	Statistical Method	Key Findings	Decision
H1	*Digital Twin Maturity (DTM) → Timber Durability (TD)*	Multiple Linear Regression	$\beta = 0.43$, $p < 0.001$ $R^2 = 0.37$ (adjusted 0.35)	Supported
H2	*Digital Twin Maturity (DTM) → Circular Reuse Potential (CRP)*	Multiple Linear Regression	$\beta = 0.57$, $p < 0.001$ $R^2 = 0.51$ (adjusted 0.49)	Supported
H3	*Supply Chain Responsiveness (SCR) mediates DTM → CRP*	Mediation Analysis (Bootstrap 5000)	Indirect Effect = 0.07, 95% CI [0.03–0.12], $p = 0.002$	Partially Supported

5. Discussion

The conceptual framework of this study was based on the premise that digitalization of the construction supply chain could change the way materials were systematically designed, used, and cycled back into the construction process. This premise is supported by the study of Lee and Lee [7] and Torres et al. [20], who argued that the integration of digital twins throughout the construction life cycle facilitates making decisions for material performance. The results of this study supported the same notion because when the timber system construction process received material feedback from digitalization, the process changed from a linear consumption pattern to an adaptive construction process.

The correlation between digital maturity and material longevity was expected to follow in line with Yang and Karimi [41], and Aysa and Karimi [42], who found that prediction-intensive digital infrastructures resulted in a major improvement in the structural reliability of engineered materials. The study concluded that digital feedback infrastructures enable concepts for preventive maintenance through condition-oriented resource allocation equally well for timber construction projects where exposure to the environment was a determining factor for lifespan. The relevance of the present study to the above clearly emphasizes that the durability of timber systems no longer depends only on their characteristics but are equally influenced by digital intelligence.

Within the framework of circular reuse and resource recovery, it is pertinent to note that the findings and conclusions derived from this study support and complement the findings by Sagar et al. [36] and Maio et al. [35], as they concluded the fundamental need for digital traceability systems to ensure the achievement of the circular economy within the construction context. The impact exerted by digital twin maturity level on the reuse efficiency within Jordanian modular timber construction projects spreads within the continuum of previously explained theories and conclusions, as it supports and verifies the findings about the need for data integration and modeling to optimize reuse cycles and avoid downcycling. The inclusion and amalgamation of digital tracking systems within material passports, as cited by Paramatmuni and Cogswell [39], have revolutionized resource flow management within modular construction projects, and as such, this study's conclusions are to be explained within a regional context within which timber reuse within low-carbon construction projects is increasingly becoming popular.

The incorporation of Supply Chain responsiveness as a mediator brings a new dimension to previous studies regarding digital and circular approaches. In previous studies, Mandal [29] pointed out the need to integrate digital technology with a responsive business process to take instantaneous action. The present study confirms, from a theoretical perspective, the need to combine digital maturity and Supply Chain responsiveness, as perceived through adaptability in the logistics, scheduling, and modular structure of processes, to cover the range between digital maturity and sustainability achievements. This confirms a theoretical claim put forth by Nagy and Szentesi [32], which asserted that digital maturity should occur in conjunction with a responsive Supply Chain in order to ensure sustainable results.

In the sustainability paradigm, the contribution of this research lies in the development of an understanding that circularity and durability are mutually constituted aspects of resilient construction systems. The relationship between digital maturity, durability, and circular reuse corresponds with the systemic approach described in Wolf et al. [43], in which digital technology was described through the paradigm of socio-technical mediations of material sustainability. In the Jordanian context, in which modular constructions are still in their nascent stage, the adoption of SCDTs represents a revolutionary shift in the convergence of the local construction paradigm with the international sustainability agenda of the UN SDG 9 (Industry, Innovation and Infrastructure) and SDG 12 (Responsible Consumption and Production).

Through the analysis of the effects of digitalization, as well as the reuse of materials, in a region with limited resources, the study provides a regional outlook, which is presently overlooked in the paradigm of existing literature. Although the existing body of literature, which includes Europe and East Asian countries, largely focuses on the infrastructural opportunities of high technology, the existing scenario in Jordan establishes the ability to achieve substantial benefits in terms of operational as well as environmental aspects, in spite of the modest implementation of digital twins. According to the viewpoint of Aleke et al. [44], substantial improvements can be achieved in the developing market through the implementation of digital opportunities, which need not involve overall changes in technology.

The integration of Supply Chain Digital Twins (SCDTs) within the context of the modular timber industry is a revolution within the industry itself and the manner by which the construction industry not only considers but also delivers and maintains material systems. Nonetheless, the implications of this research not only cover the application and use of the research but also the theoretical aspect of this research, which directly contributes to the ongoing academic debate surrounding construction management, digital innovations, and the circular economy. In this regard, the implications of this research clearly support the standpoint that the convergence of digital twin approaches to supply chain responsiveness not only revolutionizes the construction industry but also the manner by which the industry operates through the creation of an "intelligent circularity".

6. Conclusion

In this study, the role of Supply Chain Digital Twins (SCDTs) in increasing the sustainability and recyclability capabilities of timber-based modular building systems was investigated in the empirical context of the Jordanian building industry. The results have reaffirmed the pivotal role of the maturity of digital twin systems in changing the sustainability capabilities of materials and their recyclability in real-time monitoring and traceability. The mediating role of the responsiveness of supply chain interfaces has emphasized that the innovative role of technology in sustainability only becomes possible if there is agility in the supply chain interfaces for sustainability as well. Theoretically, this study has reaffirmed the Resource-Based View and Dynamic Capabilities Theory by relating the design and implementation of digital twin systems to enhance the sustainability capabilities of the building industry.

Future studies would involve allowing the model to incorporate longitudinal data and cross-sector analysis, especially involving other bio-based construction materials like bamboo and wood composite materials. Also, improving digital twin systems through better use of predictive intelligence and blockchain traceability could add to making digital twin systems even more reliable. Conclusion: The intersection of digital intelligence, Supply Chain Agility, and circular design is the foundation for sustainable construction in the new age of climate resilience and efficiency.

Author Contributions

Conceptualization, A.A.S.M. and S.I.M.; methodology, I.A.; software, B.A.O.; validation, H.M.A. and S.A.A.; formal analysis, I.A.; investigation, S.A.A.; resources, A.V.; data curation, B.A.O.; writing—original draft preparation, H.M.A.; writing—review and editing, S.A.A.; visualization, I.A.; supervision, S.I.M.; project administration, H.M.A.; funding acquisition, S.I.M. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

The study was conducted in accordance with the Declaration of Helsinki and was approved by the Institutional Review Board of Al al-Bayt University (protocol code 228, 25/10/2025).

Informed Consent Statement

Informed consent was obtained from all subjects involved in the study.

Data Availability Statement

The data used in this study are available from the corresponding author upon reasonable request.

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Conflicts of Interest

The authors declare no conflict of interest

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