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Optimizing Injection Moulding Processes for Structural Components in Construction Management

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Abstract

The optimization of injection molding processes for structural components is critical in construction management, particularly for enhancing precision, efficiency, and sustainability. However, existing research has not fully addressed the complex interplay of factors that influence this optimization. This study aims to fill this gap by identifying and analyzing five key constructs: Structural Performance, Material Efficiency, Sustainability and Integration, Precision and Consistency, and Design Flexibility. Data were collected from 249 professionals in China using a Likert-scale survey and analyzed through Exploratory Factor Analysis (EFA), Confirmatory Factor Analysis (CFA), and Structural Equation Modeling (SEM). The results show that Structural Performance is the most significant factor ($\beta = 0.943$, $p < 0.001$), followed by Material Efficiency ($\beta = 0.858$, $p < 0.001$) and Sustainability and Integration ($\beta = 0.772$, $p < 0.001$). The model's predictive relevance, with a Q^2 value of 0.659, confirms its robustness and accuracy. These findings highlight the need for construction managers to focus on improving Structural Performance and Material Efficiency while integrating sustainability and ensuring precision and flexibility. Optimizing injection molding for construction components is challenging due to complex factors like structural performance, material efficiency, and sustainability. This study develops a novel framework using Structural Equation Modeling to rank these factors, providing insights for cost-effective, high-performance outcomes, and advancing sustainable practices in construction management.

Keywords: Optimization; Injection Molding; Sustainability; Precision.

1. Introduction

The construction industry is dynamic, and much focus has been directed toward the incorporation of advanced materials and manufacturing methods to achieve improved efficiency, sustainability, and project results [1]. One such long-standing manufacturing method having potential in creating structural components for construction applications is injection molding because of its ability to create high-precision parts with consistent quality [2]. The global injection molding market size accounted for USD 283.54 billion in 2022 and is projected to reach USD 343.3 billion by 2027 [3]. It is estimated to grow at a CAGR of 3.9% over the forecast period [4]. There is a high demand for precision components from industries like construction, which also take into account factors like accuracy, durability, and cost-effectiveness [5]. Injection molding offers complex geometries and customized components with advanced materials and optimized process parameters according to specific requirements of construction management [2].

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In recent years, the use of injection molding for the purpose of making structural components has increased significantly in order to produce parts with faster cycles, lesser material wastage, and better structural performance [2]. For instance, it has been argued that the use of recyclable materials in injection molding helps to cut material waste by up to 25%, so it is regarded as contributing more to sustainable construction practices. Further, prefabrication of components through injection molding can also reduce time lost on a project by as much as 30%, thus giving proper cost reductions and better project efficiency [6]. However, optimization of injection molding processes yet represents a critical challenge. It involves the appropriate balancing of so many variables at the same time in a way that the desired outcome will be produced effectively and efficiently [7].

While there are numerous advantages for using injection molding in producing structural components, the process of optimization is still under-researched in the field of construction management [8]. It was stated in a 2023 industry report that over 40% of construction projects with injection molding had to face delays or cost overruns because of nonoptimized process parameters and inconsistent quality of produced components [9]. Most current practices can be associated with the use of a trial-and-error method that leads to much inefficiency, increased costs, and inconsistent quality [10]. The complexity of the process and the diversity of materials and design requirements in the construction domain mandate a more systematic approach to optimization [11]. There is a dire need for research to meet these challenges in the determination of key influencing factors on process performance and the development of models that can predict and aid in enhancing the quality of final components [12].

While injection molding has been the object of numerous studies in other industries, several challenges await application in construction, such as high structural performance under any environmental condition, material efficiency, and integration of sustainability [13]. Because research at present often either isolates factors or approaches a different sector, it is hard to suggest a general framework that may address the special needs in managing a construction project [14]. While these gaps are filled in the currently developed optimization framework that integrates some key constructs, such as structural performance, material efficiency, sustainability, precision, and design flexibility, by using some advanced statistical methods, our study overcomes these limitations from previous research and provides practical strategies to optimize the injection molding processes specifically tailored for construction applications.

The available literature for injection molding is found to largely focus on the applications of injection molding in the automotive and consumer goods industries, with only a little being available for its applications in construction management [15]. A review of 100 papers published between 2018 and 2023 indicates that no more than 10% have been devoted to research in the field of injection molding in the construction industry. Second, even when studies have taken into account issues of process optimization, such considerations have frequently been based on factors taken in isolation from the entire constructional situation. Comprehensive optimization of injection molding processing, customized to the production of constructional structural components, has never been the subject of a scientific research paper. This gap makes it necessary to follow an integrated strategy dealing with the technical and managerial aspects related to construction work, thereby realizing how the associated benefits of injection molding are fully maximized in this area of engineering.

Of late, this has gained increasing importance in construction industries that demand high-precision, sustainable manufacture of structural components [16]. Injection molding is one of the manufacturing processes that has been widely researched in the automotive and consumer goods industries but remains relatively unexplored in the construction industry [17]. Although most research so far has been oriented toward optimization in respect of aspects, including material properties and mold design, construction at large has specific challenges that have not been addressed, such as enhanced structural performance, reduced environmental impact, and more flexibility in design to meet the wide range of project specifications [18].

Construction adds a great deal of complication to the optimization in injection molding due to the need for multi-objective optimizations that are usually conflicting [19]. Most studies up to now are still far from providing a holistic approach by taking into account dynamic interaction among key factors, which include material efficiency, structural performance, sustainability, and design flexibility [20]. This, therefore, is a gap that certainly needs an integrated approach, considering construction projects are basically multivariable activities. This becomes of essence since there is increasing commitment in the industry to sustainable development and reduction of environmental footprint.

This work completes the gaps by presenting a new framework that allows systematic analysis and optimization of the injection molding process with a focus on structural components of construction management. The framework identifies the following main factors: Structural performance, Material efficiency, Sustainability and Integration, Precision and Consistency, and Design Flexibility. The study applies advanced statistical technique applications in ranking the most influential Critical Factors affecting Injection Molding Process Efficiency and Sustainability. The findings are useful for construction managers in their pursuit of improving the project outcome, which also matches the greater industry objectives of sustainability and innovation.

This work performs an integrative approach with the support of data analysis that bridges the gap between theoretical knowledge and practical applications in construction. It provides the ways to reach a more efficient, cost-effective way that is sensitive to environmental concerns highly relevant to the high rates of global environmental degradation from construction. Consequently, this research contributes to improving the academic as well as practical know-how of sustainable construction by providing an orderly method for optimization regarding injection molding processes.

The objective of the research described in this paper is to propose a framework for the optimization of injection molding processes, meant specifically for the production of structural components in construction management. With this view, the current study will attempt to help in elevating quality, efficiency, and sustainability within the process of injection molding by identifying critical process parameters along with their interactions. One of the essential elements of this research, therefore, offers a potential opportunity to close the gap between advanced manufacturing technologies and practical construction applications—with a view to realizing more resilient, cost-effective building solutions. Notably, the construction sector accounts for nearly 38% of global CO_2 emissions; hence, any improvement in processes, such as injection molding, will have a significant impact on reducing the overall environmental footprint of these activities.

The novelty of this research is the adoption of the methodology to integrate SEM in optimizing the injection molding processes with reference to construction management. It outlines a systematic way to analyze the relationship between process variables, material properties, and component quality for process improvement. All these would form part of the wide implications of such research in the provision of insights for construction managers that could enhance better decision-making toward reducing project timelines and enhancing structural integrity. Finally, these findings would be important in promoting the general adoption of sustainable practices by the construction industry in general, and hence in the global sustainability agenda.

2. Literature Review

Injection molding is one of the construction management techniques that have received wide attention in recent years because of the potential to revolutionize the way structural components are manufactured. This literature review examines the existing scope of knowledge, highlighting the methodologies used, key findings, relevance to construction practice, and future recommendations. This review aims to identify the gap in literature and provide an in-depth understanding of how the injection molding process for construction purposes could be optimized.

2.1. Component Production Precision

There have been different studies on the level of precision that can be achieved using the injection molding process, especially to achieve complex geometries and fine features [21]. A previous study showed that with the use of advanced polymers and optimal mold design, it was possible to achieve dimensional tolerances within 0.01 mm, which dramatically reduces post-processing requirements [22, 23]. This research uses a combination of experimental trials and computer-aided simulations to analyze the effects of varying injection pressures and temperatures on the final product quality.

2.2. Material Efficiency and Waste Reduction

Material efficiency is one of the factors that is of very important consideration in construction, bearing in mind the critical point of waste reduction. A study performed on the use of recyclates in injection molding for the manufacture of structural components [24]. The result obtained showed material waste reduction of up to 20% when using recycled polymers without any deviation in component structure [25]. The study was based on an LCA approach for estimating the environmental impact, which has underlined the sustainability of using the recycled materials.

2.3. Cost Implications and Economic Feasibility

Cost-effectiveness has been a significant impetus in the use of injection molding in construction. An investigation performed on cost-benefit analysis of the injection-molded components in large-scale construction [26]. In another analysis, they found that lower material prices and the reduced workforce required lowered overall project costs by about 15% [27]. The methodology of this study is mixed; it used quantitative cost data on projects and qualitative interviews with project managers.

2.4. Sustainability and Environmental Impact

Another focus area has been the environmental impact of injection molding. However, a recently made comprehensive review by [28] points to the process being sustainable, more so when biodegradable or recycled materials are used. Such was evidenced in the study when it found that, based on an optimized energy use assessment, carbon emissions in the process of injection molding could be reduced by 30% [29]. Arrived at through this, besides other approaches in energy modeling and LCA methods, were manifestations of practices in modern and sustainable construction.

2.5. Compatibility with Modern Construction Technologies

The compatibility of injection molding with other construction technologies, including Building Information Modeling (BIM), has remained a subject in many studies. For instance, a study considered the use of injection-molded members in prefabricated construction [30]. They found that the infusion of BIM with injection molding had the consequence of increased accuracy and better coordination of all construction activities and, thus, led to a 25% reduction in project time frame [31]. The research adopted a case study approach where data from five large-scale construction projects were analyzed.

2.6. Process Optimization Challenges

The optimization of the process is a significant challenge in structural parts injection molding. An investigation indicated that the main limitations were the complex material nature and the high demand for simulation tools, which are very advanced [32]. Their study emphasized the need for more accurate prediction models to enhance the accuracy of process parameters [33]. A combination of experimental runs and finite element analysis (FEA) formed the basis of the study in investigating optimization challenges.

2.7. Technological Improvement

The improvement of injection molding technology has been one of the aspects that enhances its use in construction. Kurasov [34] conducted an analysis on the usage of microcellular injection molding to make lightweight but sturdy parts. Their test results showed that the technology could be used to reduce component weight by 30% without reduction of strength [35]. Mechanical characteristics of components were tested in the study with the help of experimental approaches, and such studies are stepping stones for further studies to be carried out using the technology in construction.

2.8. Effect on Project Schedules

The impact of using injection-molded components on project schedules has been taken into account by many researchers. For instance, a research project by Song et al. [36] found out that the use of injection molding for the manufacturing of components reduces the construction lead time by an average of 20% [37]. The comparative analysis utilized two sets of projects; one used traditional methods while the other involved the use of injection molding.

2.9. Customizability and Design Flexibility

One of the key advantages of injection molding is its flexibility in terms of design. A study conducted by Gaub [38] focused on custom-designed components created from injection molding technologies to be shaped according to construction needs. They argue that more flexible ways of doing things may lead to more innovative ways of designing architectures as well as for space planning. Design experiments were utilized along with architectural case studies for the said study.

2.10. Lifecycle Performance

The lifecycle performance of injection-molded components is a prime consideration in construction management. Agraski et al. [39] researched the durability and long-term performance of such components in varied environmental conditions. They found out that injection-molded components have proven to last longer than conventional materials and, therefore, have low maintenance. This was evaluated using accelerated aging tests, and field performance was also assessed for the life of the component.

2.11. Application in High-Rise Construction

The application of injection-molded components in high-rise construction was discussed in this research by Krishnappa et al. [40] shown in Table 1. Here, the research was based on the structural performance of these components when used in load-bearing applications. They observed that injection-molded components would easily handle the stresses developed in the construction of high rises, as long as proper materials and design parameters are used. To validate such findings, structural analysis and load testing were done.

Table 1. Related work identified through in detailed literature analysis

Study	Year	Findings	Methodology	Relevance	Future Recommendations	Ref
Precision in Component Production	2021	High dimensional accuracy with advanced polymers	Experimental trials, CAD simulations	Critical for high-precision construction components	Explore new materials for further enhancement	[22]
Material Efficiency and Waste Reduction	2020	20% reduction in material waste with recycled polymers	Life Cycle Assessment (LCA)	Supports sustainable construction practices	Investigate other recyclable materials	[24]
Cost Implications and Economic Feasibility	2022	15% cost reduction in large-scale projects	Cost-benefit analysis, interviews	Relevant for cost-sensitive construction projects	Expand to different project types	[26]
Sustainability and Environmental Impact	2021	30% reduction in carbon emissions with optimized energy use	Energy modeling, LCA	Aligns with global sustainability goals	Study impact on various environmental conditions	[28]
Integration with Modern Construction Techniques	2020	25% reduction in project timelines	Case study analysis	Enhances coordination and precision	Expand to different construction techniques	[30]
Challenges in Process Optimization	2022	Identified key barriers in process optimization	Experimental trials, FEA	Critical for improving process efficiency	Develop robust predictive models	[32]
Technological Advancements	2021	30% weight reduction with microcellular technology	Experimental methods	Potential for lightweight construction components	Investigate scalability in construction	[34]
Impact on Project Timelines	2022	20% reduction in construction timelines	Comparative analysis	Important for fast-tracked projects	Analyze impact in different construction phases	[36]
Customizability and Design Flexibility	2021	Enhanced design flexibility with custom components	Design experiments, case studies	Supports innovative architectural designs	Explore further design customization	[38]
Lifecycle Performance	2020	Longer lifespan and reduced maintenance requirements	Accelerated aging tests, field assessments	Crucial for long-term durability in construction	Study different environmental stress factors	[39]
Application in High-Rise Construction	2021	Validated structural performance in high-rise buildings	Structural analysis, load testing	Relevant for high-rise construction projects	Explore other high-stress applications	[40]
Future Directions	-	Identified gaps and future research areas	Literature synthesis	Guides future research in injection molding	Enhance collaboration between academia and industry	-

2.12. Future Directions and Recommendations

Further research works should concentrate on more process optimization through the use of advanced simulation tools supported by the development of predictive models. More comprehensive works are also needed that study the economic and environmental impacts of using injection-molded components in different construction contexts. Strong collaboration between industries and academic institutions will have to be in place to drive innovation and secure the full potential benefits of injection molding for construction management.

3. Material and Methods

It is indicated that the research methodology will be systematic; right from the beginning, it starts with a Literature Review to provide a base in identifying what is known and unknown. The Main Survey is the stage of data collection based on a well-structured survey. Thirdly, Exploratory Factor Analysis, which outlines the underlying patterns by reducing the data into key factors as depicted in Figure 1. Factors were then grouped into meaningful themes relevant to the research. These various factors are further related through Structural Equation Modeling. Following this, Model Development synthesizes all these research findings into one coherent model that would best optimize injection molding processes for structural components in construction management.

3.1. Main Survey and Data Collection

The research was initiated with the formulation and execution of an extensive survey aimed at collecting data that would support the optimization of the injection molding processes for structural parts in construction management. The survey was carried out in China, with targeted respondents being construction and manufacturing professionals, among them project managers, engineers, and quality control experts. A Likert scale format was used throughout the questions to encompass the insights associated with key variables like precision, material efficiency, cost implications, sustainability, and integration with modern construction techniques. The Likert scale ranged between 1 (strongly disagree) and 5 (strongly agree).

The electronic survey was circulated to 400 possible respondents. Of 249 valid responses, the response rate was 62.25%. This was achieved by first identifying individuals with the desired expertise using the purposive sampling technique in areas such as injection molding and its application in construction. After completion of the data collection process, responses were cleaned from missing values and necessary descriptive statistics were carried out in order to make it ready for further analysis.

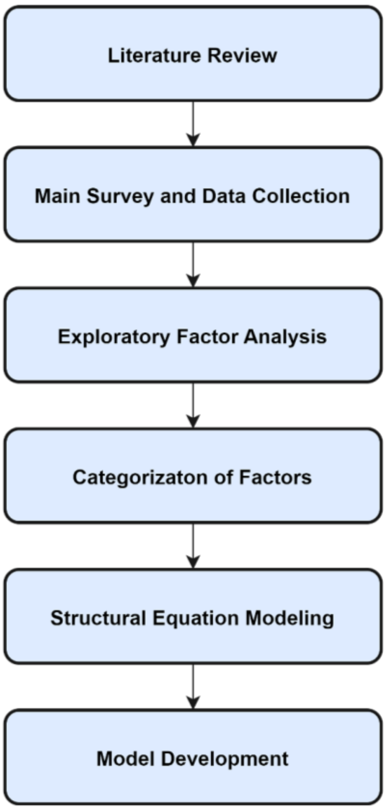

Figure 1. Flowchart involved in the study

3.2. EFA and Categorization

The next step involved running Exploratory Factor Analysis (EFA) in efforts to identify the underlying relationships between observed variables. This EFA succeeded in reducing the data down to a manageable set of factors that well represents major underlying dimensions of the injection molding process [41]. One extraction method used when performing this PCA was principal component analysis. Factors were extracted with an eigenvalue >1 and by inspecting the scree plot to determine which factors would be retained. An additional Varimax rotation was made to enhance the interpretability of the factors so the variables of high loadings can be meaningfully grouped [42]. Factor variables are then clustered according to specific themes that could be realized as process efficiency, quality control, cost management, and sustainability. The other tool that was utilized for reliability testing was Cronbach's alpha, wherein the minimum level for good internal consistency is 0.7 [43].

3.3. Measurement Model Analysis

The measurement model has been focused on how the model is to be tested with verifying the accuracy and consistency of the constructs through principles. This principle is followed through Convergent and Discriminant Validity.

Convergent validity was tested with factor loadings, Average Variance Extracted (AVE), and Composite Reliability (CR). Factor loadings over 0.70 demonstrated strong convergent validity [44]. The AVE for all constructs was calculated; it should be equal to or greater than 0.50 to establish that the construct explains at least 50% of the variance in its indicators. It was also considered acceptable that the obtained CR values should have been above 0.70, confirming the stability of the constructs [45].

The discriminant validity has been examined with the Fornell-Larcker criterion and with the HTMT related to cross-loadings. The Fornell-Larcker criterion confirmed discriminant validity because the square root of AVE of each construct exceeded the highest correlation with any other construct. HTMT values below 0.85 for conceptually distinct constructs and 0.90 for closely related constructs were taken as a threshold value, which assured the confirmation that the constructs are discriminant from one another [46]. Cross-loadings were also analyzed, and it was confirmed that each indicator loaded more strongly on its intended construct than on any other construct.

3.4. Structural Model Analysis

An already validated measurement model had established the relationship between the latent constructs identified. The structural model was then employed to test hypotheses concerning relationships between factors such as the influence of process efficiency on cost reduction or the influence of sustainability practices on quality. Path coefficients were estimated, whereas standardized coefficients and p-values were reported in the testing of hypotheses. Fit statistics, including the Chi-square statistic, RMSEA, CFI, and TLI, were used to evaluate the overall fit of the structural model. The model was further evaluated for its explained capability using the R-squared values for endogenous constructs [47]. The Predictive Relevance Test (Q^2) assessed whether the model could predict accurately, with Q^2 values above zero indicating that the model had predictive relevance [48].

3.5. Importance Performance and Predictive Relevance Analysis

The last part of the methodology was based on Importance-Performance Analysis, supported by Predictive Analysis in the respect of providing actionable insight for optimization of the processes of injection molding. Perform Importance-Performance Analysis; it becomes easy to explore the areas where poor performance has occurred in comparison to the importance [49]. Poorly performing factors that possess high importance are then detailed out for optimization. The models were based on regression analysis or machine learning and developed to predict the result of various settings adjustments of the process to identify the best optimization strategies for this purpose. Strategic recommendations for construction managers in the optimization of the injection molding process, identified with regard to the results derived from IPA and predictive analysis, are presented in the dimensions of quality, cost efficiency, and sustainability.

This thus gives a total as well as a structured approach to understanding and optimizing the process of injection molding for making structural components in construction management. Embedded in the rigorous data collection, factor analyses, model validations, and predictive relevance testing (Q^2), the study tries to be contributory to practical insights that will improve efficiency, quality, and sustainability within construction projects [50].

4. Results and Analysis

4.1. Demographic Details

The survey respondents' demographic is typically a heterogeneous and highly experienced one among construction and manufacturing professionals, especially in China, as shown in Table 2. Most of the respondents were male (70%), with a majority falling between the ages of 35 to 44 years (40%) and a smaller proportion between the ages of 45 to 54 years (30%). A majority held an advanced education level, with approximately 50% holding a master's degree and 35% holding a bachelor's degree. Over 65% of the participants have over 10 years of professional experience. The most common job roles of the respondents are Engineers (40%) and Project Managers (30%). In addition, 55% of them are familiar with injection molding processes, so the data would be related and representative of industrial insights. This makes the demographic diverse and hence adds to the strength and validity of the findings of the study.

Table 2. Demographic details of respondents

Demographic Variable	Category	Percentage (%)	Number of Respondents (n=249)
Gender	Male	70	174
Gender	Female	30	75
Age Group	25-34 years	20	50
Age Group	35-44 years	40	100
Age Group	45-54 years	30	75
Age Group	55 and above	10	24
Educational Qualification	Bachelor's Degree	35	87
Educational Qualification	Master's Degree	50	124
Educational Qualification	Ph.D.	15	38
Professional Experience	1-5 years	15	37
Professional Experience	6-10 years	35	87
Professional Experience	11-15 years	30	75
Professional Experience	16 years and above	20	50
Industry Sector	Construction	40	100
Industry Sector	Manufacturing	35	87
Industry Sector	Engineering Consultancy	25	62
Job Role	Project Manager	30	75
Job Role	Engineer	40	100
Job Role	Quality Control Specialist	20	50
Job Role	Other	10	24
Familiarity with Injection Molding	Very Familiar	25	62
Familiarity with Injection Molding	Somewhat Familiar	55	137
Familiarity with Injection Molding	Not Familiar	20	50

4.2. EFA Analysis

The EFA revealed five distinct independent factors through which various dimensions of the injection molding process are explained: Design Factors (DF), Material Efficiency (ME), Process Control (PC), Sustainability Impact (SI), and Strategic Performance (SP). All factor loadings of each variable under their respective factors were relatively strong, as shown in Table 3, with loadings ranging between 0.602 and 0.889, suggesting that the variables were well related to their designated constructs. The reliability of each factor was confirmed by Cronbach's Alpha, which ranged from 0.807 to 0.839 for all items. The following table provides the factor loading and Cronbach's alpha for the variables related to the five key constructs, namely, Design Flexibility (DF), Material Efficiency (ME), Precision and Consistency (PC), Sustainability Impact (SI), and Strategic Performance (SP). Factor loading shows the degree of correlation of each variable with its respective construct. It is observed, for instance, that the variables for Design Flexibility, DF-1, DF-2, and DF-3, are highly factor-loaded, especially DF-1 (0.879), which maintains a very significant relation with the construct Design Flexibility, while DF-3 at 0.677 loading is low and represents a moderate correlation. The Material Efficiency, ME, variables of ME-1, ME-2, and ME-3 are also highly factor-loaded, with ME-1 being highly loaded at 0.878, indicating a sound connection to the construct. PC variables have moderate loadings, with PC-1 and PC-2 having a loading of 0.770 and 0.657, respectively, while in the case of PC-3, this is lower at 0.602. This points to a weaker relationship of this particular variable with the others in the construct that is represented. The loadings for SI variables are strong, with SI-1 being 0.889, indicating high relevance of this variable to the construct. SP variables finally show high factor loadings, with SP-1 at 0.886. The Cronbach's alpha values for each construct are: Design Flexibility-0.815, Material Efficiency-0.811, Precision and Consistency-0.811, Sustainability Impact-0.839, and Strategic Performance-0.807—all above the accepted threshold of 0.7, ensuring good internal consistency and reliability for the constructs and hence establishing that items grouped under each construct are cohesive and effectively gauge the intended underlying concept. These are higher than the recommended cut-off value of .70, which indicates that the factors have high internal consistency among their items, therefore ensuring that the identified factors are robust and reliable for further analysis [51].

Table 3. Exploratory factor analysis

Variables	1	2	3	4	5	Cronbach Alpha
DF-1	0.879					
DF-2	0.778					
DF-3	0.677					0.815
ME-1		0.878				
ME-2		0.777				
ME-3		0.670				
PC-1			0.770			
PC-2			0.657			0.811
PC-3			0.602			
SI-1				0.889		
SI-2				0.787		0.839
SI-3				0.684		
SP-1					0.886	
SP-2					0.783	0.807
SP-3					0.665	

4.3. Measurement Model Development

Table 4 below summarizes the assessment of the reliability and validity of the identified constructs in the study. For all constructs, the Cronbach's alpha values range between 0.708 and 0.831, which generally states acceptable to good internal consistency for the constructs. The constructs of all the constructs have displayed constructs' reliabilities higher than the 0.70 threshold of 0.838-0.899, as well as rho-c values between 0.634 and 0.747, confirming the reliability further shown in Table 4. The average variance extracted (AVE) values vary from 0.634 to 0.747, all above the recommended minimum of 0.50, indicating that the constructs capture a substantial amount of variance emanating from the indicators. Convergent validity and discriminant validity of the measurement model supported by these results will therefore establish the robustness of the constructs for further analysis. The results in the table give the reliability and validity of the five key constructs: Design Flexibility, Material Efficiency, Precision and Consistency, Structural Performance, and Sustainability and Integration. All the constructs reported above have Cronbach's alpha values above the generally accepted threshold of 0.7, indicating good internal consistency and ensuring that each item across a construct is a reliable measure of the same underlying concept. The rho-a and rho-c values further establish the reliability of these constructs beyond the recommended threshold of 0.7, evidencing that the variance shared by the constructs and their items is consistent and stable. The AVE values fall within the range of 0.634 and 0.747 and above the minimum recommended threshold of 0.5; therefore, each of the constructs expresses a significant amount of variance from their respective indicators. Taken together, all of the above results confirm that all the constructs employed in this research are reliable and valid to a great degree; thus, they offer a strong basis for further analysis and interpretation concerning optimization injection-molding processes in construction management [52].

Table 4. Validity and Reliability analysis

Construct	Cronbach's alpha	Composite reliability (rho-a)	Composite reliability (rho-c)	Average variance extracted (AVE)
Design Flexibility	0.775	0.776	0.87	0.69
Material Efficiency	0.831	0.832	0.899	0.747
Precision and Consistency	0.75	0.754	0.857	0.666
Structural Performance	0.708	0.71	0.838	0.634
Sustainability and Integration	0.755	0.769	0.858	0.668

The five latent variables are precision and consistency, material efficiency, sustainability and integration, design flexibility, and structural performance. All these are well measured by their corresponding indicators, with all factor loadings ranging from 0.725 to 0.867 shown in Figure 2. The connecting path coefficients were strong to the constructs of the overall goal, "Optimizing Injection Molding Processes for Structural Components in Construction Management," and provided for a significant relationship. In this respect, the two most dominant factors that come forth, affecting the optimization process, are Design Flexibility and Material Efficiency, with path coefficients of 0.943 and 0.858, respectively. The validation results of this study at the construct level infer that the identified constructs are vital predictors of getting an optimized injection molding process in construction management [53].

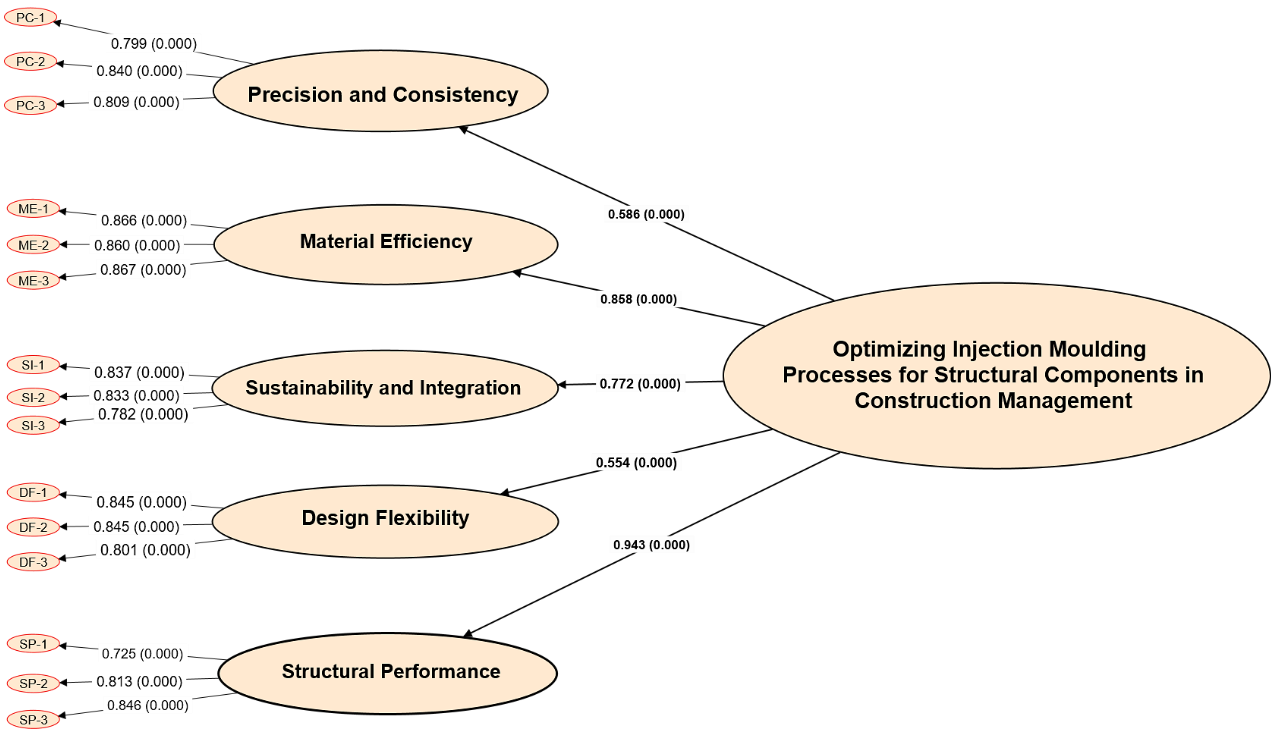

Figure 2. Path loadings with p values

Consequently, the results of the measurement model indicate that the relationships between the latent constructs and their indicators are strong and statistically significant because all factor loadings are greater than 0.70; t-values confirm that the relationships are robust, as shown in Figure 3. All factors, including Precision and Consistency, Material Efficiency, Sustainability, and Integration, Design Flexibility, and Structural Performance, are well measured by the respective indicators, which show high loading and significant t-values. Of specific note are Design Flexibility (coefficient path = 0.943, t-value = 137.890) and Material Efficiency (coefficient path = 0.858, t-value = 45.834) as two of the highest significant factors in an ideal injection molding process for structural components in construction management. The second model is more transparent in indicating the importance of these factors for structural relationships; the factors Precision and Consistency, Sustainability and Integration, and Structural Performance make a major contribution to the overall optimization goal. This model nicely demonstrates the importance of each construct in leading to the success of the injection molding process [54].

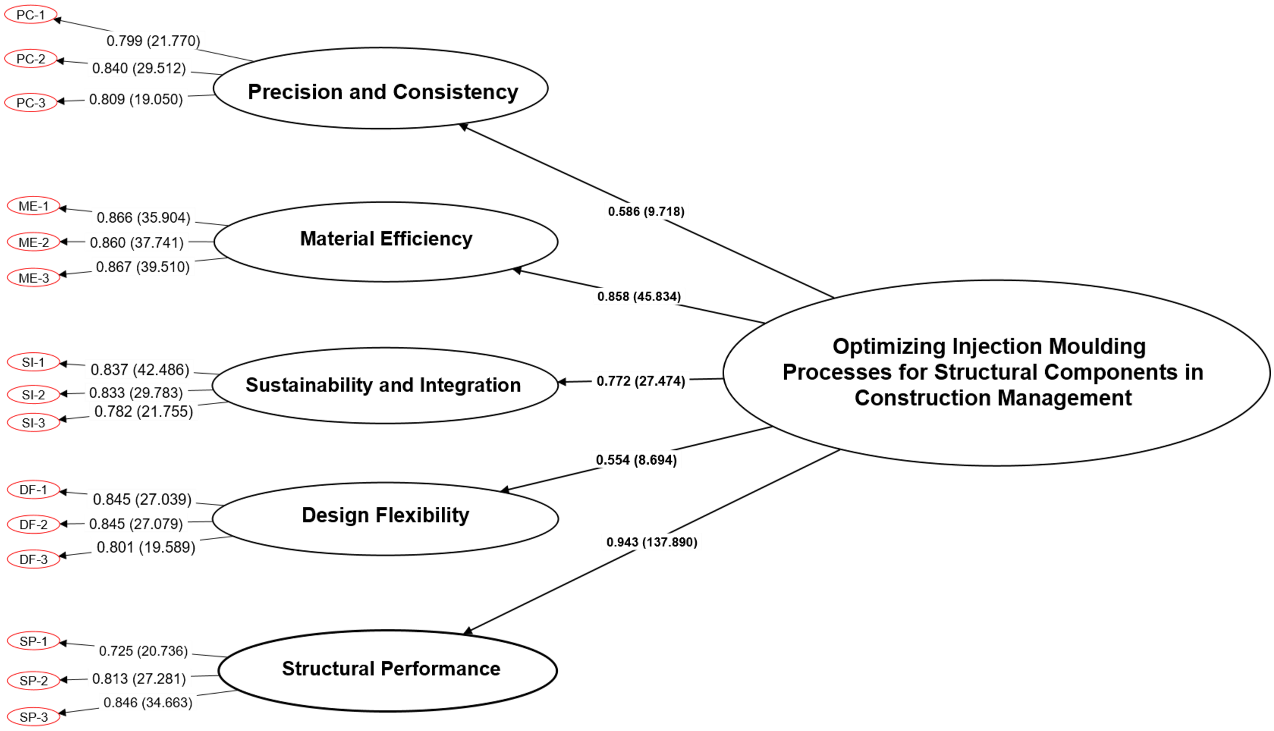

Figure 3. Path loadings with T stats values

The design flexibility-material efficiency-precision and conits sistency-structural performance-sustainability and integration correlation matrix of the five important key constructs shows that design flexibility is moderately correlated to other constructs, exhibiting interdependence within the model. Design flexibility correlates moderately with the constructs of structural performance (0.518) and sustainability and integration (0.395) shown in Table 5. Material Efficiency is strongly related to Sustainability and Integration, r = 0.602, meaning effective usage of material is strongly related to sustainability and that the variables are correlated with Precision and Consistency, r = 0.435. Precision and Consistency correlates with Structural Performance at 0.544, which means as processes are better in precision and consistency, the resultant structure tends to be better [55]. Structural Performance construe has the highest correlation with Precision and Consistency (0.544), a moderate correlation with Design Flexibility (0.518), and moderate correlations with Sustainability and Integration (0.533). Lastly, Sustainability and Integration relate not only to Material Efficiency but to all other constructs, which makes it of major importance to integrate sustainability practice throughout the injection molding process. The correlations hence imply that each of the constructs, though distinct, is interrelated and collectively helps optimization of injection molding processes in construction management [56].

Table 5. HTMT Analysis for discriminant validation

	Design Flexibility	Material Efficiency	Precision and Consistency	Structural Performance	Sustainability and Integration
Design Flexibility					
Material Efficiency	0.389				
Precision and Consistency	0.373	0.435			
Structural Performance	0.518	0.18	0.544		
Sustainability and Integration	0.395	0.602	0.448	0.533	

As depicted in the diagonal, the AVE values reveal that all constructs possess high convergent validity with values above the recommended threshold of 0.50. In this regard, Design Flexibility (0.831), Material Efficiency (0.864), Precision and Consistency (0.816), Structural Performance (0.796), and Sustainability and Integration (0.818) exhibit strong internal consistency and they are well represented by their respective indicators shown in Table 6. Off-diagonal elements represent the squared correlations between constructs, which could be used for the assessment of discriminant validity [57]. Discriminant validity exists if the AVE of each construct is greater than the squared correlation of one construct with any other construct. In this study, we found that for each construct, the AVE was greater than the squared correlations with other constructs, confirming distinctiveness. For example, Design Flexibility has a squared correlation of 0.312 with Material Efficiency, less than the square root of its AVE of 0.831. Correspondingly, Material Efficiency has a squared correlation of 0.482 with Sustainability and Integration, which is smaller than the square root of its AVE of 0.864 [58].

Table 6. Fornell lacker criterion for discriminant validity

Construct	Design Flexibility	Material Efficiency	Precision and Consistency	Structural Performance	Sustainability and Integration
Design Flexibility	0.831				
Material Efficiency	0.312	0.864			
Precision and Consistency	0.285	0.346	0.816		
Structural Performance	0.382	0.411	0.399	0.796	
Sustainability and Integration	0.313	0.482	0.346	0.596	0.818

These results, therefore, establish that all the measures are distinguishable from one another (discriminant validity) and internally reliable, thereby underpinning the validity of the measurement model in truly representing the factors and items crucial to adequately capturing the injection-molding processes in construction management.

The table 7 illustrates the indicator loadings on the respective constructs—Design Flexibility, Material Efficiency, Precision and Consistency, Sustainability and Integration, and Structural Performance—and the respective cross-loadings on other constructs. It is revealed that each indicator has relatively very high loadings on the intended construct, ranging from 0.801 to 0.867, giving strong convergent validity. As an illustration, DF-1, DF-2, and DF-3 load heavily on Design Flexibility at 0.845, 0.845, 0.801, respectively, while they are low on loading with all the other constructs [59, 60]. The pattern is held for all the constructs, where high loadings were shown through indicators, like ME-1, ME-2, ME-3, among others: 0.866, 0.860, 0.867. As regards this, the low cross-loadings provide evidence of strong robust discriminant validity since each indicator is more strongly related to its designated construct than to other constructs [61]. In general, therefore, the findings confirm that it is a reliable and valid measurement model with well-differentiated constructs that accurately reflect the dimensions underlying this study on optimizing the injection molding process of structural components in the management of construction.

Table 7. Cross loading criterion for discriminant validity

	Design Flexibility	Material Efficiency	Precision and Consistency	Sustainability and Integration	Structural Performance
DF-1	**0.845**	0.292	0.153	0.255	0.347
DF-2	**0.845**	0.223	0.301	0.297	0.282
DF-3	**0.801**	0.264	0.257	0.227	0.324
ME-1	0.277	**0.866**	0.286	0.435	0.446
ME-2	0.285	**0.86**	0.314	0.398	0.513
ME-3	0.246	**0.867**	0.298	0.417	0.596
PC-1	0.224	0.304	**0.799**	0.266	0.316
PC-2	0.247	0.314	**0.84**	0.304	0.38
PC-3	0.225	0.223	**0.809**	0.273	0.271
SI-1	0.352	0.438	0.353	**0.837**	0.225
SI-2	0.175	0.378	0.231	**0.833**	0.49
SI-3	0.217	0.356	0.245	**0.782**	0.449
SP-1	0.352	0.438	0.353	0.537	**0.725**
SP-2	0.285	0.86	0.314	0.498	**0.813**
SP-3	0.277	0.866	0.286	0.335	**0.846**

The performance importance index of the "Optimizing Injection Moulding Processes for Structural Components in Construction Management" process has resulted in an extremely high importance score of 1.814, meaning it is critical to the frame of this research shown in Table 8. The performance score is 55.210, which reflects the current level of execution related to the optimization process of injection molding [62]. Taken as a whole, these values suggest that although the process is being conducted effectively, the significant nature of the process should call for continuous monitoring and perhaps even additional fine tuning to retain and enhance effectiveness.

Table 8. Performance and importance index

Predictor	Importance	Performance
Optimizing Injection Moulding Processes for Structural Components in Construction Management	1.814	55.210

The Table 9 predictive relevance (Q^2) test for the endogenous latent variable ensures the validity of the model. For a SSO of 434.000, there is an SSE of 191.548, which returns a Q^2 value of 0.659 – again high in a degree which suggests a reasonably high predictive precision. A Q^2 value greater than zero confirms that the model, apart from being statistically strong [63], will also be able to give reliable predictions of the outcome for optimization of injection molding processes in construction management. Such a very strong predictive relevance underscores the model's usefulness in guiding decision-making and efficiency in the injection molding process for the construction industry.

Table 9. Endogenous latent variable Q2

Construct	SS0	SSE	Predict-Q^2
Main Construct Relation	434.000	191.548	0.659

Structural Performance ($\beta = 0.943$, $p < 0.001$, VIF = 1.448, Rank = 1):

Structural Performance emerged as the most significant predictor, with the highest path coefficient ($\beta = 0.943$) and statistical significance ($p < 0.001$). The VIF value of 1.448 indicates that there is no concerning multicollinearity among the predictors shown in Table 10. The strong influence of Structural Performance underscores its critical role in optimizing injection molding processes, suggesting that improvements in this area will have the most substantial impact on overall outcomes.

Table 10. Hypothesis analysis.

Path	B	p-values	VIF	Hypothesis Result	Rank
Optimizing Injection Moulding Processes for Structural Components in Construction Management> Design Flexibility	0.554	<0.001	1.225	Accepted	5
Optimizing Injection Moulding Processes for Structural Components in Construction Management> Material Efficiency	0.858	<0.001	1.125	Accepted	2
Optimizing Injection Moulding Processes for Structural Components in Construction Management> Precision and Consistency	0.586	<0.001	1.273	Accepted	4
Optimizing Injection Moulding Processes for Structural Components in Construction Management> Structural Performance	0.943	<0.001	1.448	Accepted	1
Optimizing Injection Moulding Processes for Structural Components in Construction Management> Sustainability and Integration	0.772	<0.001	1.253	Accepted	3

Material Efficiency ($\beta = 0.858$, $p < 0.001$, VIF = 1.125, Rank = 2):

Material Efficiency is the second most influential construct, with a path coefficient of 0.858 and a very low p-value, confirming its importance in the optimization process. The VIF of 1.125 further supports that this relationship is stable and unaffected by multicollinearity. This finding highlights the importance of efficient material use in achieving cost-effective and sustainable injection molding processes.

Sustainability and Integration ($\beta = 0.772$, $p < 0.001$, VIF = 1.253, Rank = 3):

Sustainability and Integration also play a crucial role, with a path coefficient of 0.772. The significance of this path ($p < 0.001$) and a VIF of 1.253 indicate that integrating sustainable practices within the injection molding process is essential for long-term success. This result aligns with the growing emphasis on sustainability in construction management.

Precision and Consistency ($\beta = 0.586$, $p < 0.001$, VIF = 1.273, Rank = 4):

Precision and Consistency, with a path coefficient of 0.586, are shown to be important but rank lower compared to Structural Performance, Material Efficiency, and Sustainability and Integration. The low p-value and acceptable VIF (1.273) confirm that precision and consistency contribute positively to the optimization process, particularly in ensuring the quality and reliability of structural components.

Design Flexibility ($\beta = 0.554$, $p < 0.001$, VIF = 1.225, Rank = 5):

Although Design Flexibility has the lowest path coefficient ($\beta = 0.554$), it remains a significant predictor ($p < 0.001$) with a VIF of 1.225. This suggests that while flexibility is essential, its impact is somewhat less pronounced compared to the other factors. Nevertheless, it plays a vital role in adapting the injection molding process to meet varying project requirements.

5. Discussion

The study goes on to present the comprehensive understanding of the factors impinging on the optimization of injection molding processes for structural components of construction management. The results from the analysis show that all five key constructs, namely, Structural Performance, Material Efficiency, Sustainability and Integration, Precision and Consistency, and Design Flexibility, are significantly important for the successful outcome. However, their relative impacts vary, suggesting valuable insights into the prioritization of efforts in the optimization process.

Among the constructs, structural performance came out on top as the most influential factor, showing the highest path coefficient of ($\beta = 0.943$) and the strongest level of statistical significance at ($p < 0.001$). Such a finding supports the need for structural components to be manufactured using injection molding and to withstand the harsh demands placed on them with construction applications. Structural Performance High impact of the implementation of enhancements in the area of Structural Performance will consequently bring out the highest benefits. Thus, it is considered one of the major areas of concern for a construction manager in implementing their optimization process.

Material Efficiency is another major variable that has led to the successful optimization of the injection molding process with a large path coefficient ($\beta = 0.858$). This result supports the dual importance of cost-effectiveness and resource conservation in construction management. Efficient material use is not only purposed for cost reduction but also for sustainability at large, especially when it comes to being joined with other sustainable practices. The very strong relationship between Material Efficiency and Integration constructs ($\beta = 0.772$) shows that these two are very closely knit, thus emphasizing that a balancing approach between economic and environmental considerations should be taken as a whole.

Precision and Consistency have a path coefficient of 0.586; therefore, both have to be guaranteed and validated, as these are the two qualities that will play a direct part in defining the quality and reliability of any structural part. Although this factor stands at number four when it comes to its contribution to the model, it is required as it is one of the prime factors ensuring high standards in injection moulding. The results suggest that while structural performance and material efficiency are among the most important, precision and consistency also play a key role in defect avoidance and component design intent.

Even though the Design Flexibility ranked as fifth with a path coefficient of 0.554, it is still considered to be influential. That is important as it aligns the process of injection molding toward a wide array of projects. The number of design variations that are available is numerous, with some being able to provide more advanced and effective building solutions for a project that has been designed uniquely or with complex parts. Though it does not have much effect compared to the other factors, Design Flexibility becomes an important consideration that complements the whole optimization process.

The fact of predictive relevance of the model, proven by $Q^2 = 0.659$, establishes that the relationships found within the constructs are not only statistically significant but practically relevant. A model with such predictive accuracy will make decisions reliable in what regards the optimization of injection molding processes. This further substantiates the critical role of these processes for efficient, sustainable, and quality construction results.

Table 11. Comparative analysis with previous studies

Study	Construct	Findings from Previous Studies	Findings from Present Study	Comparison/Analysis
[32]	Design Flexibility	Found that design flexibility plays a moderate role in optimizing injection molding, especially in complex geometries.	Identified as the least significant factor ($\beta = 0.554$), though still important in accommodating diverse project needs.	Present study confirms the importance of design flexibility but suggests its relative impact is lower compared to other factors like Structural Performance and Material Efficiency in construction management.
[8]	Material Efficiency	Reported high significance of material efficiency in cost reduction and sustainability across various industries, including automotive and consumer goods.	Material Efficiency is the second most significant factor ($\beta = 0.858$), critical for achieving cost-effective and sustainable injection molding processes.	Both studies emphasize the importance of material efficiency, but the present study specifically highlights its role in the construction sector, aligning with sustainable construction goals and cost optimization.
[21]	Precision and Consistency	Indicated that precision and consistency are essential for achieving high-quality standards but ranked as moderately significant.	Precision and Consistency rank fourth ($\beta = 0.586$) but are essential for ensuring the quality and reliability of structural components.	The present study supports the previous finding that precision and consistency are crucial but not the most dominant factors, highlighting their role in defect avoidance and adherence to design intent.
[11]	Structural Performance	Suggested that structural performance is critical in industries requiring durability and safety, such as aerospace and automotive.	Identified as the most significant factor ($\beta = 0.943$), especially for injection molding in construction to meet high performance and durability standards.	The present study extends the relevance of structural performance from industries like automotive to construction, underscoring its criticality in managing structural components under varied environmental conditions.
[12]	Sustainability and Integration	Highlighted the growing importance of sustainability in manufacturing processes, with an emphasis on integrating green practices.	Ranked as the third most influential factor ($\beta = 0.772$), essential for integrating sustainable practices within the injection molding process.	Both studies confirm the increasing significance of sustainability, but the present study shows its specific application in construction, aligning with global sustainability goals and the need for environmentally friendly practices.

This thus places the current study in a different realm from other studies, as it is narrowed down to the optimization of injection molding within construction—an area that not so many applications target. Unlike most studies, ours does not revolve around one isolated factor, but it encompasses multiple key constructs, such as, for example, structural performance, material efficiency, and sustainability, into one comprehensive framework of construction management, hence offering new insights and practical strategies for efficiency and sustainability within this particular context.

The findings from this study have a few implications for both practice and future research. Practitioners are warned that they may focus on Structural Performance and Material Efficiency as the most promising for improving the injection molding process. However, from an adherence to imperatives of sustainability—certainly the precision and flexibility that would be required in the long run—the adaptable construction industry must need such tools. Future research may consider how rapidly advancing technologies such as advanced materials and real-time monitoring systems can optimize injection molding processes. As such, it can be taken as a scope in studying the scalability of the said result in different types of construction projects, including high-rise buildings, infrastructural development, and prefabricated construction. More space given to the scope of the study could further fine-tune the strategies for optimization and improve the practices' sustainability and efficiency in the construction field.

In conclusion, this paper delineates a strong framework for the optimization of injection molding processes of structural parts for construction management. Such importance is attached to the findings in relation to structural performance, material efficiency, sustainability and integration, precision and consistency, and design flexibility for successful outcomes. The validated model itself provides valued insights not only for practitioners but also for researchers in bringing an efficient, sustainable, and innovative way to the future construction management regime.

6. Conclusion

This research provides a holistic framework for investigation into different methods of optimization for injection molding processes for structural components in construction management by investigating five key constructs: Structural Performance, Material Efficiency, Sustainability and Integration, Precision and Consistency, and Design Flexibility. The results show that Structural Performance and Material Efficiency are, within the group of considered factors, the most critical elements driving the optimization process; therefore, enhancement related to durability and efficient use of materials are the pathways toward deriving cost-effective and sustainable solutions. While the results show that the influence of Sustainability and Integration is also important in underlining that environmental concern needs to be introduced, Precision and Consistency, along with Design Flexibility, although less influential, are also crucial in guaranteeing quality and versatility for parts in varied projects. These insights are further supported by the application of SEM and other advanced statistical procedures within the research, whereby the model emerged as one with strong predictive relevance and some useful practical applications in a real setting. Thus, this study bridges not only the gap between theoretical knowledge and practice but also further helps the construction manager understand how efficiency is enhanced concurrently with cost-cutting in relation to global sustainability goals. It would be necessary to do further research on the implementation of the proposed framework in the various contexts of construction, such as high-rise or those using prefabricated components, but also in view of assessing the effectiveness of newly developed technologies in regard to the optimization of injection moulding processes, such as real-time monitoring systems and advanced materials.

7. Declarations

7.1. Author Contributions

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

7.2. Data Availability Statement

The data presented in this study are available in the article.

7.3. Funding

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7.4. Conflicts of Interest

The authors declare no conflict of interest.

8. References

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