

## DEVELOPING AN INDUSTRIAL ENGINEERING CAPABILITIES FRAMEWORK FOR THE ADOPTION OF ENGINEERED WOOD PRODUCTS IN THE SOUTH AFRICAN CONSTRUCTION INDUSTRY

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### ABSTRACT

The construction industry is embracing sustainable practices to combat environmental degradation and climate change, and engineered wood products (EWPs) offer promise as structural materials for sustainable infrastructure. Despite the benefits of EWPs, challenges such as supply chain integration and market acceptance have limited their use. This paper explores how industrial engineering could facilitate the adoption of EWPs in the South African construction industry, and provides a framework for developing critical industrial engineering capabilities that the South African timber construction sector should possess to integrate EWPs efficiently into construction projects. We used a comprehensive literature review and a curriculum analysis to achieve the study's objectives. By drawing upon these capabilities, the study identified where industrial engineering as an expertise could drive innovation adoption.

### OPSOMMING

Die konstruksiebedryf aanvaar volhoubare praktyke om omgewingsagteruitgang en klimaatsverandering te bekamp, en vervaardigde houtprodukte (EWP's) bied belofte as strukturele materiaal vir volhoubare infrastruktuur. Ten spyte van die voordele van EWP's, het uitdagings soos voorsieningskettingintegrasie en markaanvaarding die gebruik daarvan beperk. Hierdie artikel ondersoek hoe bedryfsingenieurswese die aanvaarding van EWP's in die Suid-Afrikaanse konstruksiebedryf kan fasiliteer, en bied 'n raamwerk vir die ontwikkeling van kritieke industriële ingenieursvermoëns waaroor die Suid-Afrikaanse houtkonstruksiesektor behoort te beskik om EWP's doeltreffend in konstruksieprojekte te integreer. Ons het 'n omvattende literatuuroorsig en 'n kurrikulum-analise gebruik om die studie se doelwitte te bereik. Deur op hierdie vermoëns te gebruik, het die studie geïdentifiseer waar bedryfsingenieurswese as 'n kundigheid die aanvaarding van innovasie kan dryf.

## 1. INTRODUCTION

Considering its extreme consumption of resources [1], [2], [3] and the corresponding negative effect on the environment [4], [5], [6], [7], the construction industry is under pressure to adopt sustainable solutions [3], [8]. In the building construction sector, the development of engineered wood products (EWPs) - a new class of wood materials made by combining wood elements with adhesives - has led to the revival of interest in timber applications in construction [9] and the consideration of timber as a sustainable alternative to brick, concrete, and steel [6].

EWPs have several benefits in construction. They have structural, load-bearing capabilities, since wood has a strength-to-weight (STW) ratio that is superior to conventional construction materials [10], [11]. Cross-laminated timber (CLT), one of the most commonly used EWPs, can withstand fire conditions, and delivers a better fire performance than standard concrete and steel construction because of its slow and predictable charring process and the strength of its partially burned layers [12].

The flexibility of EWPs extends to prefabricating building elements away from the construction site. This contributes to speedy construction projects and reduced labour costs [13], [14]. In addition, EWPs are more sustainable materials. They are made from wood, which is a renewable resource [15], which helps to store carbon beyond the forest [16] and produces significantly lower carbon dioxide (CO<sub>2</sub>) emissions during production and use than other materials [17]. Buildings made with EWPs also possess adequate insulation qualities, limiting the need for expensive heating apparatus and reducing energy costs and emissions [18].

Despite these benefits, the adoption of EWPs in building construction could be higher. One possible enabler to increase the adoption rate of EWPs would be collaboration between the construction industry and other sectors [19]. This study explores how industrial engineering could facilitate the adoption of EWPs in the building construction sector, and provides a framework for developing critical industrial engineering capabilities that the South African timber construction sector should possess to integrate EWPs efficiently into construction projects.

## 2. LITERATURE REVIEW

Engineered wood products (EWPs) are composite materials from wood fibres, strands, or particles bonded together using adhesives and other binding agents [9]. These products are designed to enhance the structural performance, durability, and versatility of wood in construction and other applications [20]. Sawn-board-based EWPs, including cross-laminated timber (CLT) and glue-laminated timber (glulam) [21], are some of the most widely used EWPs in building construction [9], where they are referred to as 'mass timber' [22]. Mass timber building construction (MTC) projects are seeing significant use cases in multi-storey timber construction, with the Stadhaus (an eight-storey building in the United Kingdom), the UBC Brock Commons (an 18-storey building in Canada), and the HoHo Wien (a 24-storey building in Austria) serving as some of the most widely known examples [23].

Despite the benefits of MTC and building with EWPs, adoption still needs to be improved. A review of the adoption of EWPs revealed that many of the barriers to using them are perceptions about the quality of timber, inherited from a negative historical view of solid wood as a building material, and that do not necessarily reflect the present abilities of EWPs [19]. However, some barriers are tangible and substantial. One crucial aspect is the limited supply of EWPs for building construction projects [14], [24], [25]. This is a result of several factors, including the reliance on nearby forests for timber supply [10], the lack of local production facilities in many regions [24], [26], and even transportation problems [24], [25]. Some contractors have imported EWPs for their projects. However, that increases the cost of construction and limits the cost competitiveness of MTC [12]. Without local production, widespread adoption is also difficult [14].

Legislation and building codes also contribute to limiting the adoption of EWPs. Existing construction codes and standards have restrictive rules for using timber in construction [11], [27], [28]. Fire safety regulations limit the use of timber in construction owing to concerns over the flammability and combustibility of wood [29]. These regulations may restrict the height of buildings constructed with wood [30], and include requirements for elaborate and expensive fire prevention mechanisms [31]. In recent years, many studies have demonstrated the safety capabilities of wood products when exposed to fire [32], and positive results have even led to more accommodating building codes for timber construction in some regions [30].

Establishing clear and comprehensive building codes that address the specific properties and requirements of EWP would be essential to promote their widespread adoption [33].

The lack of familiarity with timber building processes is another limiting factor. A skills and knowledge gap exists in the construction industry about using EWPs [10]. Thus decision-makers are unlikely to consider timber in the project conception phase when the choice of material is made [11]. Moreover, the dominance of concrete as the preferred construction material has led to path dependency in the industry and in established supply and value chains [31]. The perception exists that the use of timber would require a separate supply chain that might not be compatible with the existing model [34]. The dominance of concrete also leads to a reluctance among construction professionals to learn about other materials [27].

Furthermore, although EWPs are labelled as a sustainable alternative for the construction industry, several environmental concerns have attracted attention. One significant issue is the potential impact of wood-based products on forest ecosystems and biodiversity, and the implications for greenhouse gas emission reduction goals [35]. Moreover, using formaldehyde-containing adhesives in wood products has raised environmental and health apprehensions, prompting research to identify formaldehyde-free alternatives [36]. Similarly, the emission of volatile organic compounds (VOCs) from engineered wood products beyond formaldehyde has also been identified as a critical area needing further investigation [37]. Lu *et al.* [38] observed that using chemicals and energy to produce EWPs may limit their sustainability. Therefore, addressing the sustainability of EWPs would be essential for MTC [39].

Several ideas have been proposed to improve the adoption of EWPs in the construction industry. Incorporating EWPs into green building certifications might boost the visibility of MTC and the acceptance of EWPs in the construction industry [40]. Another recommendation is the establishment of more timber production facilities [10]. Timber construction professionals have also been urged to demonstrate and broadcast the positive qualities of EWPs as structural materials [41], and government support has also been deemed critical for the growth of the sector [24]. The literature is rife with suggestions that the construction industry is itself a barrier to the adoption of EWPs [12], [13], MTC [10], [26] and of new technologies generally [17], [27]. Kim *et al.* [42] have suggested that other disciplines could influence the construction industry to consider innovative and alternative approaches.

In that vein, Forbes [43] identified 20 core industrial engineering principles and methodologies that could benefit the construction industry. These principles are automation with radio frequency identification (RFID), automation or robotics, continuous improvement, cycle-time analysis, ergonomics or human factors, facilities layout, the International Standards Organization (ISO) ISO9000 standards, lean methodology, operations research and statistical applications, productivity management, quality function deployment (QFD), quality management, safety management, simulation, sustainable construction, supply chain management, systems integration, the learning curve, value engineering, and work measurement [43]. This study uses these principles to investigate possible industrial engineering applications in promoting the adoption of EWPs in the construction industry. This study provides two specific contributions to the literature. First, it combines findings from several applications of industrial engineering in MTC to provide researchers with comprehensive evidence of their effectiveness. To the best of the authors' knowledge, this paper is also the first to analyse how current South African industrial engineering coursework addresses the use of engineered wood products (EWPs) and mass timber construction (MTC). The analysis highlights a significant gap in industrial engineering curricula, and proposes enhancements to prepare students better for careers in timber construction.

### 3. MATERIALS AND METHODS

This study used a combination of a systematic literature review and a review of the curriculum guides of industrial engineering programmes in South African universities. A preliminary literature search was conducted to identify industrial engineering applications in the construction industry. Forbes [43] proved instructive, as the author identified 18 core industrial engineering principles and methodologies that could benefit the construction industry. After that, a series of search terms were developed from descriptions of the principles. These search terms were combined with "engineered wood" and "mass timber" to search for relevant articles. The Scopus and Web of Science databases were used, as they have emerged as preferred repositories for research articles [44]. The search terms and the number of results are displayed in Table 1.

**Table 1: Search terms and results**

Search terms	Number of results	
	Scopus	Web of Science
“Industrial engineering”, “ergonomics”, “work improvement”, “learning curve”, “productivity”, “continuous improvement”, “automation”, “robotics”, “ISO”, “cycle time analysis”, “supply chain”, “RFID”, “safety”, “systems”, “simulation”, “quality”, “facility”, “operations”, “statistics”, “sustainable construction”, “value engineering”.	1,362	463

From the total number of records, 731 duplicates were identified and removed from the selection. The titles and abstracts of the remaining 1094 records were reviewed to determine whether they fitted the descriptions by Forbes [43]. This resulted in a selection of 128 articles. However, only 95 were available for full-text download and retrieval.

The second method was a review of curriculum guides to determine whether industrial engineering programmes in South African institutions provided educational content and training to assist students in applying industrial engineering principles in the construction industry. A three-step process guided the investigation. An initial online search led to the South African Department of Basic Education’s list of higher educational institutions, with a database of 26 institutions on record [45]. The websites of these institutions were reviewed to identify industrial engineering programmes. Eleven institutions displayed information about having industrial engineering programmes. In the second stage of the search, the number of industrial engineering programmes from these 11 institutions was identified, amounting to 45 programmes. Full research programmes, such as Master’s by research and Doctor of Philosophy programmes, were excluded, leaving 28 programmes with teaching and learning content.

The last stage of the review involved listing the modules/subjects in these programmes to investigate their relevance. The 27 programmes contained 538 modules, of which 37 were duplicates. (Duplicate modules were defined as modules within the same institution with the same names and module descriptions across multiple programmes.) The module names for the remaining 501 modules were then reviewed against the industrial engineering principles and methodologies listed in Table 1 for their relevance. This led to the selection of 126 relevant modules. Finally, module descriptions were retrieved for analysis. When module descriptions were unavailable, module outcomes were retrieved instead, if available, to assist in deciphering the purpose of the modules. Descriptions and outcomes for 85 modules were retrieved.

#### 4. RESULTS

The results from the literature and curricula reviews are presented in two tables. Table 2 shows the distribution of articles identified for each principle/methodology outlined in this study.

**Table 2: Articles with industrial engineering applications in timber construction**

Industrial engineering principle/methodology	Number of articles	Corresponding article references
Automation	4	[46], [47], [48], [49].
Continuous improvement	2	[50], [51].
Ergonomics	1	[52]
ISO	2	[53], [54].
Operations and statistical analysis	1	[55]
Quality management	1	[56]
Safety management	4	[57], [58], [59], [60].
Simulation	37	[61], [62], [63], [64], [65], [66], [67], [68], [69], [70], [71], [72], [73], [74], [75], [76], [77], [78], [79], [80], [81], [82], [83], [84], [85], [86], [87], [88], [89], [90], [91], [92], [93], [94], [22], [95].

Industrial engineering principle/methodology	Number of articles	Corresponding article references
Supply chain management	5	[96], [97], [98], [99], [100].
Sustainable construction	3	[101], [102], [103].
Value engineering	35	[104], [105], [106], [107], [108], [109], [110], [111], [112], [113], [114], [115], [116], [117], [118], [119], [120], [121], [122], [123], [124], [125], [126], [127], [128], [129], [130], [131], [132], [133], [134], [135], [136], [137], [138].

Table 3 shows the distribution of industrial engineering modules whose descriptions aligned with the 18 relevant principles and methodologies previously identified in this paper. The table provides each module's name and the degree level at which it was offered. These levels were Diploma, Advanced Diploma, Bachelor of Engineering (BEng), Bachelor of Engineering Technology (BEngTech), Bachelor of Engineering with Honours (BEngHons), Bachelor of Engineering Technology with Honours (BEngTechHons), and Postgraduate Diploma (PGDip). The table also shows whether the modules were offered at the undergraduate or postgraduate level and at which institutions. The institutions from which this information was accessed were the Cape Peninsula University of Technology (CPUT) [139], the Durban University of Technology (DUT) [140], North West University (NWU) [141], [142], Stellenbosch University [143], the University of Pretoria (UP) [144], [145], the Tshwane University of Technology (TUT) [146], and the Vaal University of Technology (VUT) [147].

**Table 3: A selection of industrial engineering modules at South African universities**

Industrial engineering	Module	Qualification	Level	Institution
Automation/RFID/Robotics	Automation 3	Diploma	Undergraduate	VUT
Ergonomics	Industrial ergonomics 414	BEng	Undergraduate	Stellenbosch
	Human factors and ergonomics	Advanced Diploma	Undergraduate	VUT
Facilities layout	Facility layout and materials handling	Diploma	Undergraduate	CPUT
	Facilities planning	BEngTech	Undergraduate	DUT
	Facilities design	BEng	Undergraduate	NWU
	Facilities planning 320	BEng	Undergraduate	UP
	Facilities layout and material handling 2	Diploma	Undergraduate	VUT
	Facility planning and design	Advanced Diploma	Undergraduate	VUT
	Advanced facility design	PGDip	Postgraduate	VUT
Operations research and statistical analysis	Operations research	Diploma	Undergraduate	CPUT
	Statistics I	BEngTech	Undergraduate	DUT
	Operations research	BEngTech	Undergraduate	DUT
	Operations management for engineers	BEng	Undergraduate	NWU
	Statistics for industrial engineering	BEng	Undergraduate	NWU
	Operational excellence	BEng	Undergraduate	NWU
	Statistical learning for engineers	BEng	Undergraduate	NWU
	Operations excellence	PGDip	Postgraduate	NWU
	Operations management and supply chains	PGDip	Postgraduate	NWU

Industrial engineering	Module	Qualification	Level	Institution
Industrial engineering	Engineering statistics 220	BEng	Undergraduate	UP
	Operational management 310	BEng	Undergraduate	UP
	Operational research 312	BEng	Undergraduate	UP
	Operational research 410	BEng	Undergraduate	UP
	Operations research	BEngHons	Postgraduate	UP
	Operations research (Eng)	BEng	Undergraduate	Stellenbosch
	Operations research (Eng) 415	BEng	Undergraduate	Stellenbosch
	Operational research	BEngTech	Undergraduate	TUT
	Operations management	BEngTechHons	Postgraduate	TUT
	Advanced operational research	BEngTechHons	Postgraduate	TUT
	Operations research 3	Diploma	Undergraduate	VUT
Productivity management	Industrial production engineering	Diploma	Undergraduate	CPUT
	Production engineering 1	BEngTech	Undergraduate	DUT
	Production engineering 2	BEngTech	Undergraduate	DUT
	Production engineering 3	BEngTech	Undergraduate	DUT
	Production engineering 4	BEngTechHons	Postgraduate	DUT
	Productivity 220	BEng	Undergraduate	UP
	Production management 212	BEng	Undergraduate	Stellenbosch
	Production and automation	BEngTech	Undergraduate	TUT
	Production engineering	BEngTech	Undergraduate	TUT
	Production engineering 1	Diploma	Undergraduate	VUT
	Production engineering 2	Diploma	Undergraduate	VUT
Quality Management	Qualitative techniques	Diploma	Undergraduate	CPUT
	Quality engineering	Advanced Diploma	Undergraduate	CPUT
	Quality engineering	BEngTech	Undergraduate	DUT
	Quality assurance for engineers	BEngTechHons	Postgraduate	DUT
	Quality assurance	BEng	Undergraduate	NWU
	Quality management	PGDip	Postgraduate	NWU
	Quality assurance 410	BEng	Undergraduate	UP
	Quality management	BEngHons	Postgraduate	UP
	Quality assurance 344	BEng	Undergraduate	Stellenbosch
	Quality management 444	BEng	Undergraduate	Stellenbosch
	Quality engineering and management systems	BEngTech	Undergraduate	TUT
	Quality engineering	BEngTechHons	Postgraduate	TUT
	Quality assurance 2	Diploma	Undergraduate	VUT

Industrial engineering	Module	Qualification	Level	Institution
	Quality control and improvement	Advanced Diploma	Undergraduate	VUT
Safety management	Safety principles and law 1	Diploma	Undergraduate	VUT
Simulation	Simulation modelling	BEngTech	Undergraduate	DUT
	Simulation modelling	BEng	Undergraduate	NWU
	Modelling and simulation	PGDip	Postgraduate	NWU
	Simulation modelling 321	BEng	Undergraduate	UP
	Simulation modelling	BEngHons	Postgraduate	UP
	Simulation 442	BEng	Undergraduate	Stellenbosch
	Simulation design	BEngTech	Undergraduate	TUT
	Modelling and simulation	Advanced Diploma	Undergraduate	VUT
	Advanced modelling and simulation	PGDip	Postgraduate	VUT
Supply chain management (SCM)	Logistics engineering	Advanced Diploma	Undergraduate	CPUT
	Supply chain management	BEng	Undergraduate	NWU
	Industrial logistics 320	BEng	Undergraduate	UP
	Supply chain processes	BEngHons	Postgraduate	UP
	Supply chain design	BEngHons	Postgraduate	UP
	Supply chain systems	BEngTech	Undergraduate	TUT
Sustainability	Sustainable management	BEngTechHons	Postgraduate	TUT
Systems integration	Systems engineering	Diploma	Undergraduate	CPUT
	Systems engineering	Advanced Diploma	Undergraduate	CPUT
	Systems engineering	BEng	Undergraduate	NWU
	Systems engineering 410	BEng	Undergraduate	UP
	Systems engineering	BEngHons	Postgraduate	UP
	Systems engineering	BEngTech	Undergraduate	TUT
	System dynamics	BEngTechHons	Postgraduate	TUT
Work measurement	Engineering work study	Diploma	Undergraduate	CPUT
	Engineering work systems	BEngTech	Undergraduate	DUT
	Engineering work systems 2	BEngTech	Undergraduate	DUT
	Engineering work systems 3	BEngTech	Undergraduate	DUT
	Engineering work systems 4	BEngTechHons	Postgraduate	DUT

## 5. DISCUSSION

The discussion section is presented in two parts. First, a discussion of the industrial engineering applications in MTC is presented. Then, a discussion of the industrial engineering curriculum in South Africa is provided. Finally, a framework for implementing industrial engineering in adopting EWPs and MTC is provided and discussed.

## 5.1. Application of industrial engineering principles and methodologies in MTC

### 5.1.1. Automation

Automation is the process of developing systems that function autonomously [148]. Since its first reported use in the 1930s [149], automation has been used in various industries such as aerospace, agriculture, energy, healthcare, manufacturing, and transportation [148], [149], [150]. In the construction industry, automation may improve operations by using robots and RFID [43]. Robots can move components, tools, materials, and specialised equipment for intricate jobs [151], while RFID technology may help to track goods and ensure a more effective supply chain that offers real-time accountability [152]. RFID can also increase worker efficiency in repeated processes such as framing systems and modular components, and decrease equipment selection and installation errors [43].

One automation application in MTC is the Greenbuild Pavilion, a construction workflow that used a robot to develop a modular timber structure. The robot, equipped with various tools and a digital parametric model, constructed the pavilion with standard-sized timber pieces [46]. Similarly, Janakieska *et al.* [47] documented a project at the University of Stuttgart that blended computing technology and robotics to develop a lightweight structure from fibre composites. Current construction methods and materials are made for human sizes and assembly; however, engineered wood products could push the size and scale of building construction projects that can be developed. Robotics could assist in reconceptualising the design and manufacturing possibilities of MTC [49].

### 5.1.2. Continuous improvement, cycle-time analysis, productivity management, and work improvement

Adopting an approach of reviewing completed projects and endeavouring to document the lessons learned to develop best practices for construction may eventually improve the value derived from construction projects [43]. Implementing process optimisation techniques could pinpoint the optimal approaches for completing repetitive tasks, which constitute a significant part of building projects [43]. Kasbar *et al.* [50] and Poirier *et al.* [51] reviewed different aspects of the construction of the Brock Commons Tallwood House, an 18-storey mass timber hybrid building at the University of British Columbia, to derive and document lessons from the project that could inform future projects. Poirier *et al.* [51] examined innovations in the design process, and found that a ‘balanced triple-helix’ system involving the government, industry, and academia enabled innovation in the project.

Kasbar *et al.* [50] focused on the project’s productivity with specific data on crane usage, installation productivity, and schedule reliability. The findings revealed a notable increase in labour productivity that was attributed to the prefabrication of mass timber components and the integration of virtual design and construction modelling in both the planning and the construction phases [50]. The project specifically demonstrated the importance of the learning curve effect, as installation times reduced by more than half as construction approached the top floors compared with the lower floors [50]. Cycle time analysis allows for the implementation of process optimisation techniques to pinpoint the optimal approaches for completing repetitive tasks [43]. In addition, the structural installation and envelope cladding were finished almost seven weeks before schedule, demonstrating increased project productivity [50]. However, the discrepancy between estimated and actual installation times reflected the need for more familiarity with the process [50].

### 5.1.3. Ergonomics and safety management

The construction industry has a poor reputation for experiencing occupational accidents [153], [154], and safety is a significant focus [155]. Worker safety is a particular cause for concern, with stringent occupational health and safety requirements for managing safety on the construction site [156]. MTC involves the use of wood screws and nails, which require power tools such as nail guns [157]. Using these tools has health and safety consequences, including a condition known as hand-arm vibration syndrome (HAVS) that mainly afflicts carpenters and joiners [158]. Industrial ecology and safety engineering could be used to identify and quantify the effects of construction activities on worker health and safety [43]. Research by BuHamdan *et al.* [52], for instance, attempted to predict the risk of workers getting HAVS when using various carpentry tools.



#### **5.1.4. ISO and quality management**

In the current competitive global landscape, quality management is essential as businesses seek an advantage [159]. In recent years, construction companies have begun exploring methods of adopting ISO standards, with mixed results [160]. Many clients now expect vendors to have and meet these certifications and standards so that ISO standards may play a role in construction practices in the future [43]. The effect of fire on timber is one significant perception to be overcome [33], and many tests have been performed to investigate the performance of EWP. Alves *et al.* [53] conducted experimental tests to determine the behaviour of multilayered wood systems in fire, based on a specific ISO 834 standard. Similarly, Chang *et al.* [54] assessed the thermal bridging performance of CLT structures, based on the ISO 10211 standard. Tests such as these provide helpful information for designing and constructing buildings with EWPs [53].

#### **5.1.5. Simulation**

Simulation is considered one of the most essential industrial engineering methodologies, and is widely acknowledged for its value in aiding decision-making [161]. The results of this literature review support that claim, as simulation is the methodology most often used in the programmes that were reviewed. Autengruber *et al.* [62] developed a tool to analyse the scope of the heat and moisture dynamics of timber in several operational contexts because of the tendency of wood to exhibit different properties with moisture. Bezabeh *et al.* [66] used Monte Carlo simulations to assess the vulnerability of tall MTC buildings to strong winds. Similarly, Bolvardi *et al.* [68] designed a system to make tall MTC buildings more seismic-resistant, and tested the system using time-history simulations. Bui *et al.* [70] analysed the vibration frequencies of new adhesive-free EWPs and compared them with experimental results, while Caniato *et al.* [72] also simulated the sound properties of MTC buildings and proposed suggestions to make timber structures more sound-proof. One of the benefits of simulations is their ability to evaluate the results of experimental tests at lower costs [62].

#### **5.1.6. Supply chain management**

Several authors have highlighted the limited availability of EWPs as a significant barrier to adoption [12], [14], [25], [27]. Location [10], transportation [25], and inventory management [14] are some specific supply chain-related barriers that have been highlighted. One approach to managing the supply chain is identifying locations for setting up manufacturing plants [96], [98]. Long transport distances within the supply chain for EWPs may negate the carbon gains from using wood, and even demonstrate higher global warming potential (GWP) than locally produced reinforced concrete [105]. Thus locating a production facility near a forest could help to reduce the cost of EWPs [97]. An effective supply chain management system in the construction industry would require holistic approaches that considered all parts of the supply chain rather than fragmented approaches that looked to only one section of the value chain [43].

#### **5.1.7. Sustainable construction and value engineering**

One of the significant benefits of EWPs in construction is their sustainability. The use of wood in the production of EWPs allows for carbon storage beyond the forest, and timber structures have a lower environmental footprint than conventional materials [162]. Still, industrial engineering could help to ensure that this material is used along with sustainable methods and processes. For instance, studies are ongoing on the ability of bamboo to serve as an alternative 'wood' material in areas with extensive bamboo plantations, such as Ethiopia [101]. There is also an increased focus on the role of mass timber in the circular economy. A scenario analysis of post-end-of-life options for mass timber buildings showed that the reconstruction of a new building from the timber components of the old building was possible and would have the most negligible impact on the environment [104]. Tumbaga *et al.* [103] argued that MTC aligns with many of the goals of the circular economy. Thus adopting EWPs would be a valuable opportunity for proponents of sustainability.

Life cycle assessment/analysis (LCA) was a recurring methodology identified in this review. This included the comparison of different types of EWPs to measure their environmental impact [107], [136], the comparison of wood and concrete in tall building construction [133] and residential buildings [113], [116], using reprocessed wood cuttings to produce CLT panels [135], and composite timber systems [109], [131]. LCA is an effective tool for selecting, designing, and constructing building projects [133].

## 5.2. Industrial engineering studies at South African universities

The industrial engineering principles and methodologies identified and outlined in Table 1 are well represented as modules in industrial engineering programmes in South African universities. Quality management is well reflected in the curriculum, as quality modules make up a significant proportion of the industrial engineering modules in this paper. CPUT's qualitative techniques module provides an in-depth introduction to quality management, focusing on quality systems such as ISO 9000 and the challenges and opportunities in maintaining high-quality standards [139]. The quality engineering modules provide a comprehensive understanding of the critical importance of quality in maintaining a competitive advantage in various industries. Total quality management, statistical process control, and quality function deployment are some quality principles that these modules cover [139], [140].

The productivity modules teach students to measure, analyse, and improve productivity in various organisational contexts, and emphasise the importance of designing workspaces and processes that enhance worker behaviour and motivation [144]. Similarly, the engineering work modules cover various aspects of productivity, including principles, management, human factors in operations, and time study techniques to measure work [139], [140]. The ergonomics modules in this review emphasise optimising the relationship between people and their work environments [143], [147]. They explore operations analysis, work standards, and the design of effective work processes [143], [147]. Anthropology is a key focus as a tool for designing workstations and tools that fit workers' characteristics. Futuristic approaches considering cognitive work and digital technologies are also addressed, preparing students for ergonomics and safety management in a digital world [143].

The design of effective spaces is also tackled in the facility design modules. Well-designed facilities that optimise space, workflow, and productivity are essential industrial engineering goals. The modules include practical exercises that encourage students to combine various factors, such as logistics, cost, and accessibility, to design optimal spaces. The simulation modules provide a grounding in simulation approaches such as the discrete-event simulation and Monte Carlo methods [141]. In particular, identifying and representing the randomness and uncertainty of real-world systems to enable the creation of accurate and reliable models is a key focus [140]. They also introduce systems thinking and systems approach to give students a holistic perspective on the complex interactions in systems [140]. These skills are developed further in the systems engineering modules, as they provide students with real-world problems to assist them in integrating system components to work seamlessly [144], [146]

VUT's automation 3 module is one of only a few modules that focus on production systems working autonomously. It covers foundational concepts such as production, automation, and systems, and explores various considerations for automation [147]. Students learn to design progression tooling and to perform calculations to minimise material usage in order to ensure cost-effectiveness. The practical module allows students to create systems and workstations and to implement solutions in order to enhance production efficiency [147]. Similarly, the safety principles and law module provides a comprehensive overview of occupational health and safety concepts and regulations, equipping students with the ability to identify, assess, and manage workplace hazards effectively [147].

One major drawback of these modules is their limited focus on construction and the use of mass timber. A cursory review of materials-related modules in these institutions revealed an absence of wood or EWPs as materials for consideration in these programmes. Continuous improvement and cycle-time analysis are also not represented in these modules, although several module descriptions, including operations management for engineers, operational excellence, and quality assurance, adopt a continuous improvement approach to aspects of the curriculum [142]. As shown above, there are numerous potential applications of industrial engineering principles and methodologies in improving construction outputs [43], and extending the coverage of these principles to include sustainable construction practices such as timber construction could improve adoption prospects [163].

## 5.3. Industrial engineering capabilities framework

The use of engineered wood products in construction faces several significant barriers that hinder its adoption despite its environmental and structural benefits. As discussed in this paper, these barriers include uncertainties about material performance, regulatory barriers, cost concerns, and a lack of engineering and training in timber construction [19]. However, industrial engineering could play a critical role in overcoming these difficulties and promoting the adoption of EWPs. In developing the framework, similar

and related benefits were grouped, creating seven major beneficial categories to explore industrial engineering's ability to influence the use of EWP in construction. These include construction process improvement (CPO), which encompasses improving modular construction [49] and the evolution of construction into a structured manufacturing process [164]. A continuous improvement approach to MTC could lead to speedier execution of projects as knowledge is gained and shared in the building construction industry [50].

The negative perception of the fire performance of timber is a major barrier, and extensive research has been done and is ongoing to demonstrate the superior qualities of EWPs in combustion circumstances. A quality approach to fire perceptions and to material performance concerns in general could pay dividends as consumers become more quality-conscious and pay attention to ISO ratings and guidelines [43], thereby contributing to the quality management and standardisation of EWPs. Supply chain management could help to improve the availability of timber products, the design of the timber supply chain, cost reduction in the prices of EWPs, and even better sustainability outputs [97], [105]. Similarly, LCA might provide more information on the merits and demerits of MTC for continuous improvement purposes [133].

Beyond overcoming the barriers, industrial engineering may help to explore new avenues for using EWPs. Simulation and modelling software, already quite popular in research, could be used to improve product and process design [62], [63]. Proponents of green building and circular economy principles could use value engineering approaches to combine EWPs with other sustainable materials for the building industry [108]. Furthermore, although the curriculum review revealed the need for more MTC content, it has been demonstrated that the skills and knowledge they impart could still be useful in improving EWP adoption. Similarly, facility design and layout modules could prove useful as EWPs are used in more complex building construction projects [165].

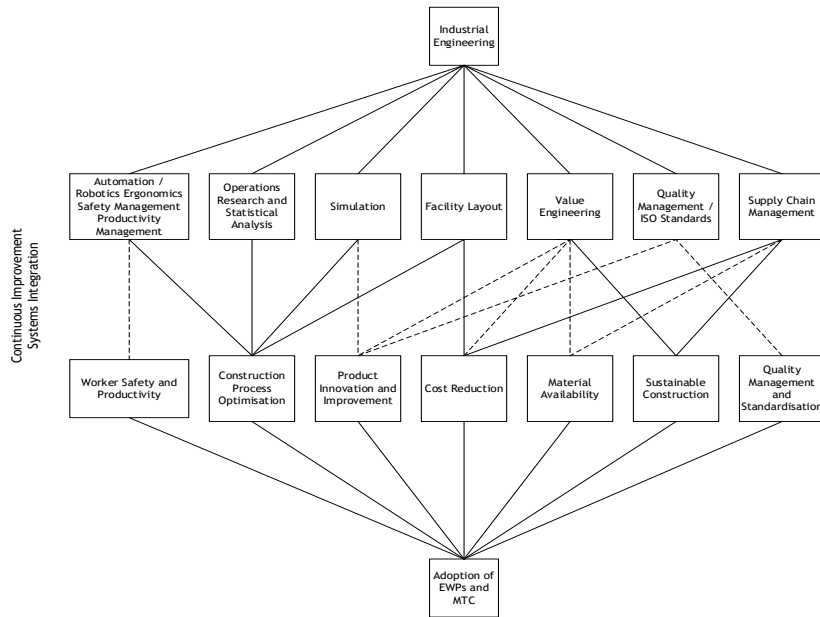
Systems thinking skills and approaches may prove useful in helping to integrate EWP and MTC into a construction industry that is infamous for being resistant to innovation [162]. A continuous improvement approach - a core tenet of industrial engineering - could be applied throughout the process to ensure that learnings from the timber construction industry are used to improve teaching and learning activities at educational institutions, and in turn to improve the principles and methodologies. Figure 1 provides a diagrammatic framework showing the areas in which industrial engineering principles and methodologies could influence the prospects of EWPs.

## 6. CONCLUSION

This paper set out to demonstrate how industrial engineering could be used to promote the adoption of engineered wood products. We identified 20 critical industrial engineering principles, and methodologies that have been recommended for the construction industry, and demonstrated how they have been used in timber construction practice and research. These principles and methods include automation, ergonomics, productivity, quality management, simulation, supply chain management, and value engineering.

Our analysis of university curricula in South Africa revealed a strong alignment with these principles and methodologies. However, it also highlighted a significant gap in construction and EWP-related content. This absence suggests that, while industrial engineering programmes are equipping students with valuable skills and knowledge, they may need to prepare them explicitly to apply these competencies in the context of timber construction. This disconnect represents a missed opportunity to leverage industrial engineering expertise in an emerging sector.

Given the substantial potential of EWPs and MTC to contribute to sustainable practices, it is imperative to bridge this gap. We have thus proposed a framework based on the principles and methodologies identified in the review as a potential starting point for industrial engineering practitioners in industry and academia to venture into the timber construction sector in order to drive the adoption of EWPs. A continuous improvement approach to these activities would, in turn, benefit the industry and academic development. We also recommend that curriculum enhancements be developed in collaboration with the timber construction industry, along with interdisciplinary research initiatives that focus on integrating industrial engineering and timber construction. One possible initiative would be a systems approach to influencing the factors that affect the adoption of timber construction.



**Figure 1: An industrial engineering capabilities framework for adopting engineered wood products**

While this paper provides a comprehensive overview of how industrial engineering principles could support the adoption of EWPs and mass timber construction, it has certain limitations. The systematic literature review, while thorough, may have included only some of the relevant studies owing to the dynamic and evolving nature of both fields. Future research could benefit from continuous updates to capture the latest developments. The curriculum analysis was also limited to publicly available information on yearbooks and prospectuses from South African universities. Future research could include information from study guides or from interviews with the lecturers teaching these modules to get a more holistic view of module content. Similarly, the opinions of industrial engineers and construction stakeholders have the potential to provide more context.

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