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Integration of Building Information Modelling (BIM) and Computer-Aided Manufacturing (CAM) for Woodwork Fabrication: A Review

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ABSTRACT

The integration of Building Information Modelling (BIM) and Computer-Aided Manufacturing (CAM) offers opportunities to improve accuracy, efficiency, material utilization, and automation in woodwork fabrication. However, empirical evidence on BIM–CAM integration in the Nigerian furniture industry remains limited. This study investigated the feasibility, perceived benefits, challenges, and production implications of BIM–CAM integration in a medium-scale furniture manufacturing company in Ibadan, Nigeria. A mixed-methods case-study design was adopted. Data were collected from personnel involved in design, manufacturing, CNC operations, supervision, management, and CAM/IT activities using questionnaires, semi-structured interviews, direct observation, workflow assessment, and production records. Of 150 questionnaires distributed, 127 were suitable for analysis (84.7% response rate). Quantitative data were analyzed using descriptive statistics and one-way ANOVA, while qualitative data were thematically analyzed. The Perceived Benefits scale demonstrated acceptable internal consistency ($\alpha = .80$). Digital integration was predominantly manual or semi-digital, with CAD + CNC without BIM being most common (37.0%) and full BIM–CAM integration reported by only 13.4%. Manual redraw into CAD was the dominant data-transfer method (68.5%), whereas direct automated transfer was reported by 7.1%. Perceived benefits included reduced human error ($M = 3.13$), improved production speed ($M = 3.13$), and fabrication accuracy ($M = 3.12$). Major barriers were high technology costs (75.6%), inadequate skilled personnel (73.2%), insufficient digital infrastructure (73.2%), employee resistance (72.4%), and unstable electricity (70.9%). Perceived benefits differed significantly across integration levels ($F(4,122) = 2.68$, $p = .035$, $\eta^2 = .08$), while customer-satisfaction impact also differed significantly ($F(4,122) = 7.60$, $p < .001$, $\eta^2 = .20$). BIM–CAM adoption remains uneven, requiring phased implementation supported by skills development, interoperability management, infrastructure, and organizational change.

Keywords: BIM, CAM, CNC, Digital Fabrication, Furniture Manufacturing, Woodwork, Nigeria

Aims Research Journal Reference Format:
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1. INTRODUCTION

Wood has remained an important construction material for centuries, valued for its versatility, structural properties, and availability. Although its use in construction declined following the widespread adoption of concrete and other conventional building materials in the nineteenth century, interest in wood has increased since the 1960s, driven largely by environmental concerns and advances in engineered wood products (Fleury & Chiche, 2006; Hildebrandt et al., 2017; Sakata & Yamazaki, 2022).

More recently, wood has gained renewed recognition as a sustainable construction material because of its renewable nature, relatively low embodied energy, and capacity to store carbon. Hurmekoski et al. (2023) highlighted the potential of wood to contribute to climate change mitigation through carbon sequestration, further strengthening its relevance in contemporary construction. However, the increasing demand for wood-based construction products has created a need for more efficient, precise, and sustainable manufacturing processes.

Despite these developments, traditional woodworking remains largely dependent on manual craftsmanship, conventional machinery, and two-dimensional (2D) technical drawings. Although these methods support customized production, they are often associated with material wastage, fabrication errors, inconsistent product quality, and extended production time. The reliance on manual interpretation of design drawings can also create discrepancies between design specifications and manufactured components, particularly in projects involving complex geometries and intricate joinery. These limitations may constrain productivity and make it difficult for traditional woodworking enterprises to meet the growing demand for high-quality, customized products within competitive production schedules. Consequently, the integration of digital technologies into woodwork design and manufacturing has become increasingly relevant.

Building Information Modelling (BIM) has transformed the architecture, engineering, and construction (AEC) industry by facilitating the creation and management of information-rich digital representations of buildings and their components (Eastman et al., 2018). Beyond its application in building design and construction coordination, BIM provides opportunities to improve the planning and production of wood-based components, including structural timber elements, cabinetry, and architectural millwork. Through detailed three-dimensional (3D) modelling, material scheduling, visualization, and clash detection, BIM enables designers and manufacturers to identify potential design inconsistencies before production. Its information-management capabilities also facilitate the incorporation of material specifications, component dimensions, and assembly requirements into digital models, thereby supporting more coordinated and informed production planning.

Computer-aided manufacturing (CAM) complements BIM by translating digital design information into instructions for automated manufacturing equipment. In woodworking, CAM software facilitates the conversion of digital models into machine-readable instructions for computer numerical control (CNC) routers, milling machines, and other automated equipment (Groover, 2016). This enables the precise cutting, drilling, routing, and machining of wood components, including those with complex geometries and intricate joints. CAM also supports material nesting and toolpath optimization, which can improve material utilization, reduce unnecessary machining operations, and enhance production consistency (Schodek et al., 2014). When integrated with BIM, CAM provides a potential link between digital design and physical fabrication, reducing reliance on manual data interpretation and supporting a more streamlined production process.

The integration of BIM and CAM represents an important development in digital fabrication because it facilitates the transfer of design information into manufacturing processes. In a BIM–CAM workflow, design models can provide geometric and material information for manufacturing, while CAM software translates the relevant data into instructions for CNC machinery. This integration can support mass customization, improve dimensional accuracy, facilitate the early identification of design and fabrication errors, and reduce material waste through optimized cutting strategies (Kolarevic, 2003; Eastman et al., 2018). Furthermore, the incorporation of parametric design and computational modelling can enable the rapid modification of furniture components in response to changes in dimensions, material specifications, and manufacturing constraints (Woodbury, 2010). These capabilities are particularly relevant to furniture manufacturing, where product customization, precision, and efficient material utilization are important production considerations.

Despite these potential benefits, BIM–CAM integration presents technical challenges, particularly in the exchange of information between design and manufacturing software. Interoperability is essential to ensure that geometric and non-geometric information is transferred accurately across different digital platforms. Although the Industry Foundation Classes (IFC) provide an open standard for exchanging BIM information, their application to manufacturing processes remains limited by the need to translate design information into machine-specific instructions and toolpaths (Eastman et al., 2018; Sacks et al., 2020). The conversion of BIM models into formats such as DWG, DXF, and STEP may also result in the loss of parametric information or manufacturing semantics, potentially necessitating additional data processing and manual intervention. These challenges can undermine the efficiency of automated workflows and create inconsistencies between the original design and the fabricated product.

The application of BIM–CAM integration is also closely associated with advances in digital fabrication and industrial automation. Digital fabrication uses computer-controlled technologies to transform digital models into physical components, facilitating the production of complex geometries, prefabricated elements, and customized products (Kolarevic, 2003; Schodek et al., 2014). In woodworking, CNC machining is particularly relevant because it enables repeatable and precise production of furniture components, including panels, joints, and customized architectural elements. Furthermore, developments associated with Industry 4.0, such as intelligent machinery, real-time monitoring, and interconnected manufacturing systems, provide opportunities to improve production planning, process monitoring, and operational efficiency (Kagermann et al., 2013; Lasi et al., 2014). However, realizing these benefits requires appropriate software, compatible machinery, technical expertise, and effective integration of design and manufacturing processes.

The adoption of BIM and automated manufacturing technologies varies across countries and industrial contexts. In developed economies, digital technologies have increasingly been incorporated into construction and manufacturing processes to improve coordination, productivity, and resource efficiency. However, adoption in developing economies is often constrained by financial, technical, and infrastructural limitations. High initial investment costs associated with BIM and CAM software, CNC machinery, hardware, training, and maintenance can present considerable challenges for small and medium-sized enterprises (Azhar, 2011; Groover, 2016). In addition, limited technical expertise, inadequate digital infrastructure, resistance to technological change, and interoperability problems may impede implementation (Eastman et al., 2018; Succar & Kassem, 2015). In Nigeria, these challenges may be compounded by unstable electricity supply, high operating costs, and dependence on imported machinery and equipment (Oke & Aigbavboa, 2017).

The Nigerian furniture industry comprises small workshops, medium-sized manufacturing enterprises, and large-scale producers involved in the production of domestic and commercial furniture and other wood-based products. The industry contributes to employment generation and the value addition of locally available timber resources (Arowosoge & Tee, 2010). Nevertheless, much of its production remains dependent on traditional and semi-mechanized methods, including manual cutting, conventional machinery, handcrafted joinery, and paper-based documentation. These practices can contribute to material wastage, inconsistent product quality, prolonged production cycles, and limited capacity for complex customization (Ogunsemi, 2012). Although some medium-sized furniture enterprises are gradually adopting CNC machinery and computer-aided design and manufacturing technologies, the integration of BIM with CAM remains insufficiently investigated in the Nigerian context.

Previous studies have established the potential of BIM to improve construction information management, collaboration, resource efficiency, and decision-making. For instance, Oladunmoye and Obakin (2021) examined BIM as a digital technology for sustainable construction in Nigeria, highlighting its potential to enhance coordination and resource management. However, their study addressed BIM within the broader construction sector rather than its integration with CAM for automated woodwork fabrication. Similarly, research on digital fabrication has demonstrated the potential of computational modelling, automated manufacturability assessment, and fabrication-oriented design to improve production planning and reduce errors (Hamid et al., 2018; An et al., 2019). Nevertheless, much of the existing literature focuses on BIM applications in building design and construction or automated manufacturing in highly industrialized sectors, with comparatively limited attention to furniture-specific BIM–CAM workflows.

In Nigeria, the limited empirical evidence on BIM–CAM integration in furniture manufacturing presents a knowledge gap concerning the practical feasibility, operational benefits, and implementation challenges of these technologies. In particular, there is insufficient context-specific evidence on the accuracy of information transfer from BIM models to CAM systems, the effects of automated fabrication on material utilization and production efficiency, and the influence of machine settings, material properties, and design complexity on manufacturing precision. Furthermore, the technical, financial, and infrastructural conditions that may affect the implementation of integrated digital fabrication workflows in local furniture enterprises require further investigation.

Addressing these gaps is important for understanding how digital technologies can be adapted to the operational realities of the Nigerian furniture industry. Therefore, this study investigated the feasibility, benefits, and challenges of integrating BIM and CAM technologies for automated woodwork fabrication in a medium-scale furniture manufacturing company in Ibadan, Nigeria. Specifically, the study examined the BIM–CAM workflow, assessed its potential benefits for production accuracy, material utilization, and efficiency, explored strategies for optimizing CAM processes, evaluated the influence of material properties, machine settings, and design complexity on fabrication precision, and investigated the potential of BIM–CAM integration to facilitate automation and digital fabrication in woodwork production.

2. MATERIALS AND METHODS

2.1. Research Design

This study adopted a mixed-methods research design, integrating qualitative and quantitative approaches to investigate the feasibility, benefits, and challenges of integrating Building Information Modelling (BIM) and Computer-Aided Manufacturing (CAM) for automated woodwork fabrication. The mixed-methods approach was considered appropriate because it facilitated the examination of measurable production outcomes alongside the experiences and perceptions of personnel involved in digital fabrication.

Quantitative methods were used to assess production performance indicators, including production time, material waste, and operational efficiency, while qualitative methods explored implementation experiences, workflow challenges, and organizational perceptions of BIM–CAM integration (Creswell & Creswell, 2018). A case-study strategy was employed, focusing on a selected medium-scale furniture manufacturing company in Ibadan, Oyo State, Nigeria. The case-study approach was suitable for examining BIM–CAM integration within its real-life industrial context and understanding the technical and organizational factors influencing its implementation (Yin, 2018).

2.2. Study Area and Study Population

The study was conducted in Ibadan, Oyo State, Nigeria, a major commercial and industrial centre with an established furniture manufacturing sector. The selected company was a medium-scale furniture manufacturer engaged in customized production, operating computer numerical control (CNC) machinery and utilizing elements of digital design and manufacturing. The company was purposively selected because its existing technological capacity and production processes provided a relevant setting for investigating BIM–CAM integration. The study population comprised personnel directly involved in furniture design, manufacturing, and production management. These included architects and designers, BIM personnel, CNC machine operators, production supervisors, factory management staff, and computer-aided manufacturing (CAM) and information technology (IT) personnel. These categories were selected because of their direct involvement in, or professional knowledge of, the design-to-fabrication workflow.

2.3. Sample Size and Sampling Technique

A total of 150 participants were selected purposively based on their professional roles, experience, and direct involvement in furniture design, manufacturing, or production management. Purposive sampling was adopted to recruit participants with relevant knowledge and practical experience of the processes investigated (Saunders et al., 2019). The participants were distributed across five occupational categories, as presented in Table 1.

Table 1. Distribution of the study sample by respondent category

Respondent category	n
Designers/BIM personnel	40
CNC machine operators	10
Production supervisors	25
Factory management staff	55
CAM/IT personnel	20
Total	150

2.4. Data Collection Instruments and Procedures

Both primary and secondary data were used in the study. Primary data were obtained through semi-structured interviews, direct observation, structured questionnaires, production workflow assessments, and production performance records. Secondary data were obtained from relevant journal articles, books, conference proceedings, company documents, publications on BIM and digital fabrication, and software manuals. Four principal instruments were used for primary data collection: a semi-structured interview guide, a structured questionnaire, an observation checklist, and a production data recording sheet. These instruments were developed based on the study objectives and relevant literature on BIM–CAM integration and automated woodwork fabrication.

2.4.1. Semi-structured Interviews

Semi-structured interviews were conducted with selected management personnel, designers, BIM personnel, and manufacturing operators. The interviews explored participants' experiences and perceptions regarding BIM adoption, CAM and CNC utilization, design-to-fabrication workflow integration, software interoperability, automation benefits, and implementation challenges.
The flexible interview format allowed participants to provide detailed accounts of their experiences and identify operational issues associated with digital fabrication.

2.4.2. Structured Questionnaire

A structured questionnaire comprising five-point Likert-scale items was used to collect quantitative data on participants' awareness and use of BIM and CAM technologies, perceived benefits of integration, interoperability experiences, technical competencies, and implementation challenges. The questionnaire facilitated the systematic assessment of participants' perceptions across the different occupational categories.

2.4.3. Direct Observation and Workflow Assessment

Direct observation was used to examine existing furniture production processes, including traditional fabrication methods, CNC operations, digital design procedures, information transfer between design and manufacturing systems, and coordination among personnel. An observation checklist guided the assessment of the design-to-fabrication workflow and the practical application of digital technologies within the company. The workflow assessment also provided an opportunity to examine the integration of digital design information with manufacturing operations and identify potential sources of inefficiency, data-transfer difficulties, and production errors.

2.4.4. Production Performance Data

A production data recording sheet was used to document relevant production performance indicators, including production time, material waste, and operational efficiency. These data were intended to facilitate a comparative assessment of traditional and automated production workflows and provide quantitative evidence of the potential operational benefits of BIM–CAM integration. Secondary data from relevant publications, company records, and software documentation complemented the primary data and provided contextual information for interpreting the findings.

2.5. Validity and Reliability of Research Instruments

The validity of the research instruments was established through expert review in construction technology and digital fabrication. The instruments were examined for clarity, relevance, and alignment with the study objectives. Pilot testing was also conducted to identify ambiguities and assess the suitability of the instruments before the main data collection. The reliability of the structured questionnaire was assessed through pilot testing involving a group with characteristics similar to those of the study participants. Internal consistency was evaluated using Cronbach's alpha, with a coefficient of 0.70 or above considered acceptable (Field, 2018). Necessary adjustments were made to the instruments based on the pilot-testing results.

2.6. Data Analysis

Qualitative and quantitative data were analyzed separately and interpreted collectively to provide a comprehensive understanding of BIM–CAM integration in woodwork fabrication.

2.6.1. Qualitative Data Analysis

Qualitative data obtained from semi-structured interviews and direct observations were analyzed thematically. The analysis involved transcription, familiarization with the data, coding, categorization, and interpretation. Codes were organized into broader themes relating to BIM–CAM integration, workflow efficiency, interoperability, automation, implementation challenges, and organizational readiness. The resulting themes were used to explain participants' experiences and contextualize the practical challenges and perceived benefits of digital fabrication within the selected company.

2.6.2. Quantitative Data Analysis

Quantitative data obtained from the structured questionnaires and production performance records were analyzed using descriptive statistics, including frequencies, percentages, and means. The results were presented in tables and charts to facilitate interpretation.

Comparative analysis was conducted to examine differences between traditional and automated production workflows in terms of production time, material waste, and operational efficiency. Microsoft Excel and the Statistical Package for the Social Sciences (SPSS) were used for data management and analysis.

2.6.3. Integration of Qualitative and Quantitative Findings

The qualitative and quantitative findings were integrated during interpretation to provide complementary insights into the study objectives. Quantitative findings on production performance were considered alongside qualitative accounts of workflow experiences, technical challenges, and organizational factors. This approach enabled the interpretation of measurable production outcomes within the operational context of the case-study company.

2.7. Ethical Considerations

Ethical principles were observed throughout the study. Permission to conduct the research was obtained from the management of the selected furniture manufacturing company. Participants were informed about the purpose of the study, and informed consent was obtained before data collection. Participation was voluntary, and participants were free to withdraw without penalty. Confidentiality and anonymity were maintained throughout the research process. Personal identifiers were excluded from the research dataset and reporting, and findings were presented without disclosing information that could identify individual participants.

3. RESULTS

A total of 150 questionnaires were purposively distributed to eligible respondents, of which 127 were completed and returned in a form suitable for analysis, yielding a response rate of 84.7%. The response rate provided an adequate dataset for the descriptive and inferential analyses conducted in the study. The internal consistency of the multi-item Likert-type scales was assessed using Cronbach's alpha. As shown in Table 2, the Perceived Benefits of BIM–CAM Integration scale demonstrated good internal consistency (α = .80) and was therefore retained as a composite scale for subsequent analysis. The Interoperability Challenges (α = .52), Automation and Industry 4.0 Relevance (α = .58), and Production Performance Impact (α = .56) scales demonstrated lower internal consistency than the conventional .70 criterion. Consequently, items within these scales were analyzed individually using their respective mean scores rather than being combined into composite scores.

Table 2. Reliability Analysis of Research Instrument

Scale	No. of items	α	M	SD
Perceived benefits of BIM–CAM integration	7	.80	19.41	4.46
Interoperability challenges	6	.52	16.03	3.09
Automation and Industry 4.0 relevance	5	.58	16.38	3.30
Production performance impact	5	.56	11.15	3.19

Note. N = 127. α = Cronbach's alpha. Only the Perceived Benefits scale met the ≥ .70 criterion (Field, 2018).

3.1. Demographic Characteristics

Table 3 summarizes respondent demographics. The majority were male (78.7%) and below age 35 (64.6%). Bachelor's degree holders formed the largest educational group (32.3%), followed by diploma (30.7%) and Higher National Diploma (28.3%). General factory workers (40.2%) and designers/architects/BIM modelers (26.8%) dominated occupations. Most (57.5%) had 1–5 years of experience, and 66.9% had received no formal BIM or digital fabrication training. Regarding digital maturity, the largest group (37.0%) reported CAD + CNC without BIM integration; only 13.4% reported full BIM–CAM integration.

Table 3. Demographic and Organizational Profile of Respondents

Variable	Category	n	%
Age group	Below 25	25	19.7
	25–34	57	44.9
	35–44	27	21.3
	45–54	18	14.2
Education	Secondary	11	8.7
	Diploma	39	30.7
	HND	36	28.3
	B.Sc.	41	32.3
Job role	Designer/Architect/BIM modeler	34	26.8
	CNC machine operator	5	3.9
	Production supervisor	22	17.3
	IT/technical staff	15	11.8
	Factory worker (general)	51	40.2
Experience	< 1 year	13	10.2
	1–5 years	73	57.5
	6–10 years	29	22.8
	> 10 years	12	9.4
Formal BIM training	Yes	42	33.1
	No	85	66.9
Digital integration	Manual only	22	17.3
	CAD only (2D)	25	19.7
	CAD + CNC (no BIM)	47	37.0
	Partial BIM–CAM	16	12.6
	Full BIM–CAM	17	13.4

Note. N = 127. HND = Higher National Diploma.

3.2. Knowledge and Current Practice

Understanding of BIM was dispersed, with moderate understanding most common (28.3%; see Table 4). A majority (58.3%) did not understand BIM-to-G-code conversion, and 75.6% were unaware of IFC. Workplace training dominated among those trained (74.8%). Most reported no use of parametric tools (70.9%) or IFC for exchange (65.4%). Data loss during conversion occurred "sometimes" for 68.5%. Manual redraw into CAD was the most common BIM/CAD-to-CNC transfer method (68.5%), followed by DWG/DXF conversion (37.8%; see Table 5). Only 7.1% reported a direct automated workflow, indicating continued reliance on semi-manual transfer.

Table 4. Knowledge and Current Practice of BIM–CAM Integration

Variable	Category	n	%
BIM understanding	Very high	25	19.7
	High	26	20.5
	Moderate	36	28.3
	Low	21	16.5
	No knowledge	19	15.0
CAM/CNC understanding	Very high	28	22.0
	High	16	12.6
	Moderate	34	26.8
	Low	29	22.8
	No knowledge	20	15.7
Training source	Workplace	95	74.8
	School/university	12	9.4
	Online courses	20	15.7
Understands BIM to G-code	Yes	32	25.2
	No	74	58.3
	Not sure	21	16.5
Aware of IFC	Yes	31	24.4
	No	96	75.6
Knowledge adequacy	Very adequate	12	9.4
	Adequate	53	41.7
	Somewhat adequate	29	22.8
	Inadequate	12	9.4
	Very inadequate	21	16.5
Uses parametric tools	Yes	30	23.6
	No	90	70.9
	Not sure	7	5.5
Uses IFC	Yes	33	26.0
	No	83	65.4
	Not sure	11	8.7
Data loss frequency	Very often	4	3.1
	Often	5	3.9
	Sometimes	87	68.5
	Rarely	25	19.7
	Never	6	4.7

Note. N = 127. IFC = Industry Foundation Classes. G-code = machine-control code for CNC equipment.

3.3. BIM-to-CNC Data Transfer Practices

As shown in **Table 5**, manual redraw into CAD was the most frequently reported BIM/CAD-to-CNC data transfer method (68.5%). DWG/DXF conversion was reported by 37.8% of respondents, while 25.2% reported the use of STEP file transfer. Only 7.1% reported using a direct automated workflow. Because respondents could select more than one method, the percentages exceed 100%.

Table 5. BIM-to-CNC Data Transfer Methods (Multiple Response)

Method	n	%
Manual redraw into CAD	87	68.5
DWG/DXF conversion	48	37.8
STEP file transfer	32	25.2
Direct automated workflow	9	7.1
Not applicable	13	10.2

Note. N = 127. Percentages sum to > 100% because respondents could select multiple methods.

3.4. Perceived Benefits

Reduced human error (M = 3.13, SD = 0.88) and improved production speed (M = 3.13, SD = 1.11) were jointly ranked highest, followed by improved fabrication accuracy (M = 3.12, SD = 0.93), indicating moderate agreement (see Table 6). Improved coordination between design and fabrication teams was lowest (M = 2.31, SD = 0.75, Disagree), alongside parametric flexibility (M = 2.45, Disagree).

Table 6: Respondents' Perceptions of Benefits of BIM–CAM Integration

Item	SD (%)	D (%)	M (%)	A (%)	SA (%)	Mean	SD	Remark
Improves fabrication accuracy	7.1	5.5	66.9	9.4	11.0	3.12	0.93	Moderate
Reduces human error	6.3	4.7	68.5	11.0	9.4	3.13	0.88	Moderate
CNC improves speed	8.7	22.0	25.2	36.2	7.9	3.13	1.11	Moderate
Improves coordination	4.7	68.5	20.5	3.1	3.1	2.31	0.75	Disagree
Improves customizatio n	6.3	53.5	27.6	7.1	5.5	2.52	0.93	Moderate
Improves material optimization	10.2	18.1	61.4	6.3	3.9	2.76	0.87	Moderate
Parametric flexibility	9.4	62.2	11.8	7.1	9.4	2.45	1.07	Disagree

Note. N = 127. SD = strongly disagree, D = disagree, M = moderate/neutral, A = agree, SA = strongly agree.

3.5. Interoperability Challenges

Difficulty integrating BIM and CAM systems ranked highest (M = 3.02, SD = 0.96), representing the most strongly perceived challenge (see Table 7). Manual correction after BIM export ranked lowest (M = 2.24, Disagree), suggesting most did not consider manual correction frequently required, alongside lack of standardization (M = 2.30, Disagree).

Table 7. Respondents' Perceptions of Interoperability Challenges

Item	SD (%)	D (%)	M (%)	A (%)	SA (%)	Mean	SD	Remark
Systems difficult to integrate	7.1	13.4	59.8	9.4	10.2	3.02	0.96	Moderate
IFC lacks manufacturing support	8.7	22.8	53.5	7.1	7.1	2.81	0.95	Moderate
Conversion causes errors	11.0	20.5	56.7	5.5	6.3	2.76	0.95	Moderate
Proprietary formats limit use	4.7	23.6	55.1	9.4	7.1	2.91	0.90	Moderate
Manual correction required	14.2	59.8	15.7	7.9	2.4	2.24	0.88	Disagree
Lack of standardization	14.2	63.0	9.4	5.5	7.9	2.30	1.04	Disagree

Note. N = 127. IFC = Industry Foundation Classes. Scale as in Table 6.

3.6. Automation and Industry 4.0

Real-time monitoring of production ranked highest (M = 3.71, SD = 1.14, Very Important), the only item escaping the moderate band (see Table 8). Automation improving productivity ranked lowest (M = 2.91, SD = 1.00), though still moderate.

Table 8. Respondents' Perceptions of Automation and Industry 4.0 Relevance

Item	NI (%)	SI (%)	MI (%)	VI (%)	EI (%)	Mean	SD	Remark
Improved productivity	11.8	11.8	58.3	10.2	7.9	2.91	1.00	Moderate
Reduced production time	7.1	10.2	58.3	11.8	12.6	3.13	1.00	Moderate
Industry 4.0 relevant	10.2	8.7	53.5	11.0	16.5	3.15	1.12	Moderate
Smart systems improve workflow	7.1	15.7	10.2	55.1	11.8	3.49	1.11	Moderate
Real-time monitoring implemented	7.9	8.7	9.4	52.8	21.3	3.71	1.14	Very Important

Note. N = 127. NI = not important, SI = slightly important, MI = moderately important, VI = very important, EI = extremely important.

3.7. Barriers to Integration

High cost of BIM and CNC equipment ranked highest (75.6% combined major/moderate barrier), followed by lack of skilled personnel and insufficient digital infrastructure (both 73.2%; see Figure 1). Employee resistance (72.4%) and unstable electricity (70.9%) were also substantial. Government/industry support ranked lowest (69.3%) but recorded the highest "Not a Barrier" share (13.4%), indicating divided opinion. Because the scale included an "Uncertain" category not representing a further severity point, items were ranked by combined major/moderate percentages rather than means.

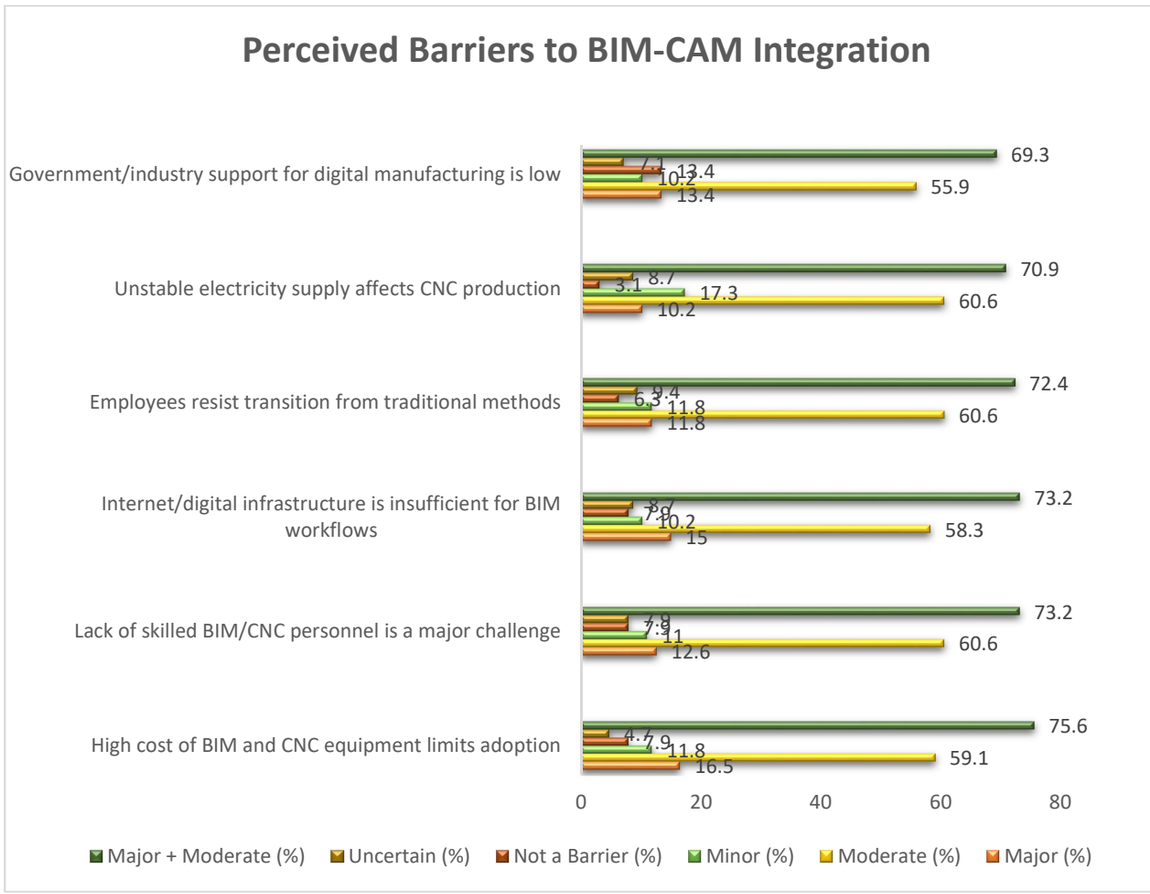


Figure 1. Perceived Barriers to BIM–CAM Integration (Percentage Rating Each Item a Major or Moderate Barrier)

3.8. Production Performance Impact

All five items fell within the Moderate Positive Impact band (Ms = 1.98–2.35 on a 1 = major positive to 5 = negative scale; see Table 10). Waste reduction showed the strongest perceived impact (M = 1.98, SD = 1.16), while scheduling improvement was weakest though still positive (M = 2.35, SD = 1.13).

Table 10. Respondents' Perceptions of Production Performance Impact

Item	MPI (%)	MoPI (%)	MiPI (%)	NoI (%)	NI (%)	Mean	SD	Remark
Reduces waste	49.6	17.3	22.8	6.3	3.9	1.98	1.16	Moderate positive
Reduces rework/errors	14.2	61.4	10.2	8.7	5.5	2.30	1.00	Moderate positive
Improves consistency	11.0	61.4	18.1	4.7	4.7	2.31	0.90	Moderate positive
Improves scheduling	18.1	52.0	11.0	9.4	7.9	2.35	1.13	Moderate positive
Improves satisfaction	22.0	52.0	10.2	7.9	6.3	2.22	1.08	Moderate positive

Note. N = 127. MPI = major positive impact, MoPI = moderate positive impact, MiPI = minor positive impact, NoI = no impact, NI = negative impact. Lower means indicate more positive perceived impact.

3.9. Comparative Analysis by Level of Digital Integration

A one-way analysis of variance (ANOVA) was conducted to determine whether perceived benefits and production performance differed across the five levels of digital integration: manual only, CAD only, CAD + CNC without BIM, partial BIM–CAM, and full BIM–CAM.

3.9.1. Perceived Benefits by Digital Integration Level

As shown in Tables 11 and 12, the mean perceived benefits differed significantly across the five levels of digital integration, $F(4, 122) = 2.68$, $p = .035$, $\eta^2 = .08$. The highest mean benefit score was observed among respondents with partial BIM–CAM integration ($M = 3.19$, $SD = 0.80$), followed by those with full BIM–CAM integration ($M = 2.82$, $SD = 0.92$). The lowest mean score was observed among respondents using manual-only processes ($M = 2.54$, $SD = 0.59$). The effect size indicated that approximately 8% of the variance in perceived benefits was associated with differences in digital integration level.

Table 11. Mean Benefits Composite Score by Level of Digital Integration

Level	n	M	SD
Manual only	22	2.54	0.59
CAD only (2D)	25	2.70	0.63
CAD + CNC (no BIM)	47	2.76	0.39
Partial BIM–CAM	16	3.19	0.80
Full BIM–CAM	17	2.82	0.92
Total	127	2.77	0.64

Note. Benefits composite (7 items, $\alpha = .80$). Higher means indicate stronger perceived benefits.

Table 12. One-Way ANOVA: Benefits Composite by Level of Digital Integration

Source	SS	df	MS	F	p
Between groups	4.13	4	1.03	2.68	.035
Within groups	46.91	122	0.38		
Total	51.04	126			

Note. $\eta = .28$, $\eta^2 = .08$.

3.10. Production Performance by Digital Integration Level

Mean scores for the five production performance indicators across digital integration levels are presented in Table 13. The corresponding ANOVA results are presented in Table 14. There were no statistically significant differences across digital integration levels for perceived reduction in waste, $F(4, 122) = 0.57$, $p = .682$; reduction in rework/errors, $F(4, 122) = 1.42$, $p = .232$; consistency, $F(4, 122) = 1.16$, $p = .332$; or scheduling, $F(4, 122) = 1.73$, $p = .147$.

In contrast, perceived improvement in customer satisfaction differed significantly across digital integration levels, $F(4, 122) = 7.60$, $p < .001$, $\eta^2 = .20$. The mean satisfaction-impact scores ranged from 1.63 among respondents reporting partial BIM–CAM integration to 3.00 among those reporting full BIM–CAM integration. Since lower scores represent more positive perceived impact, the observed group differences indicate substantial variation in perceived customer-satisfaction impact across digital integration levels.

Table 13. Mean Production Performance Impact Items by Level of Digital Integration

Level	n	Waste	Rework	Consistency	Scheduling	Satisfaction
Manual only	22	2.14	2.14	2.18	2.32	1.86
CAD only	25	1.76	2.64	2.36	2.40	2.80
CAD + CNC	47	2.09	2.30	2.26	2.30	2.00
Partial BIM–CAM	16	1.75	1.94	2.13	1.88	1.63
Full BIM–CAM	17	2.00	2.35	2.71	2.88	3.00
Total	127	1.98	2.30	2.31	2.35	2.22

Note. Lower means indicate more positive perceived impact (1 = major positive impact to 5 = negative impact).

Table 14. One-Way ANOVA: Production Performance Items by Level of Digital Integration

Item	F (4, 122)	p	η	η²
Reduced waste	0.57	.682	.14	.02
Reduced rework	1.42	.232	.21	.04
Improved consistency	1.16	.332	.19	.04
Improved scheduling	1.73	.147	.23	.05
Improved satisfaction	7.60	< .001	.45	.20

Note. Only customer satisfaction differed significantly across integration levels.

4. DISCUSSION

4.1. Gap Between BIM–CAM Theory and Practice

The findings demonstrate a substantial gap between the theoretically envisioned BIM–CAM workflow and its implementation in the study setting. BIM–CAM integration is commonly conceptualized as a digital continuum in which design information can move from BIM environments into computer-aided manufacturing and ultimately CNC production with minimal manual intervention (Eastman et al., 2018; Kolarevic, 2003).

However, the present findings indicate that this level of integration has not yet been fully realized in the study company. Manual redraw into CAD was the most commonly reported method of transferring information to CNC systems (68.5%), whereas only 13.4% of respondents reported operating a full BIM–CAM workflow. This finding is consistent with evidence that BIM adoption in Nigeria remains at an emerging stage, particularly when compared with more digitally mature production environments (Aibinu & Venkatesh, 2014). It also corresponds with earlier observations of relatively low levels of digital integration among furniture-sector enterprises (Ogunsemi, 2012). However, the present findings extend this literature by showing that the dominant pattern is not simply the persistence of completely manual production. Rather, respondents reported a mixture of manual, CAD-based, CNC-based, and partially integrated processes. This suggests an incremental transition from conventional production towards digital manufacturing, in which individual technologies may be adopted before they become fully interconnected.

The persistence of semi-manual workflows has important implications for the realization of BIM–CAM benefits. Where design information must be manually redrawn or reformatted before fabrication, opportunities for automated information exchange are reduced and additional points of human intervention are introduced. The finding that only 7.1% of respondents reported a direct automated workflow further demonstrates that the technological components required for digital fabrication may exist without constituting a fully integrated production system.

4.2. Interoperability as a Persistent Barrier

Interoperability emerged as an important limitation to BIM–CAM integration. Awareness and use of IFC were low, with only 24.4% of respondents reporting awareness and 26.0% reporting use. At the same time, DWG/DXF conversion and STEP file transfer were considerably more common, reported by 37.8% and 25.2% of respondents, respectively. Manual redraw remained the dominant transfer approach. These findings are consistent with concerns regarding the limitations of open BIM standards in representing manufacturing-specific information.

Although IFC facilitates information exchange across construction and design applications, fabrication processes may require information relating to manufacturing operations, toolpaths, machine-specific parameters, and CNC logic that is not necessarily transferred seamlessly through conventional BIM exchange mechanisms (Eastman et al., 2018; Sacks et al., 2020). The present finding that 68.5% of respondents experienced data loss during conversion at least sometimes provides further empirical evidence of this challenge within the study setting.

Perceptions of interoperability challenges were also evident in the moderate ratings for difficulty integrating BIM and CAM systems ($M = 3.02$, $SD = 0.96$), proprietary formats limiting interoperability ($M = 2.91$, $SD = 0.90$), and IFC's limited manufacturing support ($M = 2.81$, $SD = 0.95$). These findings reinforce the argument that achieving digital continuity requires more than acquiring BIM, CAD, or CNC technologies individually. Effective integration depends on the ability of these technologies to exchange usable manufacturing information consistently.

However, lack of standardization and the need for manual correction after export were not strongly endorsed as challenges. This may reflect differences in respondents' familiarity with interoperability standards or the normalization of existing workarounds within the company. It may also indicate that respondents experience interoperability problems primarily as system-integration difficulties rather than explicitly identifying them as failures of standardization. These possibilities warrant investigation using qualitative or observational methods.

4.3. Cost, Skills, and Infrastructure Constraints

The principal barriers identified by respondents were high costs of BIM and CNC equipment (75.6%), lack of skilled BIM/CNC personnel (73.2%), and insufficient digital infrastructure (73.2%). Unstable electricity supply (70.9%) and employee resistance to transition (72.4%) were also frequently identified. The prominence of cost is consistent with previous literature identifying the financial burden of digital technologies as an important constraint, particularly for smaller and medium-sized enterprises (Azhar, 2011). The present study extends this observation to a medium-scale furniture manufacturing environment, where the challenge involves not only software acquisition but also CNC equipment, computing infrastructure, training, maintenance, and associated implementation costs.

The skills-related finding is particularly notable. Two-thirds of respondents (66.9%) had received no formal BIM training, while workplace training accounted for 74.8% of reported training sources among respondents who had received training. This pattern is consistent with concerns regarding shortages of appropriately skilled personnel during digital transformation (Succar & Kassem, 2015). The limited understanding of BIM-to-G-code conversion and low use of parametric tools further suggest that exposure to individual digital technologies does not necessarily translate into competence across the complete digital fabrication workflow.

Infrastructure constituted another important constraint. The similar ratings for insufficient digital infrastructure (73.2%) and unstable electricity supply (70.9%) highlight the importance of the broader operating environment in determining the feasibility of advanced digital manufacturing. Digital transformation therefore requires not only technological investment but also reliable supporting infrastructure. Employee resistance was similarly prominent, with 72.4% identifying resistance to transition as a major or moderate barrier. This finding is compatible with diffusion-of-innovation perspectives, which emphasize the influence of perceived uncertainty, organizational context, and user acceptance on technology adoption (Rogers, 2003). In the present context, resistance should not necessarily be interpreted solely as an individual attitude; it may also reflect concerns about changing work processes, inadequate training, role displacement, or uncertainty about new responsibilities.

4.4. Selective Adoption of Industry 4.0 Technologies

The findings suggest that Industry 4.0-related technologies are being adopted selectively rather than as a fully integrated production ecosystem. Real-time production monitoring received the highest rating (M = 3.71, SD = 1.14) and was the only item classified as very important. Smart systems for improving workflow received a mean of 3.49, whereas the perceived relevance of Industry 4.0 itself was moderate (M = 3.15). Improved productivity received the lowest rating among the five items (M = 2.91). This pattern differs from the integrated vision of Industry 4.0, in which interconnected digital systems, automation, real-time information exchange, intelligent decision-making, and continuous optimization operate as components of a broader cyber-physical production environment (Kagermann et al., 2013; Lasi et al., 2014; Wang et al., 2016). In the study setting, individual applications appear to be valued or implemented without necessarily being embedded within an integrated digital manufacturing architecture.

The
relatively high importance attached to real-time monitoring may indicate that organizations recognize the immediate operational value of visibility into production processes even when more advanced forms of automation and integration remain limited. This provides further evidence that digital transformation may occur incrementally, with organizations adopting technologies that address immediate operational needs before progressing towards more complex forms of autonomous or interconnected manufacturing.

4.5. Variation in Perceived Benefits Across Integration Levels

An important finding was the significant difference in perceived BIM–CAM benefits across levels of digital integration, $F(4, 122) = 2.68$, $p = .035$, $\eta^2 = .08$. Respondents in the partial BIM–CAM group reported the highest mean benefit score ($M = 3.19$, $SD = 0.80$), followed by the full BIM–CAM group ($M = 2.82$, $SD = 0.92$), while the manual-only group reported the lowest score ($M = 2.54$, $SD = 0.59$). This finding suggests that perceived benefits were associated with the level of digital integration, but the relationship was not strictly linear across the five categories. In particular, the highest observed benefit score occurred among partial rather than full integrators. This differs from a simple assumption that increasing technological integration necessarily produces progressively greater perceived benefits (Eastman et al., 2018; Groover, 2016).

Several explanations are possible. Firms at the partial-integration stage may have already obtained some of the immediate benefits of digital technologies while retaining relatively familiar production processes. In contrast, organizations operating more extensively integrated systems may face greater demands for interoperability, workforce competence, process redesign, maintenance, and organizational coordination. These additional requirements could affect perceptions of benefits during implementation. However, this explanation should be regarded as a hypothesis rather than a demonstrated causal mechanism. The cross-sectional design does not establish that transition-related difficulties caused the observed difference, and the study did not measure the duration or maturity of each firm's integration process. Longitudinal studies would therefore be required to determine whether perceived benefits initially increase, decline during transition, and subsequently improve as organizations become more experienced with integrated production systems.

4.6. Digital Integration and Production Performance

The overall production-performance findings were positive but did not demonstrate statistically significant differences across integration levels for all indicators. At the aggregate level, waste reduction received the most positive rating ($M = 1.98$, $SD = 1.16$), followed by satisfaction ($M = 2.22$, $SD = 1.08$), rework reduction ($M = 2.30$, $SD = 1.00$), consistency ($M = 2.31$, $SD = 0.90$), and scheduling ($M = 2.35$, $SD = 1.13$). When the five integration groups were compared, no statistically significant differences were observed for waste reduction, rework reduction, consistency, or scheduling. This indicates that the presence of a higher level of digital integration was not, by itself, associated with statistically different perceptions of these production outcomes in this sample. Customer satisfaction was the exception, with a statistically significant difference across integration levels, $F(4, 122) = 7.60$, $p < .001$, $\eta^2 = .20$.

The relatively large effect size indicates that integration level accounted for a meaningful proportion of the variance in perceived satisfaction impact. The partial BIM–CAM group recorded the lowest mean score ($M = 1.63$), indicating the most positive perceived impact, whereas the full BIM–CAM group recorded the highest mean score ($M = 3.00$). Because the overall ANOVA does not identify which specific groups differ from one another, the observed group means should not be interpreted as evidence that partial integration is statistically superior to full integration without appropriate post-hoc testing. Nevertheless, the pattern warrants further investigation because it demonstrates that greater technological integration does not automatically correspond to progressively more favorable perceptions of every production outcome.

4.7. Implications for BIM–CAM Implementation

The findings suggest that BIM–CAM implementation in the study context should be approached as an organizational transformation rather than simply a technology-acquisition exercise. The combination of limited formal training, interoperability difficulties, infrastructure constraints, and employee resistance indicates that successful implementation requires simultaneous attention to technology, people, processes, and organizational support.

The particularly high representation of CAD + CNC without BIM (37.0%) identifies an important transitional group. These organizations already possess components of a digital production environment but have not yet connected them through BIM. Support directed at this group could therefore focus on interoperability, parametric modeling, manufacturing information exchange, and controlled progression towards integrated workflows. The findings also support a phased approach to implementation. Rather than assuming that immediate movement from conventional production to complete BIM–CAM integration is feasible, organizations may benefit from progressive implementation accompanied by training, workflow testing, data-validation procedures, and change-management activities. Such an approach may reduce disruption while allowing organizations to identify interoperability and workforce problems before full-scale implementation.

4.8. Limitations of the study

Several limitations should be considered when interpreting the findings.

- First, the study used purposive sampling within a single medium-scale furniture company in Ibadan, limiting the generalizability of the findings to other furniture firms, production scales, and geographical settings in Nigeria.
- Second, the study relied primarily on self-reported perceptions rather than objective production measures. Consequently, outcomes such as waste reduction, defect rates, dimensional accuracy, production time, and rework were assessed through respondents' perceptions rather than direct production records. The findings relating to these outcomes should therefore be interpreted as perceived impacts rather than objectively measured production effects.
- Third, three multi-item scales, interoperability challenges, automation and Industry 4.0 relevance, and production performance impact, demonstrated Cronbach's alpha values below .70. Their constituent items were therefore analyzed individually rather than as composite constructs. Future studies should refine and psychometrically revalidate these measures before using them as multidimensional scales.
- Fourth, the cross-sectional design limits causal inference. In particular, the finding that partial integrators reported higher mean benefit and customer-satisfaction scores than full integrators cannot establish that partial integration causes better outcomes. Differences in firm characteristics, implementation duration, workforce experience, production complexity, or organizational management may contribute to the observed pattern.

5. CONCLUSION

This study examined the feasibility, perceived benefits, barriers, and production implications of BIM–CAM integration for automated woodwork fabrication in a medium-scale furniture company in Ibadan, Nigeria. The findings indicate that digital integration remains uneven, with production processes characterized predominantly by manual or semi-manual data transfer. Manual redraw into CAD was the most common BIM/CAD-to-CNC transfer method, while direct automated workflows were uncommon. Awareness and use of IFC were also limited. BIM–CAM integration was associated with perceived benefits relating particularly to reduced human error, production speed, and fabrication accuracy. However, interoperability limitations, high technology costs, skills shortages, inadequate digital infrastructure, unstable electricity, and employee resistance represented important barriers to further integration. Industry 4.0 adoption also appeared selective, with real-time monitoring receiving greater perceived importance than broader productivity and smart-system applications.

The comparative analysis demonstrated significant variation in perceived benefits across digital integration levels and a significant difference in perceived customer-satisfaction impact. However, most production-performance indicators did not differ significantly across integration levels. These findings indicate that the relationship between technological integration and perceived production outcomes is complex and should not be assumed to be linear. Overall, the study provides empirical evidence that the transition towards integrated BIM–CAM manufacturing in the Nigerian furniture sector is shaped by interconnected technological, human, infrastructural, and organizational factors.

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