Assessing the performance of segmented timber shell structures within the South African built environment based on the holistic interplay between regional material, manufacturing and assembly conditions

by
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ABSTRACT

The construction industry faces multifaceted challenges of environmental degradation and declining productivity amidst the continual need to build. Biomimetics has emerged as a field of research that addresses these challenges by emulating the performative capabilities of natural systems, which has been made possible with the advent of integrative computational design (ICD) tools. Despite its potential, the application of these tools remains largely under-investigated in developing economies such as South Africa, where the need for expressive and regenerative architecture is becoming increasingly important amidst rapid urbanisation and burgeoning infrastructure demands. Segmented timber shell structures represent a convergence of innovations within this field. Thus, the study aims to create a framework that assesses the performance of this building system across material, manufacturing and assembly processes within the South African built environment. A scoping literature review distils the characteristics of the nation's construction industry. These findings are then investigated as qualitative themes through quantitative parameters in a simulation case study of a segmented timber shell. Leveraging the simulation and analytical capabilities of ICD tools, the system's structural and fabrication requirements are considered in conjunction with the nation's contextual conditions. The findings indicate that there are opposing requirements in terms of material resourcefulness, structural integrity, fabrication management capabilities and skills availability. A balanced consideration leads to distilling hexagons as the regionally optimal geometric segmentation method, with an edge length approximation within a flexible range of 800mm to 1000mm. Moreover, the choice of local mass timber manufacturers does not play a significant role in the overall performance of segmented shells. The value of this research lies in its mixed-method approach, which defines the boundary of what is practically producible, both structurally and, more importantly, contextually.

KEYWORDS

Integrative computational design, Biomimetics, Segmented timber shell structures, Parametricism, Mass timber

LIST OF KEY TERMS

Biomimetics

Biomimetics in architecture is a branch of research that seeks to transfer functional principles in natural systems that give it its performative capabilities. It refers to architectural innovation that extends beyond the mere aesthetic inspiration of the natural world, but seeks to transfer the underlying principles of formation in biology, which lends these systems their material, structural, and functional performance (Knippers, Schmid & Speck 2019: 6).

Natural morphogenesis

The integrated growth processes by which biological structures obtain their complex forms through the interaction between system intrinsic characteristics and external stimulus from environmental influences and resource availability (Menges 2007:727). *Natural morphogenesis* demonstrates an exceptional capacity to utilise material and energy economically while balancing system-internal requirements with system-external influences, leading to the evolved ingenuity of complex structures (Oxman 2010: 41–43).

Computational morphogenesis

The process of materialising architectural intent through the holistic integration of material properties, manufacturing constraints and assembly logic through the simulation and analytical capabilities of integrative computational design tools (Menges 2007: 727).

Complexity

In the context of this research, complexity results from the interaction between internal conditions and external forces that shape a given system. The high level of functionality and performative capabilities of this system correspond to the sophistication of its operation (Menges 2011:72).

Parameter

A numerical or other measurable factor that sets the conditions of a system’s operation. A parameter is a limit defining the scope of a particular process (Oxford Dictionary n.d.).

Integrative computational design

An approach to architectural production that employs digital technologies to comprehensively rethink and align design and construction processes through the integration of interdisciplinary research fields across architecture, engineering, computer science and social science. The aim is to improve productivity, energy and resource efficiency to create sustainable and expressive built environments (Knippers, Kropp, Menges, Sawodny & Weiskopf 2021).

Technology

Technology refers to the application skill and knowledge to facilitate the transformation of, and interaction with the natural environment (Darvill 2008: 1567). Encompassing more than just tools and instruments, technology is a means of revealing. It involves understanding the processes that bring forth the potentialities of nature and human activity. By understanding these essences, technology enables interacting with, and transforming human-made environments in meaningful ways (Heidegger 1977).

LIST OF ABBREVIATIONS

AEC	Architecture, Engineering and Construction
CAD	Computer-Aided Drawing
CLT	Cross Laminated Timber
CNC	Computer Numerical Control
DfMA	Design for Manufacture and Assembly
ICD	Integrative Computational Design
TBL	Triple bottom line framework for sustainability

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1 INTRODUCTION

"In biology material is expensive but shape is cheap" (Vincent 2009: 78).

This observation captures the essence of biological structures. Oxman (2010: 41-44) contends that the natural world demonstrates an exceptional ability to utilise material and energy economically, often through the evolved ingenuity of complex forms and their growth processes. The high level of functionality and performative capabilities of these natural systems result from the sophisticated way energy and material are negotiated between the system's internal requirements, such as its genetic coding, and the external environmental force acting upon it. This negotiation ensures that the system is optimised for survival within its habitat, resulting in intricate structures where form and formation are unified (Menges 2011: 72).

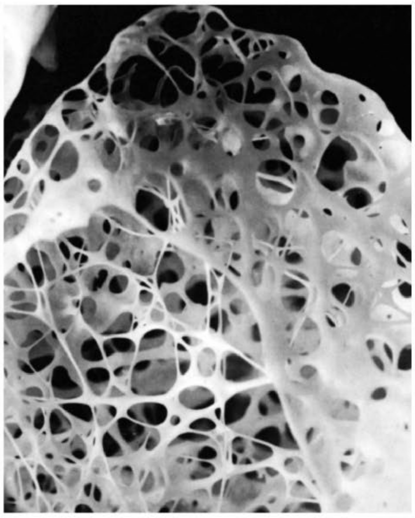


Figure 1: Femur bone structure (Oxman 2010: 58)

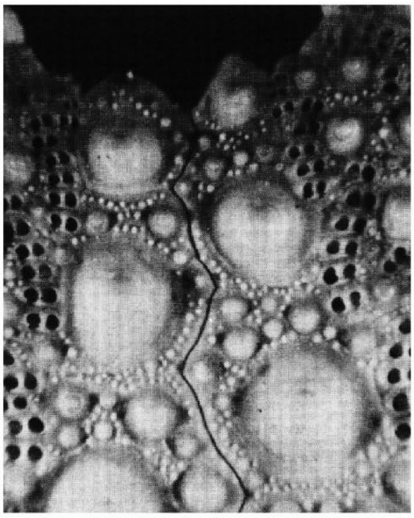


Figure 2: Shell surface of a sea urchin (Olaf et al. 1998: 140)

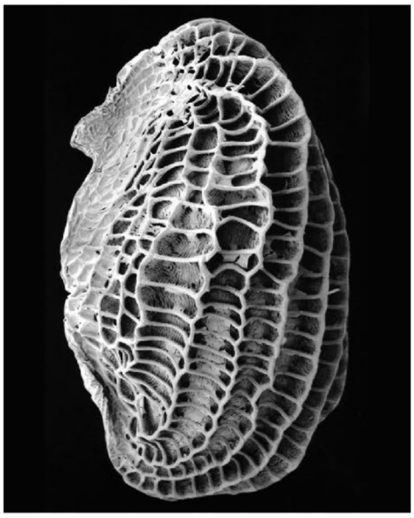


Figure 3: Yellow Owl's Clover (Oxman 2010: 38)

In contrast, in the contemporary built environment, the realisation of architectural intent typically follows a separate relationship that prioritises the definition of form over its subsequent construction process. This separation occurred incrementally over the long trajectory of architectural history, with the Modern Movement representing the height of this hierarchical relationship (Oxman 2010: 27). Craft production starkly contrasts this compartmentalisation, as materiality, form and formation are entangled within the vernacular traditions of making (Sennett, 2008). As the vernacular gave way to the global onslaught of industrial modernisation, so too did materialisation become secondary to form (Oxman 2010: 27–28)

1.1 BACKGROUND

1.1.1 Performance challenges in the global AEC sector

In light of the current ecological crisis, the shortcomings of the modernist design tradition, a product of the industrial age, have received increased criticism (Pawlyn 2019: 129; Schumacher 2016; Oxman 2010: 31). A recent publication by the UN Environment Programme highlights that the Architectural, Engineering and Construction (AEC) sector accounts for 37% of global carbon emissions, making it a significant contributor to the ongoing crisis (UNEP 2023: 1). Relative to other sectors, the construction industry has been plagued by stagnating productivity over the past two decades (Barbosa, Woetzel & Mischke 2017: 15). Its poor performance has been widely attributed to its resistance to change, hindering the adoption of digital innovation and its associated performance advantages (Demirkesen & Tezel 2022: 1487; Krieg & Menges 2022: 13). Amidst the need to digitise and decarbonise, the AEC sector is set to double floor space worldwide by 2060 (UNEP 2023: 1). Thus, a paradox exists between the ongoing need to build and the significant contribution of the global construction industry to the ongoing ecological crisis (figure 4).

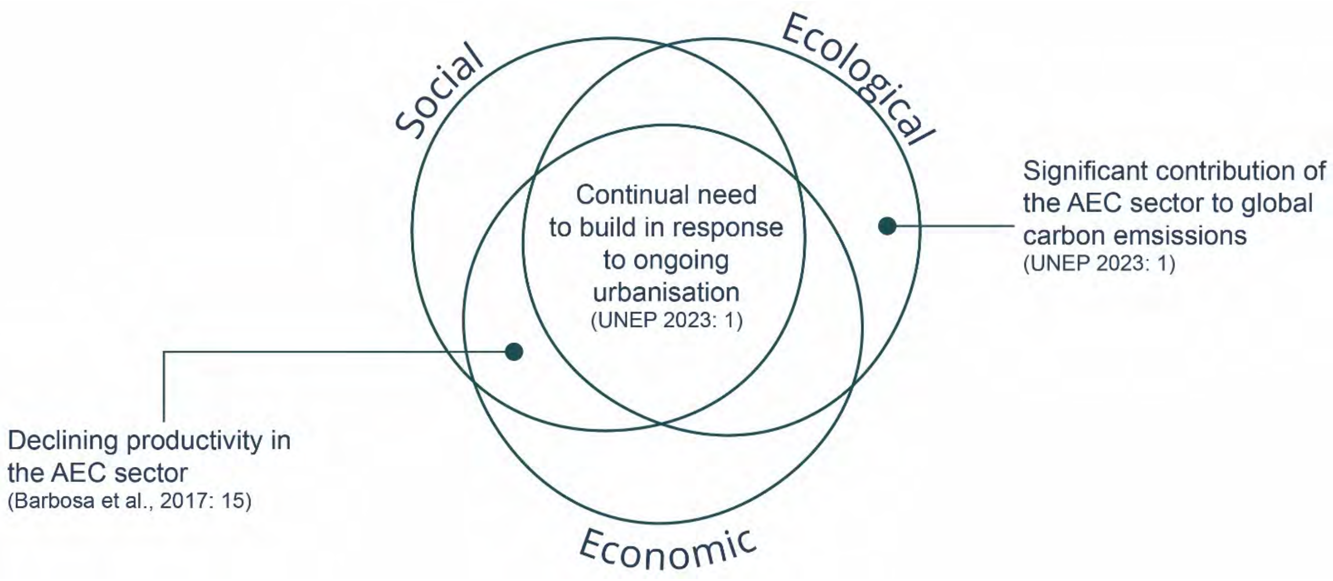


Figure 4: Multifaceted challenges faced by the global AEC sector across socio-economic and environmental spheres (Author 2024) based on (UNEP 2023: 1; Barbosa et al. 2017: 15)

1.1.2 Performance challenges in the South African AEC sector

In the African context, the extent to which modernisation has supplanted the vernacular has had a profound impact on spatial production (Low 2016:15). South Africa is no exception. The nation's architectural landscape has developed in tangent to the global onslaught of modernisation, subjecting it to the consequences of industrialisation. Notably, South Africa ranks third globally for the intensity of greenhouse gas emissions produced by its construction industry (Crawford 2022: 3). South Africa's AEC sector has been grappling with persistently low productivity for decades (Adebowale & Agumba 2023: 11; Adebowale & Smallwood 2022: 3–4). Notwithstanding, the African continent will account for close to 40% of global construction activity in the coming future (Gatsby Africa 2023). The paradox between the need to build and the poor performance of the AEC sector, while a problem globally, is notably more severe in developing economies such as South Africa (figure 5).

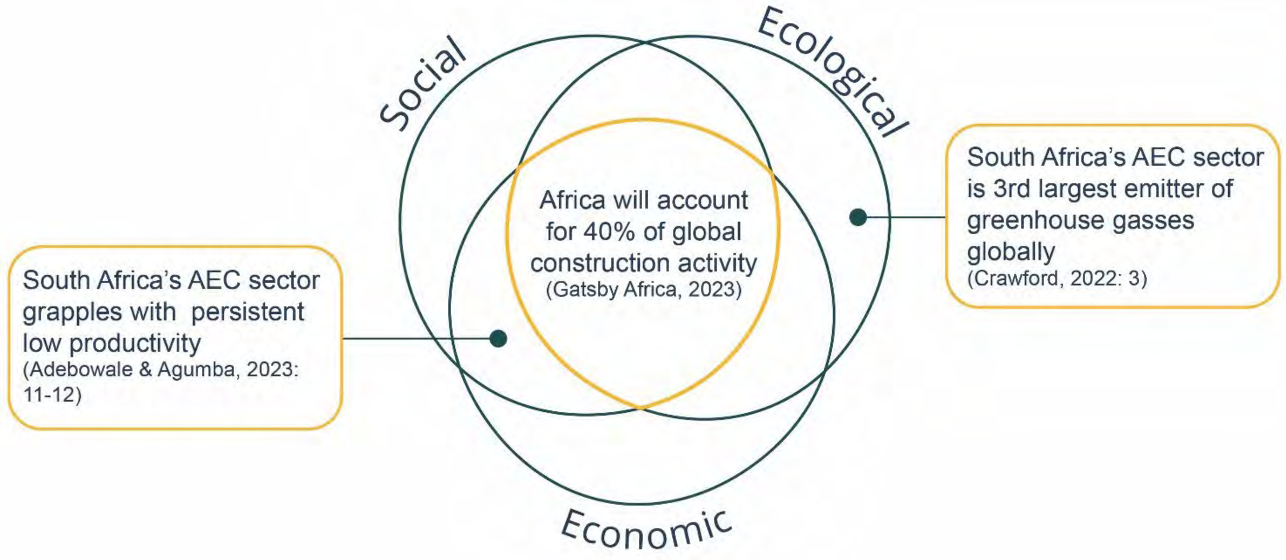


Figure 5: Performance challenges of the global AEC sector exacerbated in the South African context (Author 2024) based on (Adebowale & Agumba 2023: 11–12; Gatsby Africa 2023; Crawford 2022: 3)

1.1.3 Biomimetics and Integrative Computational Design

Complex challenges require complex solutions. The biological world offers a rich source of solutions that have benefited from 3.8 billion years of iteration and development. The exceptional performance with which natural systems operate, forged by the pressures of survival, is therefore considered optimal for addressing the increasingly complex challenges faced by the built environment (Pawlyn 2019: 1). In the context of this thesis, the functionality and resilience arising from the intersection between the system's internal and external conditions are of particular relevance.

The multifaceted challenges faced by the global construction sector have led to growing research interests seeking to develop building systems that mimic the behaviour and performative capabilities of natural systems. Integrative computational design (ICD) and Biomimetics have emerged as an approach to this challenge through a consideration of innovative design, manufacturing and fabrication methods with the use of bio-based materials (Krieg & Menges 2022: 3). This approach relies on digital models and visual programming tools that not only describe complex geometric forms, but can increase system performance by assessing and optimising various factors across the formation process (Knippers et al. 2021: 2). Digitisation allows stakeholders to balance the system's inherent logic and behaviour with its fabrication constraints and the external forces acting upon it, resulting in architecture with advanced functionality across socio-economic and environmental spheres (Menges 2007: 727).

1.1.4 Segmented timber shell structures

Segmented timber shells represent a convergence of developments within the field of ICD and Biomimetics (figure 6) (Krieg & Menges 2022: 71). This structural typology holds great potential for lightweight construction systems with far-spanning capabilities, exemplifying the biological pursuit of maximum efficiency with minimal resources (Oxman 2010: 41). Building materials fit for this type of construction must offer an optimal weight-to-strength and stiffness ratio (Bletzinger & Ramm 2001: 2053). Engineered timber products boast some of the highest strength-to-weigh ratios and the lowest environmental impact among load-bearing materials (Wikstrom 2023: 177). These products are most readily available in straight planar elements, informing a standardised and economic manufacturing process leveraging the most digitally advanced subsector within the AEC industry. The result is simple yet geometrically unique segments, allowing for on-site assembly of prefabricated modules at a pace much faster than in-situ construction (Bechert, Sonntag, Aldinger & Knippers 2021: 4815). As approximations of 3-dimensional curved geometries with the use of 2-dimensional planar timber elements, segmented shells integrate the structural performance of catenary curves with the fabrication efficiency of design for manufacturing and assembly (DfMA) workflows (Bechert et al. 2021: 4814–4815). Form and formation are finely attuned.

Figure 6: BUGA Wood Pavilion (ICD University of Stuttgard 2019)

1.2 RESEARCH GAP

Biomimetics and integrative computational design remain a relatively new field of research and represent a small portion of the AEC sector (Knippers et al. 2021: 2). Its potential for addressing industry challenges has been investigated in numerous professional and research projects in the global North (Krieg & Menges 2022; Bechert et al. 2021; Robeller & Von Haaren 2020; La Magna et al. 2013; Oxman 2010). However, only a select few studies have investigated its application in the context of the global South (Llach & Burbano 2020; Al-Jokhadar & Jabi 2016). This thesis will fill that gap by examining the performative capabilities of integrative computational design and delivery processes within the South African built environment. The focus on segmented timber shells will provide insight into how these advancements can be adapted and optimised for the unique conditions and challenges of this context.

1.3 RESEARCH AIM

The principal aim of this thesis is to create a framework that accounts for how well segmented timber shells will perform within the South African built environment. This performance will be assessed in terms of balancing the internal structural and fabrication requirements of the specified building system with the external contextual constraints of the South African construction industry. The balancing of internal and external requirements will be qualitatively assessed through contextually relevant parameters that provide quantitative data outputs. These outputs will be obtained from a data-driven design case study of a segmented timber shell structure that leverages the simulation and analytical capabilities of integrative computational design tools. This framework can be used by architects and computational designers alike for the design and delivery of regionally appropriate timber shell systems in South Africa that attain socio-economic and ecological significance.

1.4 RESEARCH QUESTIONS

To achieve the aforementioned aim, the following research questions will be posed:

1.4.1 Primary question:

What are the relationships between system-internal requirements and system-external conditions in optimising material, manufacturing, and assembly processes for segmented timber shell structures within the South African built environment?

From this, the following sub-questions arise:

1.4.2 Sub-question 1:

What are the key challenges and opportunities for advancing sustainability through technological innovation within the South African construction industry?

1.4.3 Sub-question 2:

What parameters can be used to assess the performance of segmented timber shell structures across material, manufacturing and assembly processes?

1.4.4 Research Outcomes

Upon understanding the relationships between system-internal requirements and system-external conditions of segmented timber shell structures within the South African built environment, the intended outcome of the research will be:

1. To build familiarity with regionally specific qualitative assessment proxies within quantitative data outputs.
2. The identification of the ideal geometric segmentation method.
3. The identification of the optimal segment size approximation.
4. Understand the implication of South African mass timber manufacturers' standardised panel sizes on material performance.

1.5 RESEARCH ASSUMPTIONS

The assumption is made that there is value in introducing this novel building system to the South African context. The assumption is twofold. Segmented shells fall within the paradigm of regenerative architecture that addresses industry challenges by leveraging digital technologies (Knippers et al. 2021: 12). Therefore, the building system is assumed to be well-suited to address the exacerbated challenges faced by the South African construction industry (figure 5).

1.6 RESEARCH DELINEATIONS

Multi-objective optimisation and performance of various formation processes will be investigated through a data-driven case study, serving as proxies for assessing the regional appropriateness of segmented timber shells. The research does not include structural design and optimisation, as numerous international case studies have demonstrated the structural validity of this building system (Bechert, Groenewolt, Krieg, Menges & Knippers 2018; Bechert et al. 2021; Robeller & Von Haaren 2020; La Magna et al. 2013). It is assumed that a qualified structural engineer will be appointed during the design and delivery of a segmented shell. Rather, the study focuses on integrating existing research on the system's structural behaviour and fabrication requirements, with the contextual conditions of the South African built environment.

2 THEORETICAL FRAMEWORK

This thesis forms part of the larger academic discourse of leveraging digital technologies to advance sustainability in the built environment. The theoretical framework will therefore open by outlining the value of such an endeavour, and in getting to the specifics regarding timber shells within the South African built environment, lead to a consequential discussion on the following themes:

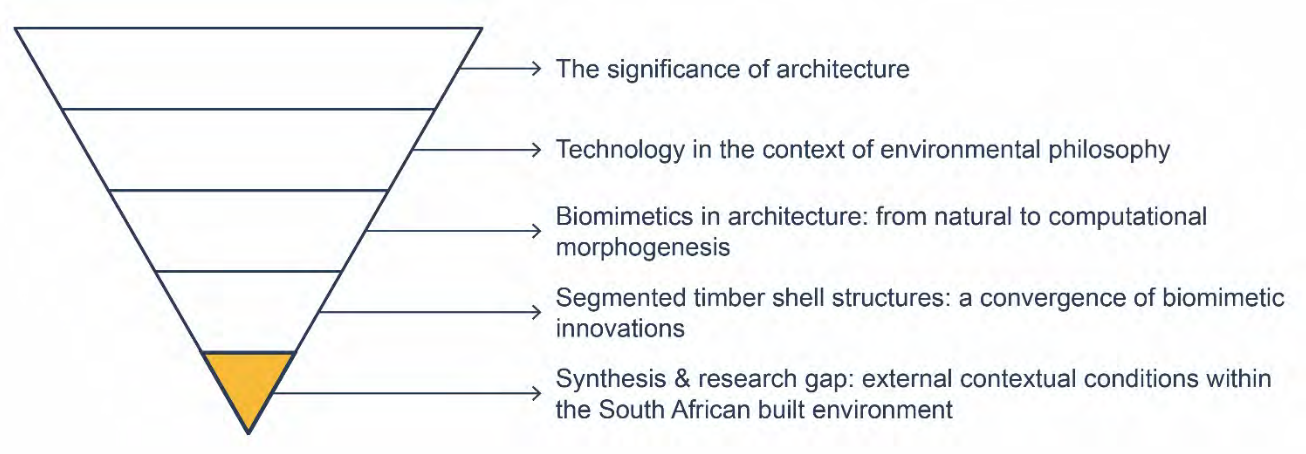


Figure 7: Thematic structure of the theoretical framework (Author 2024)

2.1 THE SIGNIFICANCE OF ARCHITECTURE

“Fitness, not form, is what actually matters” (Oxman 2010: 32).

Fitness is synonymous with suitability. The suitability or appropriateness of something is a precursor to the significance thereof. Both Menges (2007) and Sennet (2009) discuss the suitability and significance of architectural practice, albeit from varying positions on the technological spectrum. Sennet (2009: 21-22) asserts that humanity’s wandering existence has attained meaning through the craft process. The author critiques the digitalisation of the drawing process, arguing that it has led to a separation of head and hand, impairing the cognitive and creative aspects of craftsmanship (Sennet 2009: 44). Conversely, Menges (2007: 726-727) is situated on the opposite side of the technological spectrum, arguing that architecture attains socio-economic and ecological significance through the unification of form and formation. Central to the author’s argument is the use of advanced computational design and delivery processes. Frampton (1983), known for his seminal work on critical regionalism, discusses the significance of architecture from the perspective of locality and identity. Referring to the technological spectrum, the author takes a balanced view. Frampton remains critical of the continual advancement of technology and its close association with the onslaught of globalisation and the loss of regionality, yet warns against the trap of nostalgia where historicism bears no relevance for the contemporary context (Frampton 1983: 16–19). Rather, the author contends that architecture gains significance by fostering a sense of place through the holistic integration of cultural and environmental factors, ultimately imbuing the resulting artefact with a distinct regional identity.

All three authors converge on the notion that architecture derives its significance from a construction and realisation process deeply intertwined with its contextual milieu. Herein lies the nexus between contextuality and sustainability, wherein sustainability is construed as a comprehensive and holistic entanglement of contextual nuances (figure 8). This concept is commonly encapsulated by the triple bottom line (TBL) framework, which distils these varying dimensions according to socio-economic and environmental spheres (Elkington & Rowlands 1999). Often referred to as *people, planet and profit*, this framework has been instrumental in holistically measuring sustainability performance (Slaper & Hall 2011: 1).

In the AEC sector, Goh et al. (2020: 2) note that while it may be difficult to quantify sustainability through the TBL framework, there is still value in outlining how construction processes can be adapted and contextualised to perform in a balanced manner across these spheres. From a social perspective, there is advocacy for architectural solutions to be centred around people through attractive and functional spaces (Grierson 2009: 73), participatory construction (Low 2016: 295), interdisciplinary collaboration (Butt & Dimitrijević 2022: 15–16), and an acknowledgement of the various needs of stakeholders involved in any project (Goh, Chong, Jack & Faris 2020: 7). From an economic perspective, it is important to recognise that the AEC sector plays a major role in the global economy, thereby making a significant contribution to the livelihoods of people worldwide (Barbosa et al. 2017: 1). Financial feasibility and the equitable distribution of economic benefits among stakeholders are considered relevant for a construction project's economic sustainability (Abidin 2010: 424–425). From an ecological perspective, there is widespread advocacy for resource efficiency and natural materials to mitigate the ecological impact of the AEC sector (Knippers et al. 2019: 6; Pawlyn 2019: 1; Oxman 2010: 41; Grierson 2009: 73).

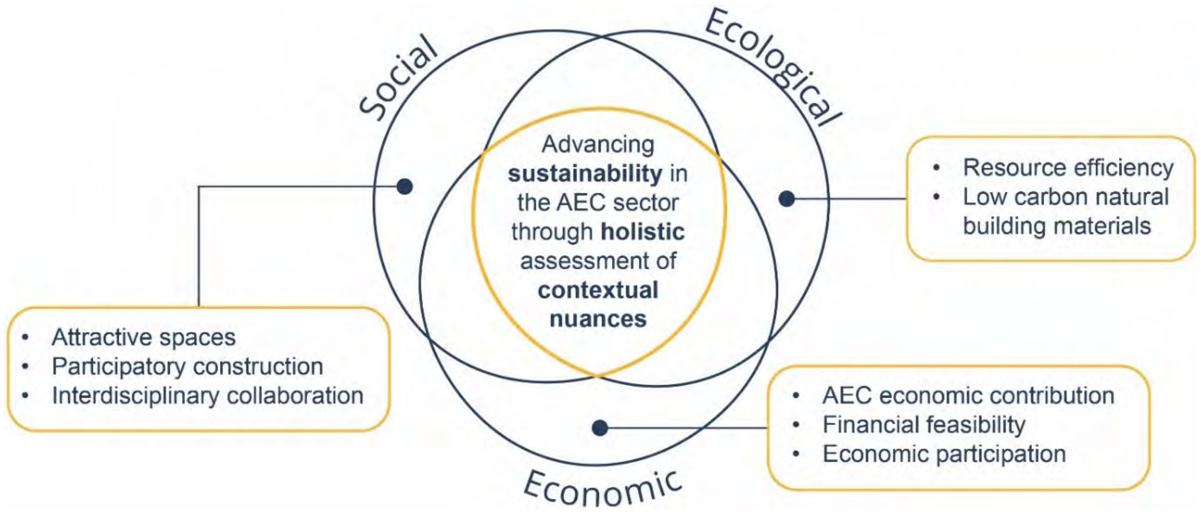


Figure 8: Advancing sustainability in the AEC sector through a holistic consideration of contextual nuances across socio-economic and environmental spheres (Author 2024)

The capacity of architecture to attain significance across socio-economic and environmental spheres is ultimately dependent on a holistic consideration of various contextual nuances (figure 8). Technology can be defined as the application of skill and knowledge to facilitate the transformation of the natural environment (Darvill 2008: 1567). Therefore, it can either enable or undermine sustainable innovation depending on how it is conceptualised.

2.2 TECHNOLOGY IN THE CONTEXT OF ENVIRONMENTAL PHILOSOPHY

The current geological epoch, known as the Anthropocene, is distinguished by the profound impact of human activities on the natural world. Geologists posit that the Anthropocene commenced the first Industrial Revolution, which marked a major shift in the trajectory of technology during the time of its inception (Crutzen 2016: 23). As such, current discourse around environmental philosophy often frames technology with an anthropogenic undertone (Chapman 2020: 75).

2.2.1 Conceptualising technology

Martin Heidegger, one of the most influential philosophers of the 20th century, is argued to have laid the foundations of environmental philosophy (Chapman 2020: 76; Glazebrook 2013: 433). Yet his writings offer a nuanced perspective on technology that transcends simplistic notions of good or bad. In "The Question Concerning Technology", Heidegger offers two perspectives: *bringing-forth thinking* and *challenging-forth thinking.* (Heidegger 1977).

Challenging-forth thinking, characteristic of modern technologies, is premised on exploiting and mechanising nature for human domination and gain. This type of thinking frames our way of relating to the world through the lens of efficiency, control and exploitation (Chapman 2020: 79). Oxman's assertion that modern architecture prioritises form over its materialisation process, unlike in the biological world, exemplifies this way of conceptualising technology (Oxman 2010: 27–29).

Conversely, *bringing-forth thinking* regards technology as a process of revealing or unconcealing, elevating it to a poetic medium. Heidegger associates this mode of thinking with craftmanship and traditional technologies (Chapman 2020: 76). This aligns with Sennet's view that the craft process, particularly evident in vernacular building technologies, enriches the human experience with meaning (Sennet 2009: 21–22). However, the *bringing-forth mode* of thinking can also be found on the opposite end of the technological spectrum. Both Menges (2007), and Oxman (2010), whose work is premised on advanced computation, exemplify how technology can be leveraged to redefine the relationship between the built and the natural environment and foster dialogue between different disciplines in an increasingly fragmented AEC sector. A contradiction thus exists. The emergence of *bringing-forth thinking* by seminal scholars at different points along the technological spectrum further exemplifies Heidegger's assertion that technology is not an instrument for good or bad, but should rather be seen as a way of understanding and relating to the world (Heidegger 1977: 12).

Yet in a world where the only permanence is the impermanence thereof, the question then becomes not whether technology is good or bad, anthropogenic or not, but how one chooses to engage with it and what kind of world is envisioned through its use. This question has continually been asked and answered throughout the long trajectory of technological innovation. The desire for change and the need to adapt is argued to be what drives human intelligence to pioneer new technological epochs (Wolff 2021: 1). This phenomenon echoes Darwin's theory of evolutionary biology, where performance within a specific ecosystem drives continual mutation and adaptation (Darwin 1859). Only the fittest survive. Whether biological innovation is a function of intelligence or chance is subject to intense debate (Bissen 2014). Regardless, technology mirrors biology in its need to innovate and adapt amidst the relentless passage of time (figure 9). Fitness is what truly matters.

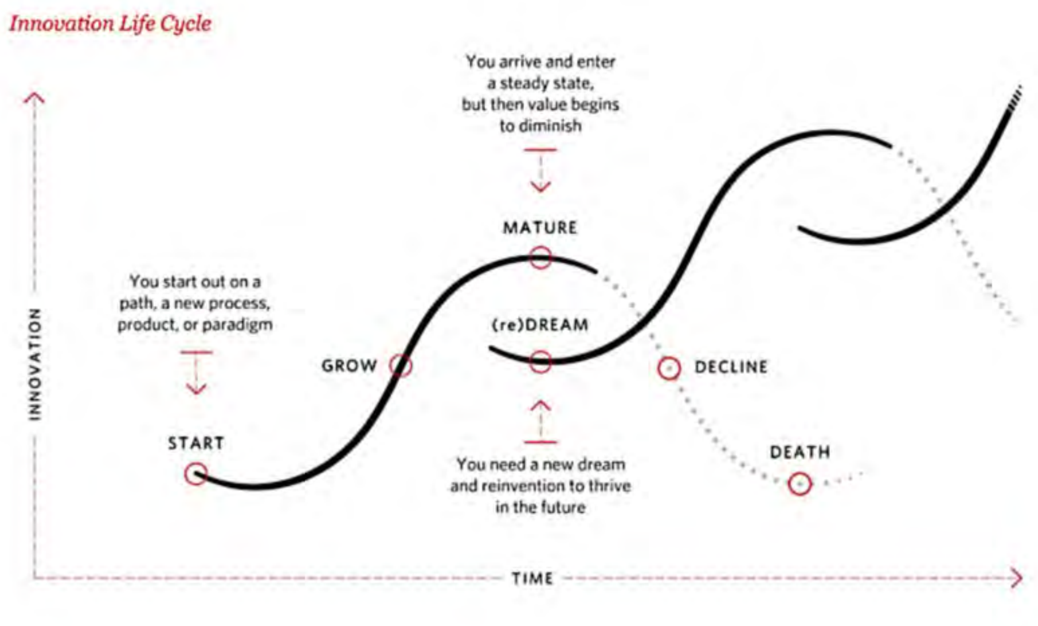


Figure 9: The evolutionary trajectory of technology driven by innovation and the need to adapt amidst the continuum of time (Ferroso 2019: 29)

2.2.2 Industry 4.0: the dawn of a new technological epoch

The advent of the 4th industrial revolution, known as Industry 4.0, marks the latest phase in the genealogy of technological advancements that drive all domains of civilisation (Ghobakhloo 2020: 2; Schumacher 2016: 10). This epoch is characterised by a shift towards interconnected cyber-physical systems, the Internet of Things, artificial intelligence and data exchange, driving efficiency and reshaping human-machine interactions. Schwab (2017: 1) describes it as a convergence of physical, digital and biological spheres.

Ensuring that Industry 4.0 supports and promotes sustainability is crucial to prevent worsening the current ecological crisis (Shabur 2024: 17). The United Nations advocates for digitisation to drive sustainable development, specifically focusing on its application in the construction industries of emerging economies (UNEP 2023: 18). Manda and Dhaou (2019: 251) concur with the potential of digitalisation in the global South, highlighting the opportunity to leapfrog stages of development, yet warn that failure to situate these technologies appropriately will exacerbate existing socio-economic disparities. This underscores the importance of taking a balanced stance towards digitalisation, recognising the potentials and risks, and exemplifies Heiddeger's conception of technology as being either *challenging-forth* or *bring-forth* in essence. Biomimetic design represents the latter.

2.3 BIOMIMETICS IN ARCHITECTURE: FROM NATURAL TO COMPUTATIONAL MORPHOGENESIS

Throughout the history of architectural production, humans have taken inspiration from the natural world. The ongoing digital revolution has brought about a new opportunity to redefine the relationship between the natural and the built environment. Biomimetics has unlocked the capacity to not merely take aesthetic inspiration from natural structures, but to transfer the underlying principles of formation in biology which lend these systems their material, structural, and functional performance (Krieg & Menges 2022: 30; Knippers et al. 2019: 6).

2.3.1 Natural morphogenesis

Natural morphogenesis refers to the process by which biological matter obtains its complex form, versatility and organisational structures by balancing the availability of material and energy between the organism's genetic code and intrinsic characteristics, with the external environmental forces acting upon it (figure 10) (Menges 2007: 727). Beauty and intellect are one. The sophistication of this interaction determines the exceptional functionality and performative capabilities of these natural systems (Menges 2011: 72). However, there is no optimal or standard solution for this interaction. A single ecosystem typically houses a vast range of organisms with morphological variations, as evidenced by Southern Africa’s rich biodiversity (Department of Forestry, Fisheries and the Environment 2022: 4). La Magna et al. (2013: 27) assert that the variety observed within natural habitats suggests that different solutions may perform more optimally in different scenarios. This underscores the importance of regionality in building system resilience.

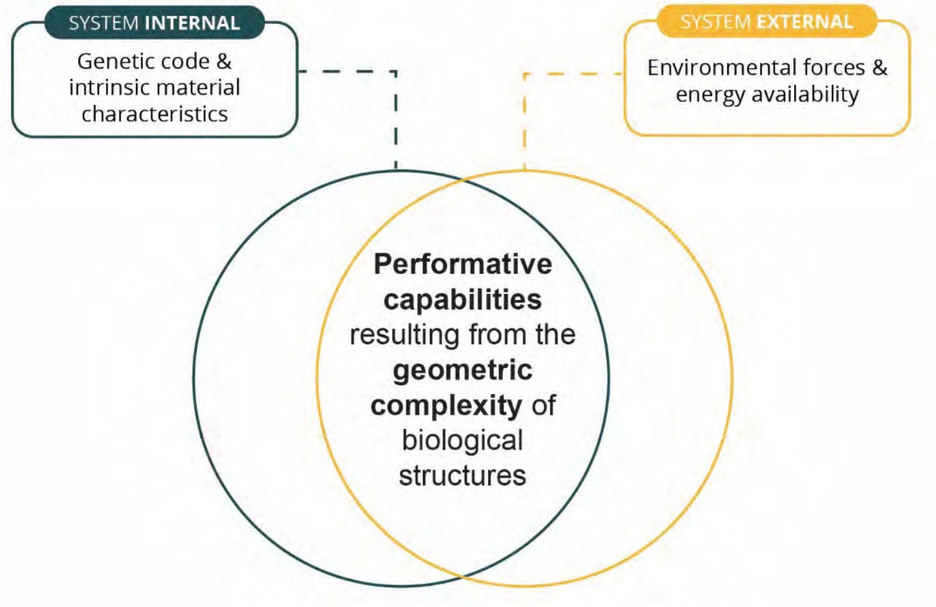


Figure 10: Natural morphogenesis (Author 2024) based on definition by (Menges 2007: 727)

2.3.2 Computational morphogenesis and the boundary of the producible

The integral processes of growth and formation in natural structures starkly contrast the material practice of architecture, where efficient formation has become secondary to form (Oxman 2010: 70). The underlying logic of algorithmic thinking is argued to unfold a new paradigm of architectural production. One by which morphological complexity is derived through a holistic multi-objective optimisation process across various realms within the construction process. Menges (2007:727) highlights the term *computational morphogenesis* as this alternative. Utilising power of computation, this process enables the materialisation of architectural intent through the holistic integration of material properties, manufacturing constraints and assembly logic (figure 11). For the sake of clarity, the three realms of material, manufacturing and assembly processes will herewith be referred to as the *factors of formation*.

As articulated through the concept of *natural morphogenesis*, there is often a balancing of energy across various growth processes. It is this balance by which an organism attains its morphological identity and resilience. Translated into architecture, the negotiation between often opposing fabrication requirements across the *factors of formation* can limit and, therefore, more closely define what is practically producible within a given context (Krieg & Menges 2022: 38). The overlapping of various requirements during formation will herewith be referred to as the *boundary of the producible.*

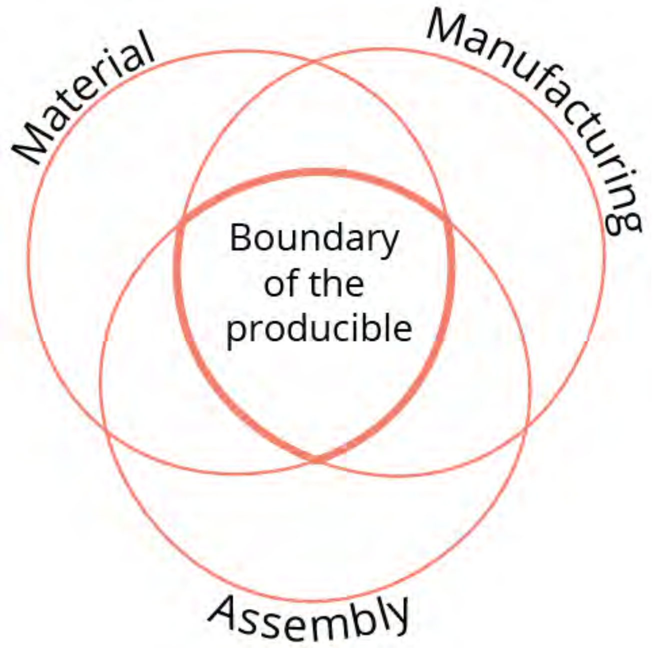


Figure 11: Factors of formation that define the boundary of the producible through a multi-objective optimisation process (Author 2014) based on (Krieg & Menges 2022: 38; Menges 2007: 727)

Referring to figure 11, a balanced multi-objective optimisation across the realms of material, manufacturing and assembly processes will become the basis for the framework to assess the performance of timber shells in the South African built environment. Critical to this aim is acknowledging the limitations of the traditional drawing process.

Tedeschi and Wirz (2014:16) contend that the additive logic of pen and paper, which has persisted with the advent of computer-aided drawing (CAD), cannot predict the design outcome from the interaction between physical forces and material properties. Rather, defining the *boundary of the producible* necessitates a shift towards an associative logic of production whereby adaptive relationships can be established between various dimensions in the formation process.

2.3.3 Form finding for Biomimetic architecture: from the physical to the digital

> *“The blueprint signalled, moreover, one decisive disconnection between head and hand in design: the idea of a thing made complete in conception before it is constructed” (Sennet 2009: 42).*

2.3.3 A) Physical form-finding and mono-parametric optimisation

Recognising the limitations of the blueprint, early pioneers such as Otto, Isler and Gaudi looked towards the formation processes in nature to create novel optimised structures through physical simulations. The negotiation of material properties with external forces was revolutionary for its time. These simulations are argued to be mono-parametric as they optimised material placement for a single objective: gravity (Tedeschi & Wirz 2014: 18–19).

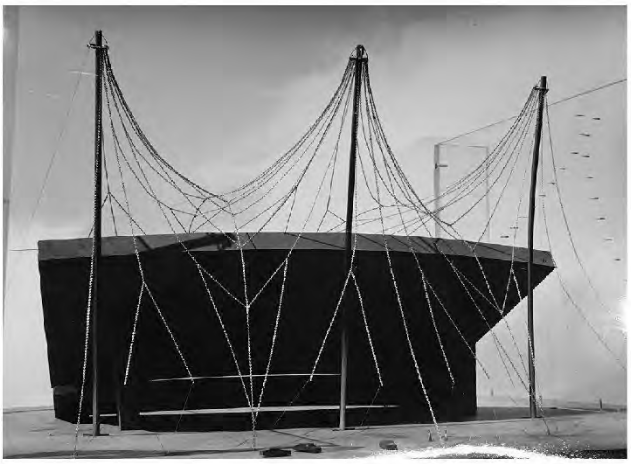


Figure 12: Physical model of a tensile roof by Frei Ott (Boller & Schwartz 2020: 570)

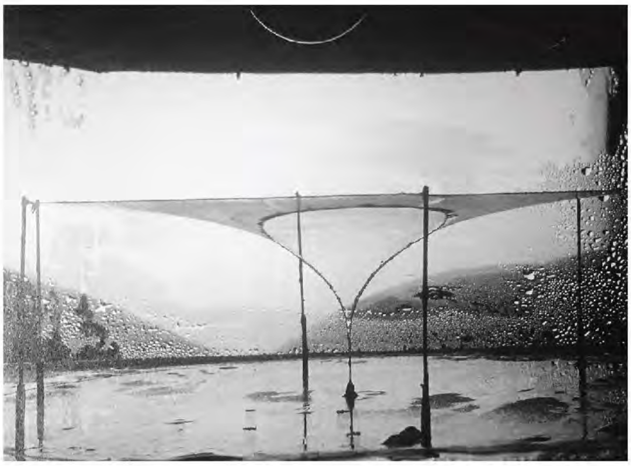


Figure 13: Physical model of a tensile roof by Frei Ott (Boller & Schwartz 2020: 570)

Figure 14: Final hanging chain model for Mannheim Multihalle (Liddell 2015: 41)

Figure 15: Mannheim Multihalle (Nicholas, Hernández & Gengnagel 2013:16)

These pioneers have had a profound impact on the emergence of Parametricism, which Schumacher (2016: 20) defines as a design methodology to generate and create a set of rules that collectively outline the connection between design intent and response. Form and formation can be defined simultaneously. The existence of physical form-finding in the predigital era counters any claim that Parametricism is merely a response to the digital revolution (Schumacher 2016: 13). Rather, it should be understood as an ecology of interactive systems. It just so happens that coding and computation have elevated its capacity to move beyond the mono-parametric objective of gravity, enabling it to respond to the multitude of challenges in an increasingly complex contemporary condition.

2.3.3 B) Digital form finding and multi-parametric optimisation

The advent of visual scripting tools has enabled a multi-parametric approach to building performance whereby form and formation can be assessed and optimised across various dimensions. This includes, but is not limited to, geometry, environmental forces, social data and economic constraints (Tedeschi & Wirz 2014: 19). The computer becomes an extension of the mind to synergise contextual informants across formation processes. This approach relies on programming languages that express instructions in a step-by-step procedure: the algorithm (figure 16).

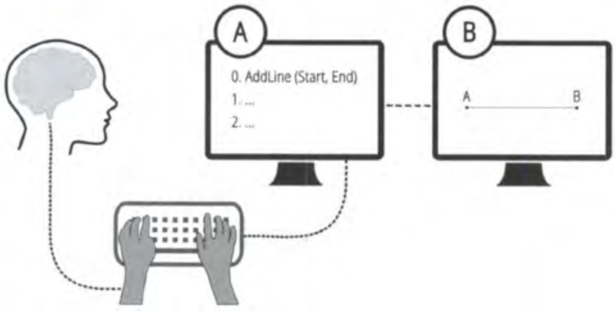


Figure 16: Algorithmic modelling process (Tedeschi & Wirz 2014: 24)

2.3.4 Multi-parametricism: factors of formation as proxies for sustainability

Aligning with Heidegger's *bring-forth* mode of conceptualising technology, it can be argued that the vast range of possibilities enabled by algorithmic thinking adds a new dimension to the aforementioned nexus between regionality and sustainability (figure 8). The practical constructability with the resources at hand becomes the mechanism by which form and formation attain enhanced performance and significance across socio-economic and ecological spheres. Enabled through an optimisation process across multiple objectives, the overlapping of the *factors of formation* and definition of the *boundary of the producible* runs simultaneously to, or rather simulates, the entanglement of contextual considerations within the TBL framework. Simply put, sustainability can be explored through proxies in a data-driven design and delivery process (figure 17).

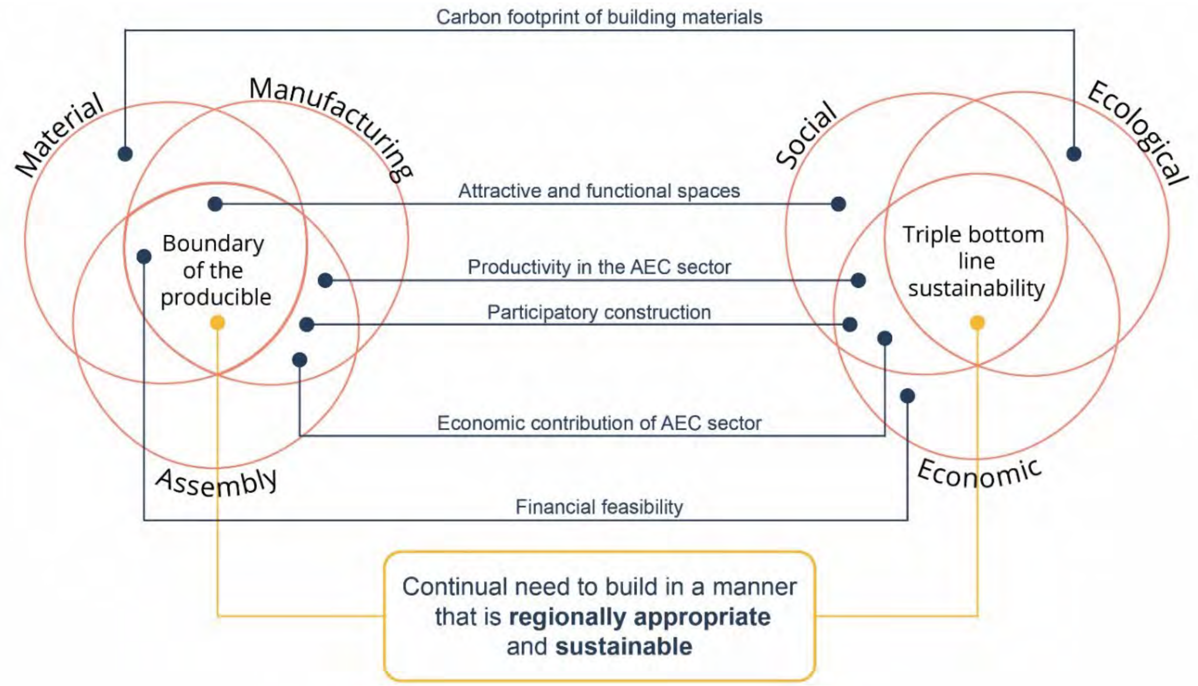


Figure 17: Factors of formation as proxies for sustainability in the AEC sector (Author 2024)

2.4 SEGMENTED TIMBER SHELL STRUCTURES: A CONVERGENCE OF BIOMIMETIC INNOVATIONS

Contemporary segmented timber shell structures represent a convergence of innovations in the realm of Biomimetic design, digital form finding and fabrication processes using engineered timber (Krieg & Menges 2022: 71). Despite its novelty, the shell, dome or vault as a structural typology dates back to antiquity and can be found in many vernacular building traditions across the globe.

2.4.1 Vernacular shell structures

The widespread use of the shell typology is attributed to its spanning capabilities and economic use of materials (Nanayakkara 2019: 1). These morphologies exemplify Heidegger's *bringing-forth* mode of conceptualising technology through the cultural significance and regional suitability of its formation processes.

Figure 18: Zulu beehive dwelling, South Africa (Nguyen et al. 2019)

Figure 19: Igloo, Greenland (Comberg 2018)

Figure 20: Gol Gumbaz, India (Pemmaraju 2023)

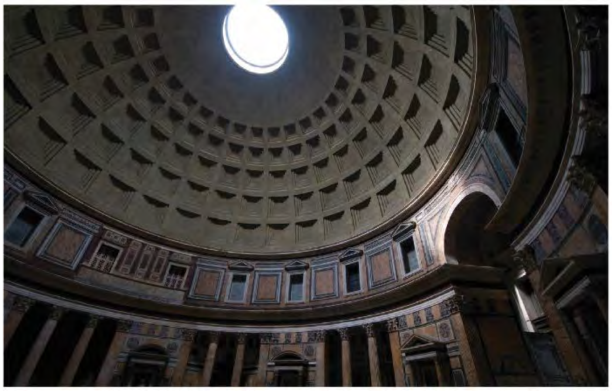


Figure 21: Roman Pantheon, Italy (Fiederer 2016)

2.4.2 Continuous concrete shell structures

The discovery of concrete marked a shift toward shell structures of the 20th century, which unlocked the material's innate capabilities (Menges 2007: 726). The typology of the thin continuous shell achieves structural efficiency by leveraging concrete's exceptional performance under compression, which mirrors gravitational forces along its surface curvature (figure 22) (Noh 2005: 1420). However, the constructability of concrete shells has consistently been their most difficult aspect (Krieg & Menges 2022: 71). Notably, its formwork is both material and labour-intensive (figure 23) (Schumacher 2016: 70). The same can be observed in Bosjes Chapel, a 21st-century South African example of a concrete shell (figure 24). Its morphology intersects the compressive capabilities of concrete with the region's Cape Dutch architectural heritage (Pereira 2016). Notwithstanding its grandeur, the building's form came at the cost of a difficult and material-intensive construction process (figure 25). Fitness of formation fell victim to form.

Figure 22: Concrete shell by Candela (Pereira 2018)

Figure 23: Material-intensive formwork of a concrete shell by Candela (Pereira 2018)

Figure 24: Bosjes Chapel by Steyn Studio, South Africa (Pereira 2016)

Figure 25: Construction of Bosjes Chapel (Keskeys 2019)

2.4.3 Plate shell structures

A solution to the challenges of building contemporary shells lies in differentiating between continuous shells (figure 22-25) and segmented shells (figure 6 & 29). The natural world offers this alternative.

2.4.3 A) Biological background to shell structures

The sea urchin exhibits this segmentation most clearly. Its skeleton is described as a modular polygonal plate system joined by interlocking calcite protrusions (Krieg & Menges 2022: 72–73). The non-continuous hard tissue surface allows for growth and adaptation. This is crucial for fitness and survival. However, the disruption to material continuity compromises structural performance (Ellers, Johnson & Moberg 1998: 142–143). The biological shell exemplifies *natural morphogenesis* (figure 10) as it negotiates the need for environmental adaptation, facilitated by its segmentation, and the need for structural rigidity, enhanced through its joints. A balance is struck between system-internal and external.

Figure 26: Skeleton of a sea urchin (La Magna et al. 2013: 30)

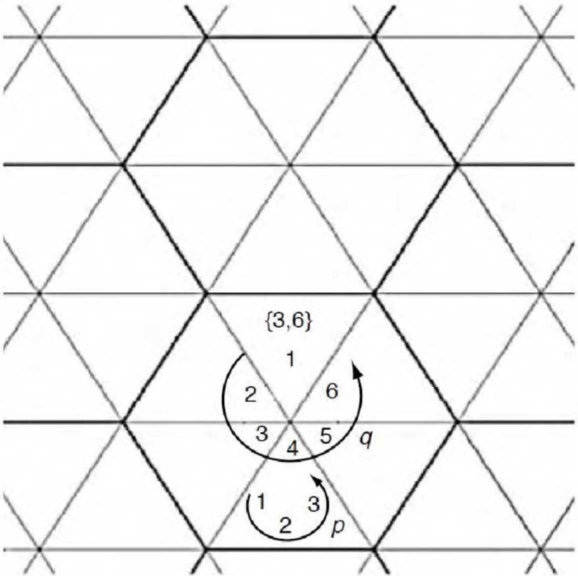


Figure 27: Three-plate principle (La Magna et al. 2013: 32)

2.4.3 B) Geometric background: three-plate principle

Many variations of biological shells exhibit a topological rule where no more than three planes can meet at a given point. This is defined as the three-plate principle (La Magna et al. 2013: 32). The implication is that only triangular segments, or factors thereof, such as hexagonal segments, can distribute loads as in-place forces. Every vertex on the curved surface is replaced by a plane. In the realm of architecture, the three-plate principle removes the need for structural components other than the planar segment itself (Bagger 2010: 4).

Figure 28: Triangular and hexagonal segmentation patterns for planar components based on the three-plate principle (Bagger 2010: 4)

2.4.4 Factors of formation: building segmented timber shell structures

The negotiation of internal and external, as observed in biological shells, can be transferred to architectural shell structures for enhanced performance (Krieg & Menges 2022: 71–73) This necessitates an overview of the internal structural and fabrication requirements of segmented timber shells, which will be outlined according to their material, manufacturing and assembly characteristics (figure 11).

Figure 29: Segmented timber shell at Rosenstein Museum (ICDD University of Stuttgard 2017)

2.4.4 A) Material characteristic of segmented timber shell structures

Shell morphologies attain structural performance through a curved surface area, which mirrors vertical forces of gravity into primarily compressive forces along the curvature. These loads need to be transferred without disproportionally disturbing the material continuity (Bechert et al. 2018: 1), which refers to the consistency of material characteristics throughout a structure. As naturally grown material, timber attains its material properties for functional purposes such as nutrient transportation within a tree. This informs the grain or growth direction of wood cells (Krieg & Menges 2022: 60). Its anisotropic character means that timber performs better when subjected to forces parallel to its grain direction, while it is more susceptible to deformation under perpendicular forces (Herzog, Natterer, Schweitzer, Volz & Winter 2012: 32). Cross Laminated Timber (CLT) rationalises material continuity by layering timber with alternating grain directions. This increases the directions in which timber can effectively withstand forces (Kurzinski, Crovella & Smith 2023: 14; Wikstrom 2023: 167). Segments are nested onto CLT panels, aligning in-plane forces with the major strength direction of the CLT manufacturer's standardised sheet. Material continuity and the proportional transfer of loads across CLT segments are important considerations for the structure's material performance.

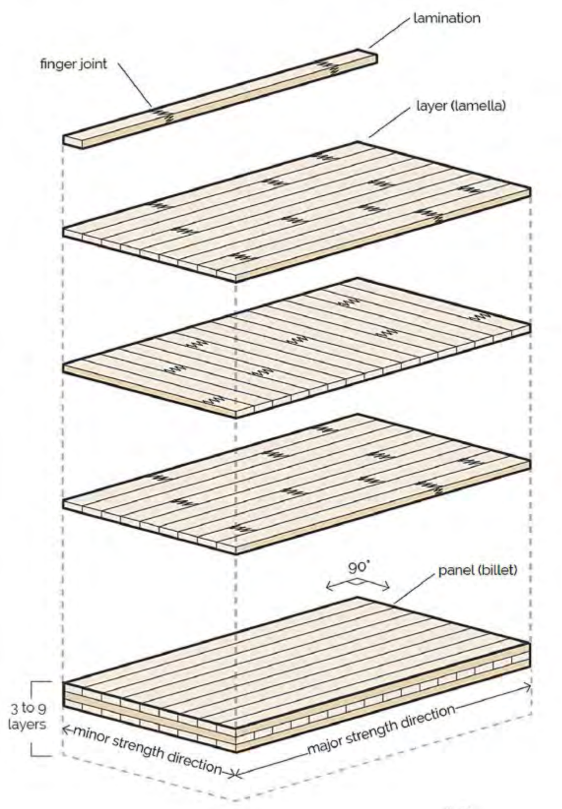


Figure 30: Layer configuration of CLT to rationalise dimensional stability (Tallwood Design Institute 2019)

2.4.4 B) Manufacturing characteristics of segmented timber shell structures

CLT's materiality informs the manufacturing process for segmented timber shells, highlighting the interrelated nature of the *factors of formation* (figure 11). As a highly modified wood product, CLT is produced in a factory environment (Wikstrom 2023: 171). The renewed interest in wood, particularly engineered timber products, can be attributed to its machinability. It allows for a design for manufacturing and assembly (DfMA) process that leverages the precision of computer numerical control (CNC) machinery and industrial robots (Krieg & Menges 2022: 62). The material's anisotropic behaviour, coupled with a digital manufacturing process, mirrors the connection between materials, tools and resulting structure, which has always been understood by skilled craftspeople (Menges, Schwinn & Krieg 2016: 6). Wikstrom (2023: 171) emphasises the importance of skill in the digital manufacturing process, contending that while speed and precision are enhanced, these machines need to be programmed and managed by highly trained individuals. Klinger (2001: 243) describes this as an evolved role of the architect and a return of the master builder in a digital era. In this regard, the master builder has strong design capabilities and extensive knowledge of various software, enabling them to computationally transform architectural geometry into constructible parts fed directly into fabrication machinery. This challenges the need for traditional representation such plans or sections, and shortens the distance between design thinking and fabrication (Klinger 2001: 239).

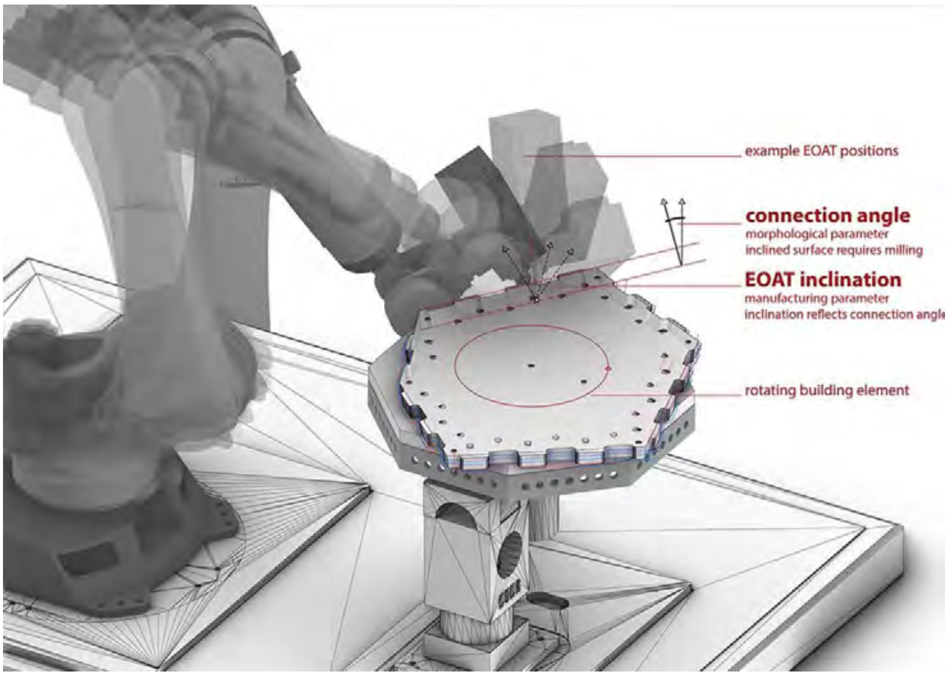


Figure 31: Digital prefabrication process of segmented timber shell (Krieg & Menges 2022: 99)

2.4.4 C) Assembly characteristics of segmented timber shell structures

The digital prefabrication of individual segments enables a fast on-site assembly process (figure 33), again underscoring the entangled nature of the *factors of formation* (figure 11). The planarity of segments means that loads are mostly transferred as in-plane forces (Bechert et al. 2018: 1). Therefore, maximising surface area in comparison to the circumference of an individual segment becomes an important consideration for structural performance. Different polygons have different edge-to-area ratios. Existing research indicates that hexagonal segmentation has a lower edge-length-to-area ratio (Robeller & Von Haaren 2020:128). The edges of individual segments disrupt material continuity, meaning that segmented shells typically require a large number of connections on these edge lengths to counteract the weakened structural rigidity (Bechert et al. 2018: 1).

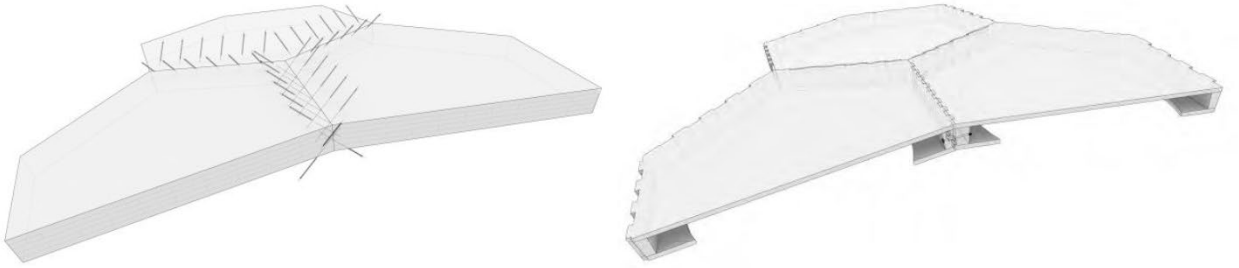


Figure 32: Joinery systems for segmented timber shells (Bechert et al. 2018: 3)

Figure 33: Assembly process for HexBox Canopy (Pintos 2019)

2.4.5 Internal structural and fabrication requirements for segmented shells

The previous sections have outlined existing literature on the structural and fabrication requirements of segmented timber shells. Building on the research framework (figure 11), these findings can be synthesised as the building system's internal requirements across material, manufacturing and assembly realms.

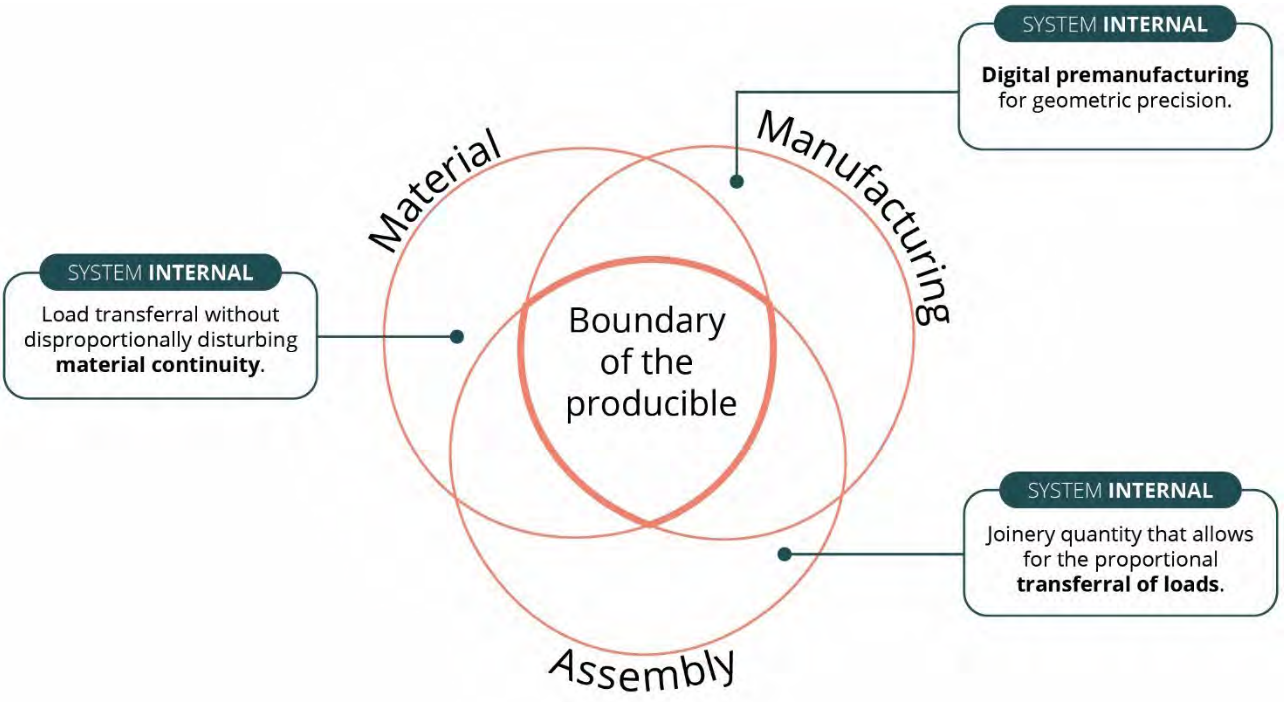


Figure 34: Internal structural and fabrication requirements of segmented timber shells across the factors of formation (Author 2024)

2.5 SYNTHESIS OF THE THEORETICAL FRAMEWORK

Considering the exacerbated performance challenges faced by the South African AEC sector (figure 5), the research is situated within the general gap of investigating the potential of integrative computational design and delivery processes in the global South. An investigation into Biomimetic architecture, specifically the parallels Menges (2007: 727) draws between *natural* (figure 10) and *computational morphogenesis* (figure 11), clarifies the conception of performance resulting from the complex negotiation between a system's internal and external requirements. Consequently, the theoretical framework reviews existing literature on internal structural and fabrication requirements of segmented timber shells (figure 34). In light of the nexus between regionality and sustainability (figure 17), the gap becomes more specific in understanding the external contextual constraints within the South African built environment that will define the performance of this building system across material, manufacturing and assembly processes. This gap is premised on the importance of fitness for context, both in the biological sense of performance and survivability and, more importantly, in the architectural sense of attaining significance across socio-economic and environmental spheres.

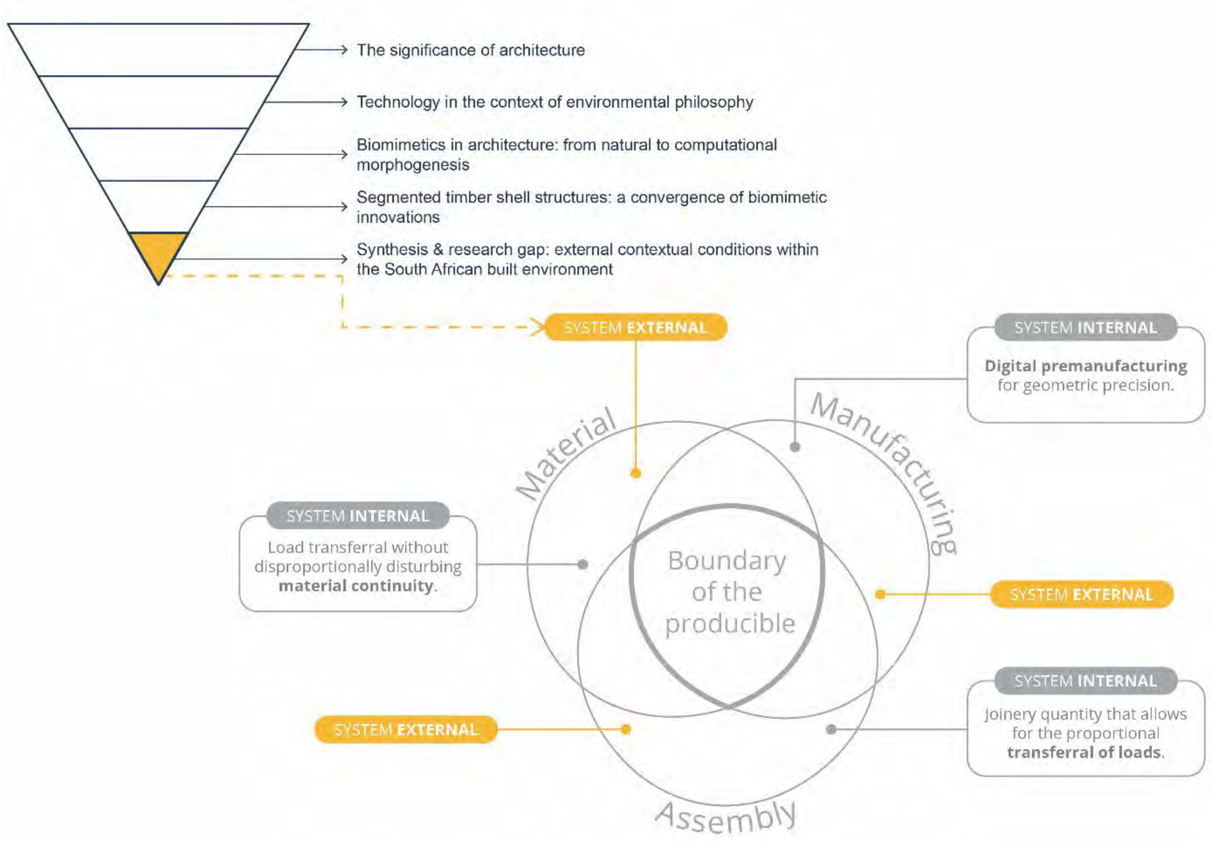


Figure 35: Synthesis of theoretical framework leading to the research gap (Author 2024)

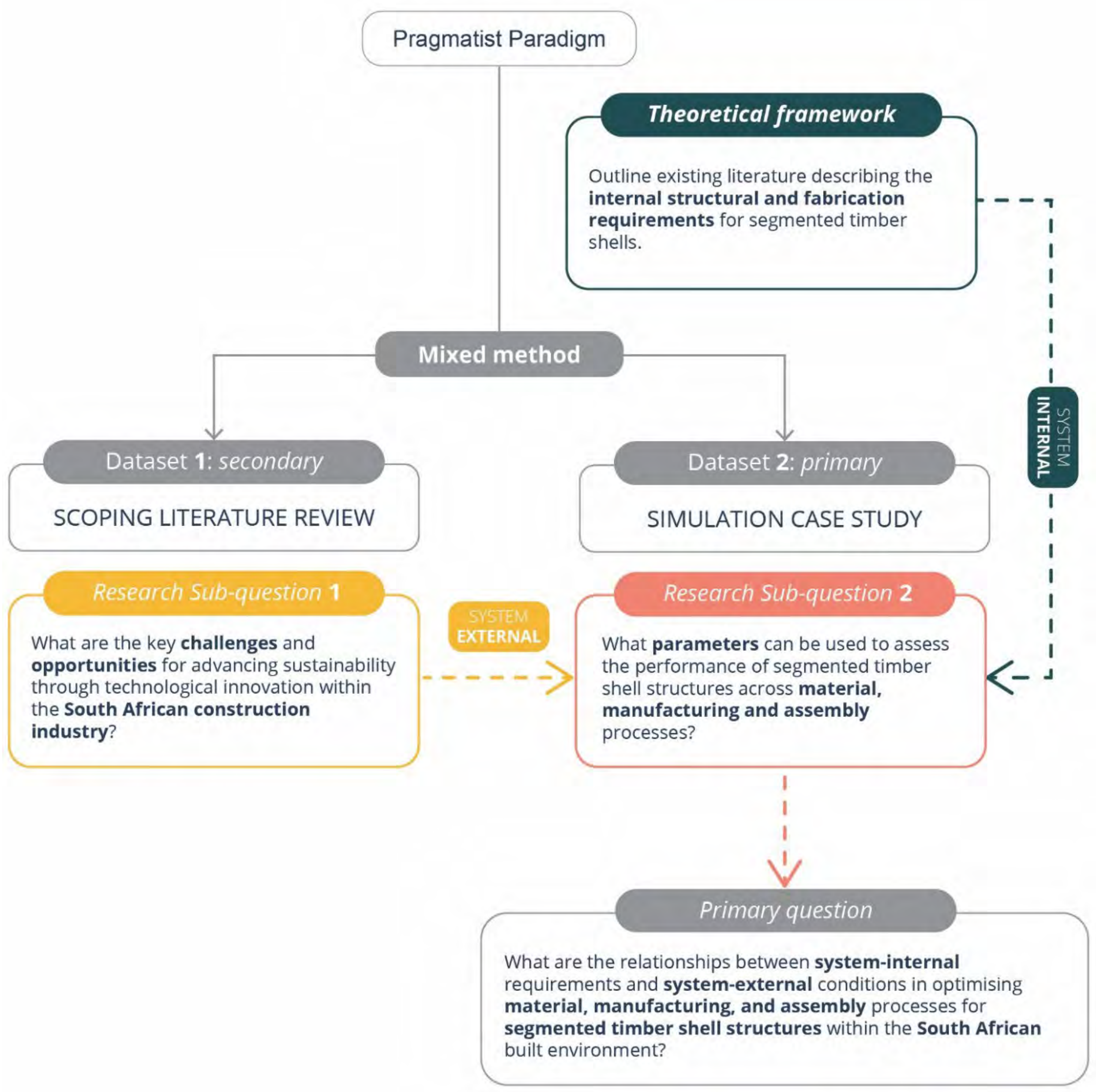
3 METHODOLOGY

The relationships between the system-internal requirements and system-external conditions are investigated as qualitative themes through quantitative parameters in a data-driven design case study of a small segmented timber shell.

This chapter will present a mixed-method research methodology to address the research aim and questions (figure 36). The chapter will start by outlining a literature search methodology to unpack the contextual characteristics of the South African construction industry (figure 37). This will be followed by a methodology for a simulation case study (figure 39) providing quantitative data outputs, referred to as parameters, through which the relationships between internal structural and fabrication requirements and contextual conditions of the South African construction industry can be analysed.

3.1 RESEARCH DESIGN

The study is situated in the Pragmatist Paradigm and framed as applied research (Du Toit 2014: 65). The study combines a scoping literature review as a secondary data source with a simulation case study as a primary data source.



Outline existing literature describing the **internal structural and fabrication requirements** for segmented timber shells.

What are the key **challenges** and **opportunities** for advancing sustainability through technological innovation within the **South African construction industry**?

What **parameters** can be used to assess the performance of segmented timber shell structures across **material, manufacturing and assembly** processes?

What are the relationships between **system-internal** requirements and **system-external** conditions in optimising **material, manufacturing, and assembly** processes for **segmented timber shell structures** within the **South African** built environment?

Figure 36: Research design (Author 2024)

The novelty of this research lies in combining datasets 1 and 2, as this will contribute to research that investigates the potential of integrative computational design tools in the context of developing economies such as South Africa. The methodology for data collection and analysis for each respective dataset is outlined in subsequent sections.

3.2 DATASET 1: SCOPING LITERATURE REVIEW

A scoping literature review is devised to gain a descriptive overview of the challenges and opportunities for advancing sustainability through technological innovation within the South African built environment. This type of review is suited for the study as it allows for a comprehensive investigation into the scope, extent and nature of available literature on the given topic (Munn et al. 2018: 4). This approach addresses the research gap (figure 35) by enabling the identification of key characteristics within material, manufacturing and assembly processes.

The following two sub-sections outline the methodologies for data collection and analysis of the scoping literature review.

3.2.1 Dataset 1: Data collection methodology

A literature search was conducted using the following search methodology:

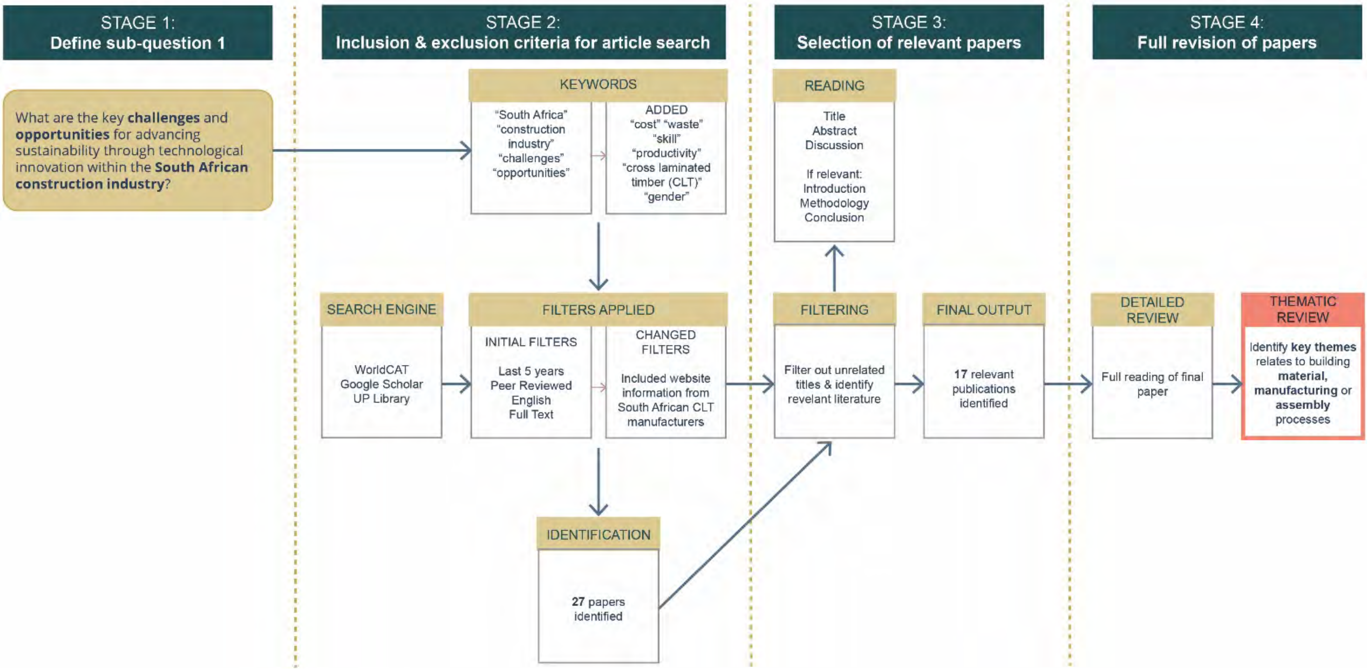


Figure 37: Methodology for scoping literature review on the challenges and opportunities within the South African construction industry (Author 2024)

The initial search has a limited set of keywords. As themes emerged during the review process, additional keywords related to these themes were incorporated, allowing for a more comprehensive overview of the identified topics.

3.2.2 Dataset 1: Data analysis methodology

The findings from the scoping literature review are qualitatively analysed to identify the external contextual characteristics informing the construction of segmented timber shells in South Africa. The analysis involves mapping these themes onto the research framework, allowing comparison with the internal structural and fabrication requirements (figure 35). This framework will become the basis by which building performance is assessed across the different formation processes and inform the data-driven design case study.

3.3 DATASET 2: SIMULATION CASE STUDY

The case study for the simulation of a small segmented timber shell structure is conducted using Grasshopper, a visual programming environment operating as a plugin for McNeel's Rhino 3D modelling software (Robert McNeel & Associates n.d.).

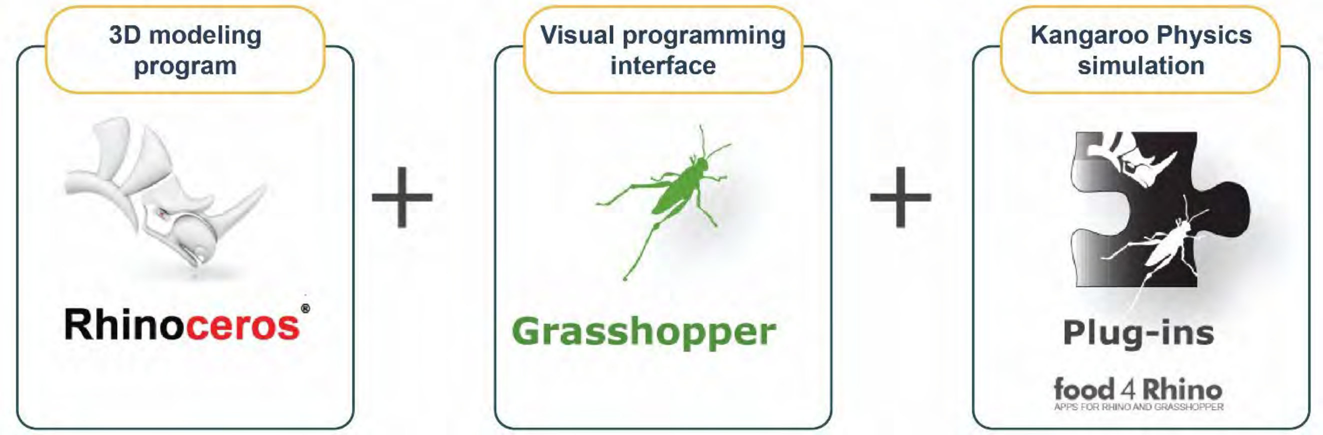


Figure 38: Integrative computational design tools used in the study (Author 2024)

The following two sub-sections outline the methodologies for data collection and analysis of the simulation case study.

3.3.1 Dataset 2: Data collection methodology

The data collection methodology is conducted in 7 steps:

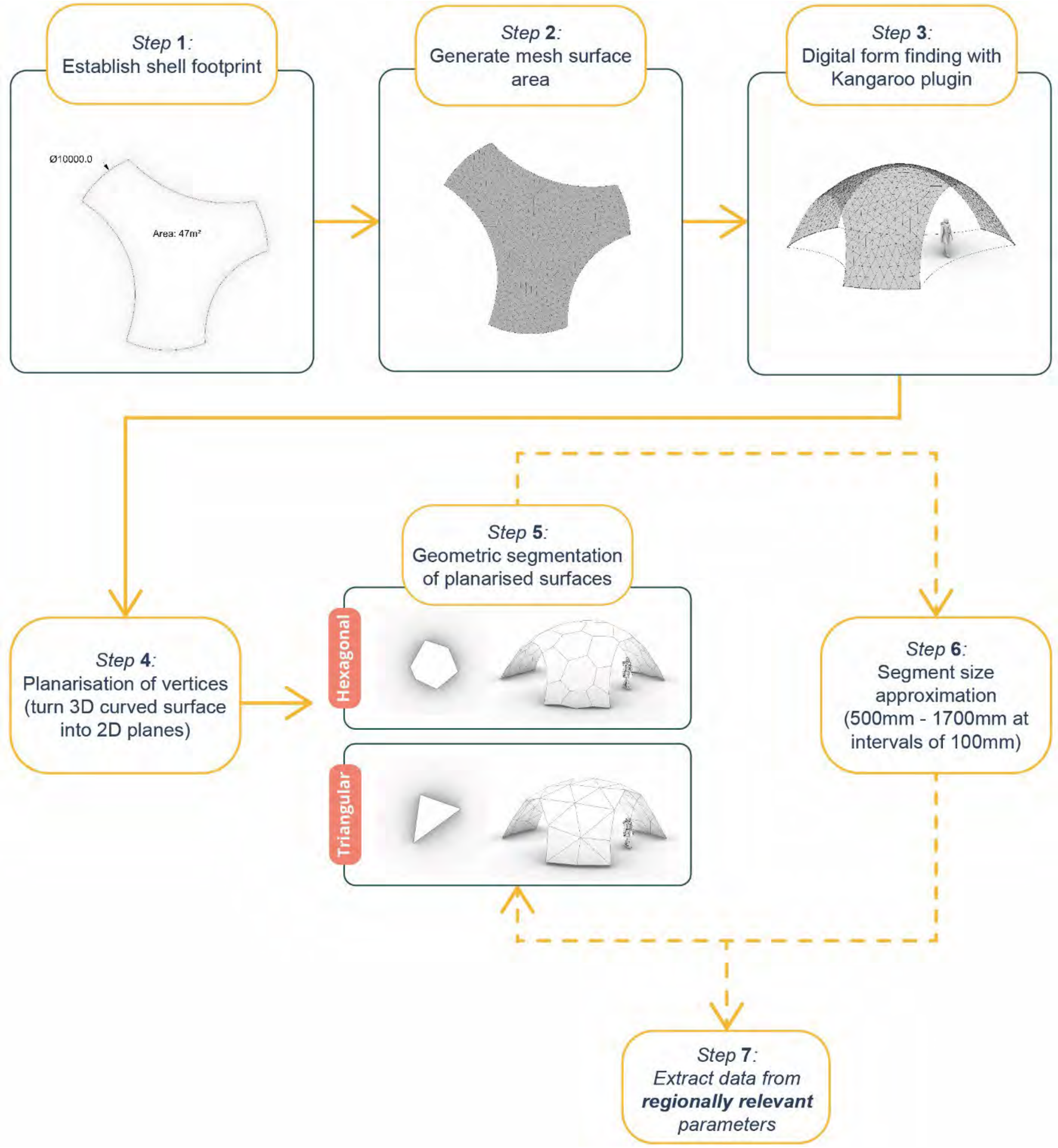


Figure 39: Data collection methodology for the simulation case study of a segmented timber shell (Author 2024)

3.3.1 A) Step 1: Establish shell footprint

A floor plan of the shell is created on a circular footprint with a diameter of 10m, covering an area of 47m². The footprint size is selected for two reasons. Firstly, this is the typical size range of shell pavilions as seen in international research (Robeller & Von Haaren 2020; ICDD University of Stuttgard 2017). Secondly, a larger footprint will require higher computing intensity when various parameters are simulated. This will slow the data collection process without adding more value to the research aim, questions and objectives.

3.3.1 B) Step 2: Generate mesh surface area

Once a footprint is established, a mesh surface is generated. A mesh is defined as a collection of points connected with lines and grouped into polygons. This represents the footprint's surface area. The mesh is used to create a *particle-spring system*, a well-established technique for digital form-finding (Tedeschi & Wirz 2014: 361–362).

3.3.1 C) Step 3: Digital form finding with Kangaroo plugin

Kangaroo Physics (Piker n.d.) is a plugin that simulates physical forces onto a mesh representative of the target geometry. Each point on the mesh represents a lumped mass, and each line represents a spring. The points change position and velocity according to the elasticity of the spring and the forces acting upon it. The Kangaroo solver iteratively adjusts the points to minimise total system energy, exemplifying the biological phenomenon where complex form results from the economical use of energy and material (Oxman 2010: 41–44). The result is a catenary shell optimised according to external forces acting upon the elasticity of the mesh.

Steps 1 to 3 outline a computational methodology to achieve optimised form according to the singular objective of gravity. Given the multifaceted challenges faced by the AEC sector, both globally and more acutely in South Africa (figure 5), it is equally important to prioritise a construction process that attains relevance across socio-economic and environmental spheres. The next steps outline an iterative multi-parametric methodology to iterate and test the performance of the shell's formation processes.

3.3.1 C) Step 4: Planarisation of vertex

Once form is established, the 3-dimentional geometry is approximated into constructible 2-dimentional components. The CoPlanar component in Grasshopper replaces every vertex in the curved individual segments with a unique plane. This step is informed by the three-plate principle in biological shells (Bagger 2010: 4–5). The planarisation of these curved geometries into flat surfaces is twofold. Regarding structural performance, it allows loads to be distributed as in-plane forces (Bechert et al. 2018: 1). In terms of fabrication performance, it allows for segments to be nested onto flat standardised cross-laminated timber (CLT) sheets.

3.3.1 D) Step 5: Geometric segmentation of planarised surface

Once the curved geometry is planarised, these individual planes can be conceived as different geometric modules. The three-plate principle informs an investigation into two geometric segmentation methods: triangles and hexagons, both trivalent networks (Bagger 2010: 4). Existing literature indicates that hexagonal segmentation is optimal in terms of maximising surface area in comparison to edge length for the transferral of planar forces (Robeller & Von Haaren 2020: 128). The use of triangular segmentation is not well documented but is included to investigate if it will perform more optimally when other regionally relevant parameters are considered.

3.3.1 E) Step 6: Segment size approximation

Once the shell is rationalised into flat constructible parts, the dimensions of these parts are simulated at different sizes. Important to understand is that each segment is similar in its family of polygon, either a triangular or a hexagonal module. However, each polygonal module has a unique geometric identity and topological arrangement based on the angle between edges and the variation in edge lengths that outline the polygon (Robeller & Von Haaren 2020: 126). The algorithm is defined to approximate the edge lengths of each geometrically unique polygonal module based on a numerical input. A series of 13 numerical inputs, starting at 500mm and ranging up to 1700mm at increments of 100mm, is plugged into the two geometric segmentation methods. The minimum input is defined by a size that can be carried by an individual construction labourer. The maximum input is defined by the size of locally available CLT panels. Each input serves as a target that individual edge lengths approximate within a polygonal module.

Steps 5 to 6 are restimulated according to the series of 13 numerical inputs. This process results in 26 shell structures recorded within the Rhino modelling environment. These iterations display different segmentation sizes ranging from 500mm – 1700mm for both hexagonal and triangular segments.

3.1.1 F) Step7: Measure data from specified parameters

Upon reiteration of steps 5 to 6, specific parameters are extracted as quantifiable metrics that can be used to evaluate the relationships between the building system's internal and external conditions. The Grasshopper script can be adjusted to provide data outputs for a vast range of possibilities. Therefore, the relevant parameters are only specified and extracted upon conclusion of the scoping literature review. By considering the conditions specific to the South African construction industry, the assessment parameters are contextually informed.

3.3.2 Dataset 2: Data analysis methodology

The parameters are mapped onto the research framework (figure 34) where it fits most appropriately between internal structural and external contextual requirements of the building system. Initially, the data from each parameter is analysed individually to understand the nature and scale of optimisation and stagnation within different formation processes, and across various geometric segmentation and size approximation scenarios. Then, the data will be mapped onto the research framework as a multidimensional axis where the centre point represents the direction of optimisation for each regionally relevant parameter. This allows for a holistic data-driven assessment of system-internal and external requirements to define the *boundary of the producible* within the South African context, leading to practical outcomes such as regionally optimal segmentation geometry and size.

4 FINDINGS

The findings are presented according to the two datasets: the scoping literature review and the simulation case study. Thereafter, the findings are consolidated into the research framework (figure 34) to allow for a holistic discussion of the primary research question (figure 36).

4.1 RESULTS FROM DATASET 1: CHALLENGES AND OPPORTUNITIES FOR INNOVATION WITHIN THE SOUTH AFRICAN BUILT ENVIRONMENT

This section presents findings on the challenges and opportunities of technological innovation in pursuit of advancing sustainability within the South African construction industry. A broad reading into this topic reveals that technological innovation has garnered increased attention among scholars and industry stakeholders as a solution to address local industry challenges (Aghimien, Aigbavboa & Thwala 2019; Manda & Dhaou 2019; Olojede, Agbola & Samuel 2019).

Despite this awareness, social acceptance is widely discussed as the most significant barrier when it comes to adopting innovative construction practices (Aghimien et al. 2019: 1122; Manda & Dhaou 2019: 250; Olojede et al. 2019: 176). This resistance arises from various contextual challenges related to the practicalities of construction and can, therefore, be discussed according to material, manufacturing and assembly process.

4.1.1 Material considerations within the South African built environment

4.1.1 A) Challenges related to building materials

Dosumu and Aigbavboa (2021: 98) found that the cost of construction is the most significant factor hindering the adoption of construction innovation. The cost of building materials is discussed more specifically by Aghimien et al. (2019: 1122), who found that material cost is among the top factors hindering innovation. The continual fluctuation of these material costs is another significant challenge, which is exacerbated by the country's weak currency and dependency on imported building materials (Alabi & Fapohunda 2021: 2). Fitchett and Phuluphedziso (2022: 106-109) draw comparisons between construction material waste, another significant industry challenge, with its ecological and financial implications. The authors attribute inadequate planning and skills deficiencies in construction labourers as the leading cause of high rates of material wastage in the country, accounting for 20% to 30% of project cost overruns.

4.1.1 B) Opportunities related to building materials

The high cost of construction can be a driver for alternative building practices on the condition that it is cost-competitive (Dosumu & Aigbavboa 2021: 98). To reduce dependency on imported building materials, the South African government and private sector are actively exploring ways to leverage the country's forestry resources and emerging timber-value chain (Grobbelaar & Visser 2021). Tshidzumba and Chirwa (2022: 2) highlight the significant role the forestry sector can play in fostering growth in rural communities. In addition to the socio-economic benefits of a local timber value chain, the machinability of wood products presents an opportunity for enhanced construction productivity through Design for Manufacturing and Assembly (DfMA) processes.

4.1.2 Manufacturing considerations within the South African built environment

4.1.2 A) Challenges related to manufacturing

The current lack of graduate outputs with sufficient technological literacy will affect the extent to which the performance advantages of digital manufacturing can be leveraged. The number of enrolments in Science, Engineering and Technology (SET) fields has not increased over the past decade (Department of Science and Innovation 2023:54). Moreover, the 2019 White Paper on STI indicates that the country does not generate enough skills in SET for the nation to fully capitalise on the benefits of Industry 4.0. The skills shortage among manufacturing stakeholders mirrors the widespread consensus that poor planning capabilities and difficulties in managing complex construction processes are stagnating industry performance. (Adebowale & Smallwood 2022: 13; Fitchett & Rambuwani 2022: 109–110; Adebowale, Kukoyi, Olagoke & Ademola 2020: 7). Adebowale et al. (2020: 9) recommend selecting appropriate planning tools and technology based on project complexity.

4.1.2 B) Opportunities related to manufacturing

Despite the skills shortage, South Africa is positioned as the most prepared nation in Africa to leverage the benefits of the ongoing digital revolution, comparing well with its BRICS counterparts (World Economic Forum 2016). This can be attributed to South African universities offering some of the best higher education on the continent (Manda & Dhaou 2019: 249). An opportunity thus exists to leverage the nation's availability of high-quality tertiary education institutions to produce graduates with the technological literacy to harness the performance advantages of Biomimetics and integrative computational design tools.

The continent's only two mass timber manufacturers are situated in South Africa and distributed across two of its economic centres. XLAM is located in Cape Town (XLAM n.d.), and MTT is located in Johannesburg (MTT n.d.). This is an opportunity to reduce transportation costs and emissions based on project location. The presence of Africa's only two mass timber manufacturers exemplifies the nation's capacity for technological innovation. A dichotomy exists between the educational infrastructure capable of producing skills for digital manufacturing, and the underutilisation of this opportunity, as evidenced by the low output of technologically skilled graduates.

4.1.3 Assembly considerations within the South African built environment

4.1.3 A) Challenges related to building assembly

The issue of skill becomes central to the regional fitness of segmented shells, especially in terms of socio-economic performance, affecting both off-site manufacturing stakeholders and on-site assembly labourers. Skill deficiencies among construction labourers are widely discussed as a key industry challenge (Adebowale & Agumba 2023: 12; Adebowale & Smallwood 2022: 11). This hinders construction productivity due to on-site errors, rework, and material wastage (Fitchett & Rambuwani 2022: 109–110). Notably, the skill challenge affects performance within other realms of the formation process.

South Africa faces a severe unemployment crisis, which is argued to be the root cause of broader societal challenges such as poverty and crime (Wakefield, Yu & Swanepoel 2022). The construction sector is a significant contributor to job opportunities, meaning that many citizens depend on this sector for socio-economic welfare (Mkhize 2019: 17). However, these opportunities are disproportionately limited to male construction workers, mirroring global trends. Norberg and Johansson (2021: 4) argue that the gender gap in construction arises from the long-held belief that building is inherently masculine due to the physical demands of on-site tasks. This notion has extended into the realm of manufacturing and planning, where physical strength is not relevant, yet gender biases remain. Regardless, the issue of economic participation in the realm of assembly extends beyond gender to become one of socio-economic transformation and its impact on technological innovation. Manda & Dhaou (2019: 250) capture this problem by asserting that an untransformed labour force will result in resistance to adopting novel technologies, as it can exacerbate existing socio-economic inequalities.

4.1.3 B) Opportunities related to building assembly

An intricacy exists between the nation’s ability to produce highly skilled digital craftspeople (Manda & Dhaou 2019: 249), despite the low graduate output, and a large number of low-skilled individuals dependent on economic participation and upliftment (Adebowale & Agumba 2023: 12; Mkhize 2019: 17). The precision of digital prefabrication allows for the inclusion of hand-based assembly by a diverse range of low-skilled labourers. Resolving joinery type and technique for this specific aim becomes an opportunity for segmented shells to attain regional significance in its socio-economic domain.

4.1.4 Synthesis of findings from scoping literature review

The previous sections outline the contextual challenges and opportunities within the South African construction industry across the three *factors of formation*. These findings can be added to the research framework as the system-external requirements, contributing to defining the *boundary of the producible* (figure 40).

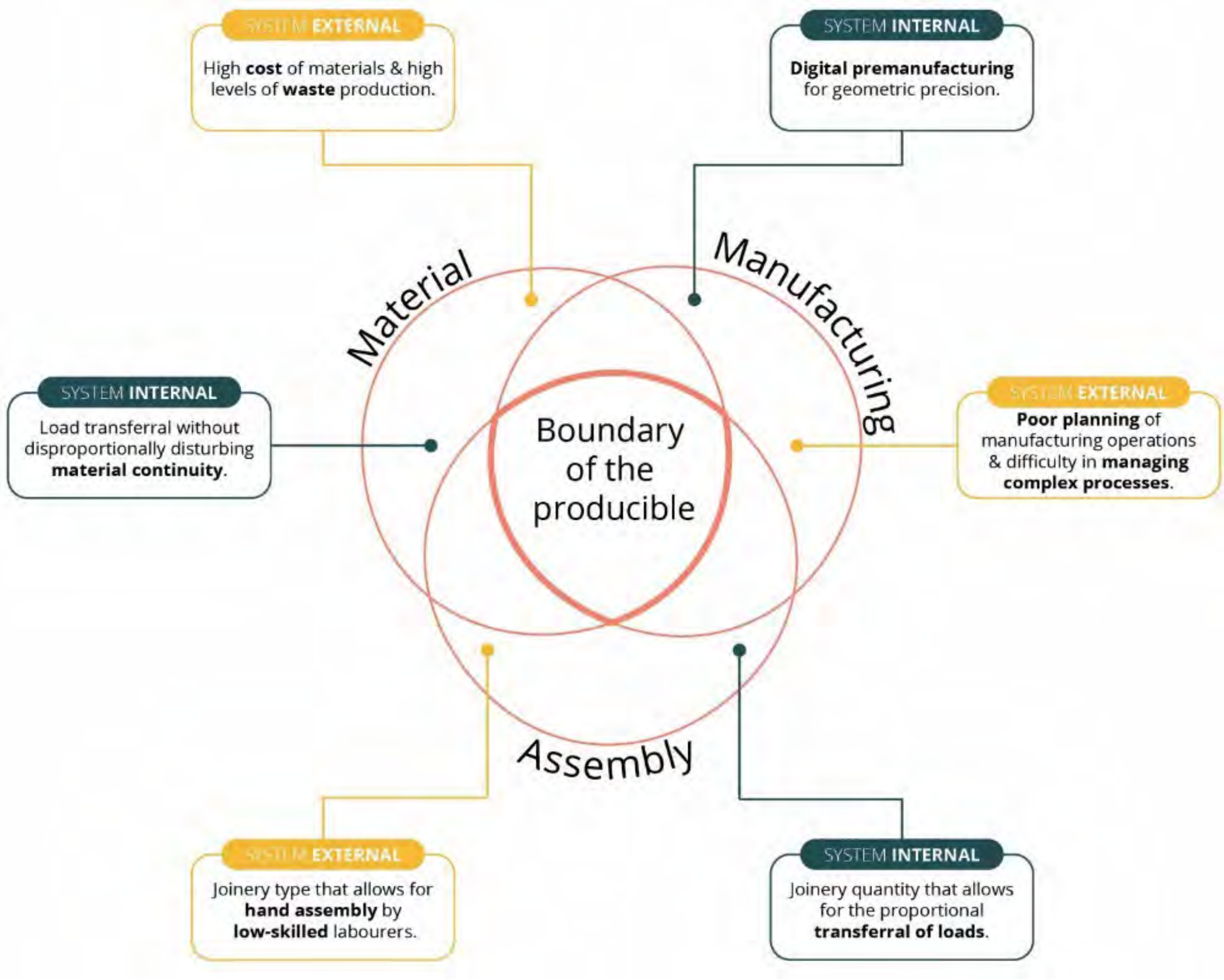


Figure 40: System-internal and system-external characteristics for building segmented shell structures in South Africa (Author 2024)

4.2 RESULTS FROM DATASET 2: SIMULATION CASE STUDY OF A SEGMENTED TIMBER SHELL STRUCTURE

Upon conclusion of the scoping literature review (figure 40), it was decided that nesting efficiency, segment quantity and total segment edge length are the relevant parameters by which the internal conditions of segmented shells can be balanced against the external contextual conditions of the South African built environment (figure 41). This section will present the relevance of these parameters and the quantitative data outputs obtained.

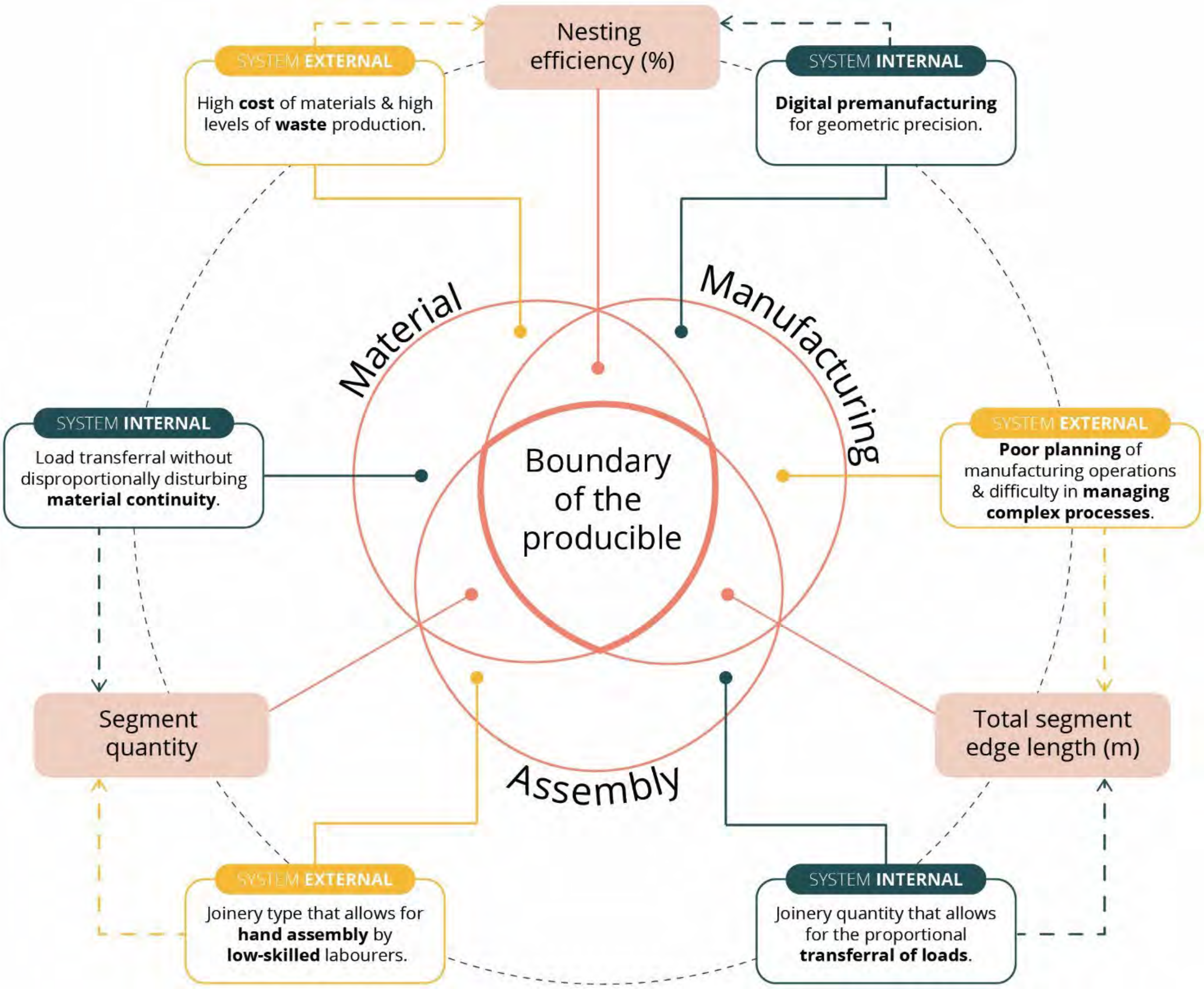


Figure 41: Relevant parameters to assess the interplay between internal and external conditions of segmented timber shells in the South African built environment (Author 2024)

4.2.1 Parameter 1: Nesting efficiency

4.2.1 A) Relevance of nesting efficiency as a parameter

The contextual need to reduce the cost of building materials and waste informs nesting efficiency as a parameter (figure 42). When designing a segmented shell, this parameter measures how effectively segments are arranged on standardised CLT panels to maximise the use of available material while reducing waste, exemplifying the biological pursuit of maximising performance with minimal resources (Oxman 2010: 42). The internal requirement for following a digital manufacturing process means that a designer can use the Grasshopper environment to simulate various nesting layouts using the OpenNest plugin (Vestartas n.d.).

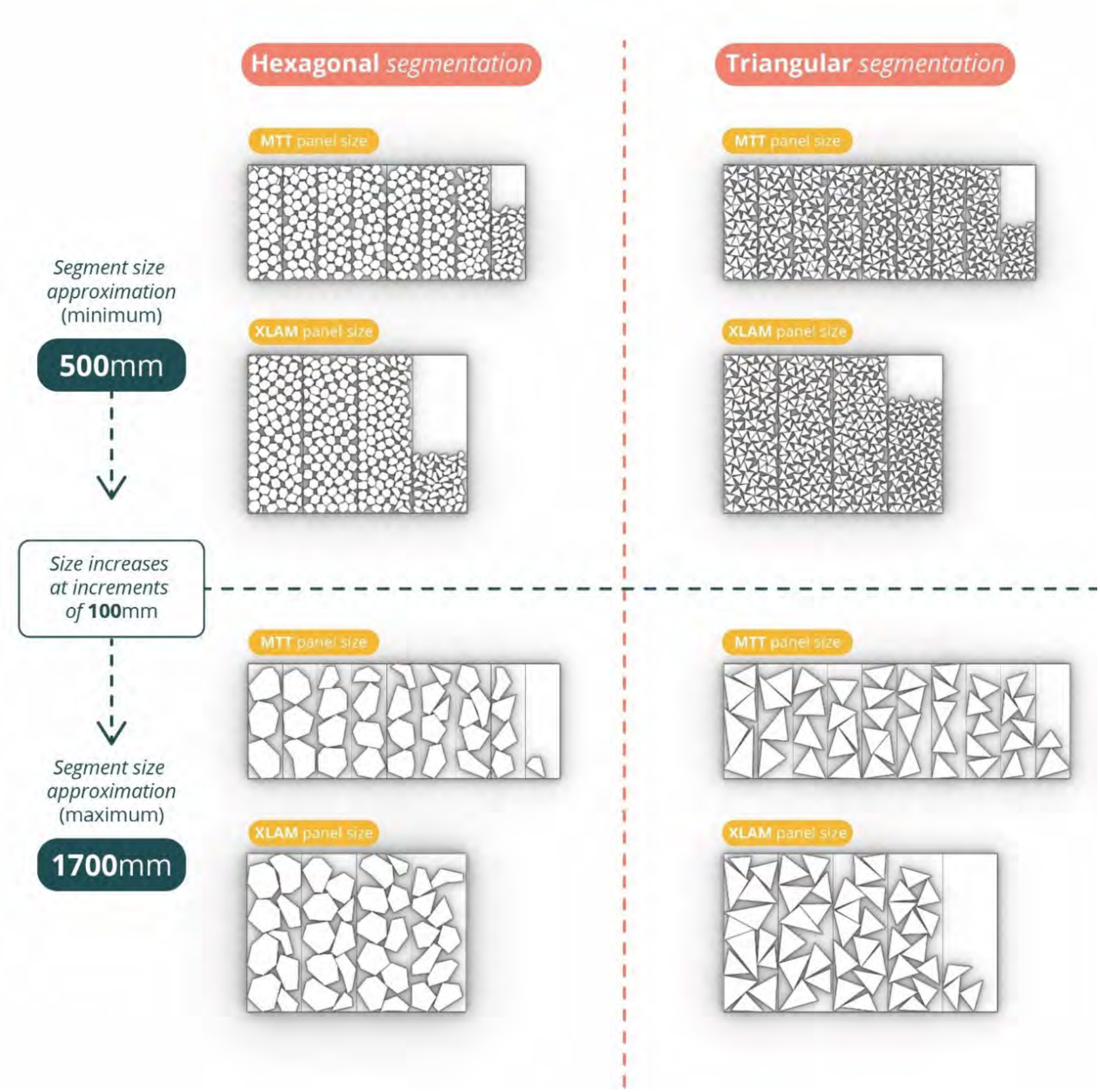


Figure 42: Nesting efficiency for different segmentation geometries and sizes for both MTT and XLAM's largest available panel sizes (Author 2024)

4.2.1 B) Results for nesting efficiency

Both hexagonal and triangular segments are nested onto the largest standardised panel dimentions of the two CLT manufacturers in South Africa. XLAM offers a panel area of 23.5 m² (XLAM n.d.), and MTT offers a smaller panel area of 10.8 m² (MTT n.d.).

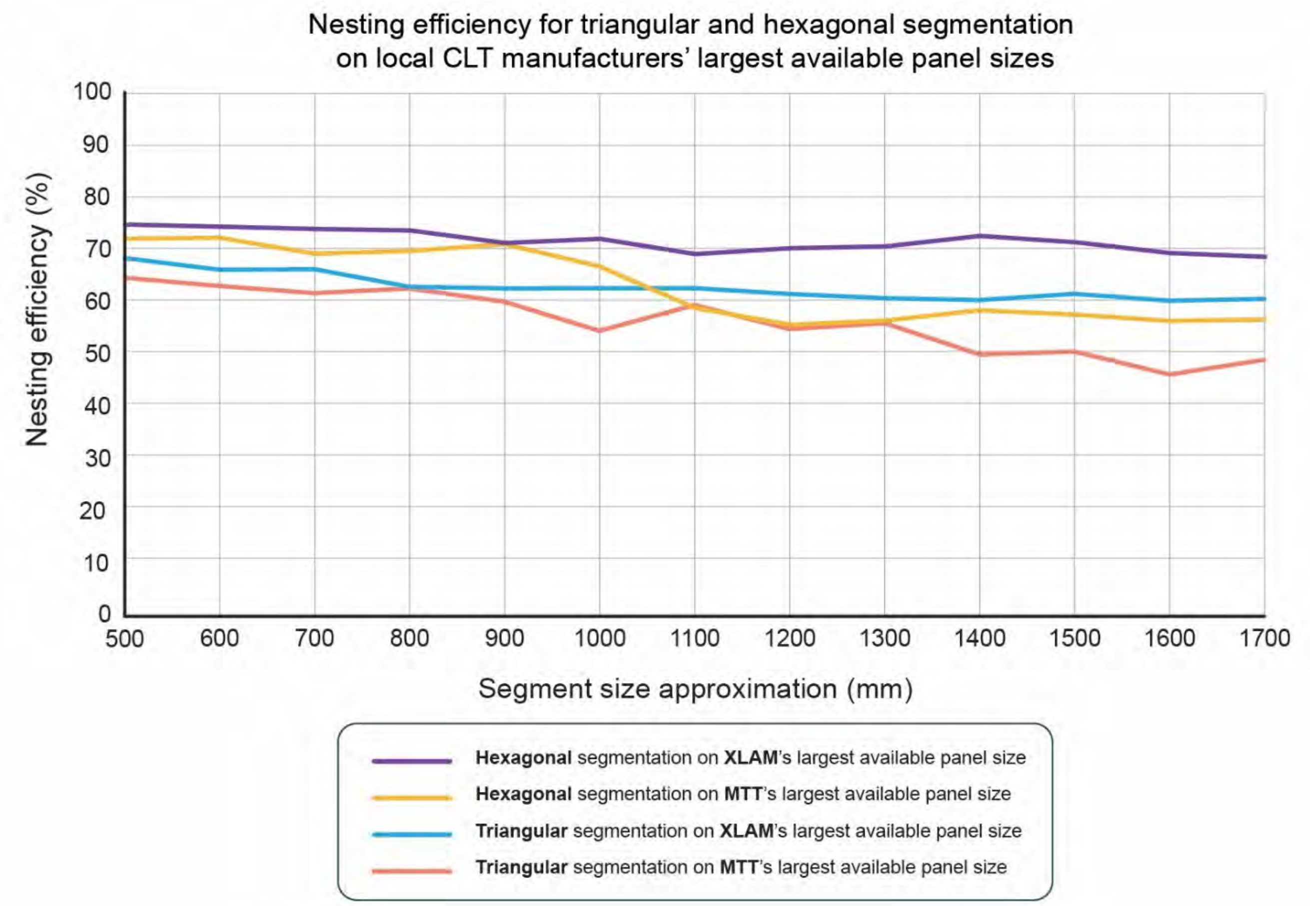


Figure 43: Results for nesting efficiency (Author, 2024)

Figure 43 shows that nesting efficiency changes depending on the dimension of a CLT manufacturer's panel dimensions, as well as the size and geometry of nested segments. XLAM has a larger available panel size, resulting in nesting being 3% better averaged between both segmentation geometries at a size approximation of 500mm, and being 12% better at 1700mm compared to MTT's largest available panel size. The difference in nesting efficiency between different panel sizes becomes more pronounced as segment sizes increase, with smaller sizes being more optimal. Moreover, hexagonal segments nest on average 8% more efficiently than triangular segments across the two different manufacturer's panel sizes and segment size approximations. The degree to which nesting efficiency can be improved stagnates as segment sizes decrease.

4.2.2 Parameter 2: Total segment edge length

4.2.2 A) Relevance of total segment edge length as a parameter

The contextual challenge of managing complex manufacturing processes informs total segment edge length as a parameter. When robotically cutting segments from CLT panels, the total segment circumference is a proxy for the intensity and complexity of the digital premanufacturing process. Internally, it refers to the quantity of joinery required to transfer forces proportionally between planarised surfaces. A lower total edge length is more optimal as it reduces manufacturing intensity and the quantity of joinery required (figure 44).

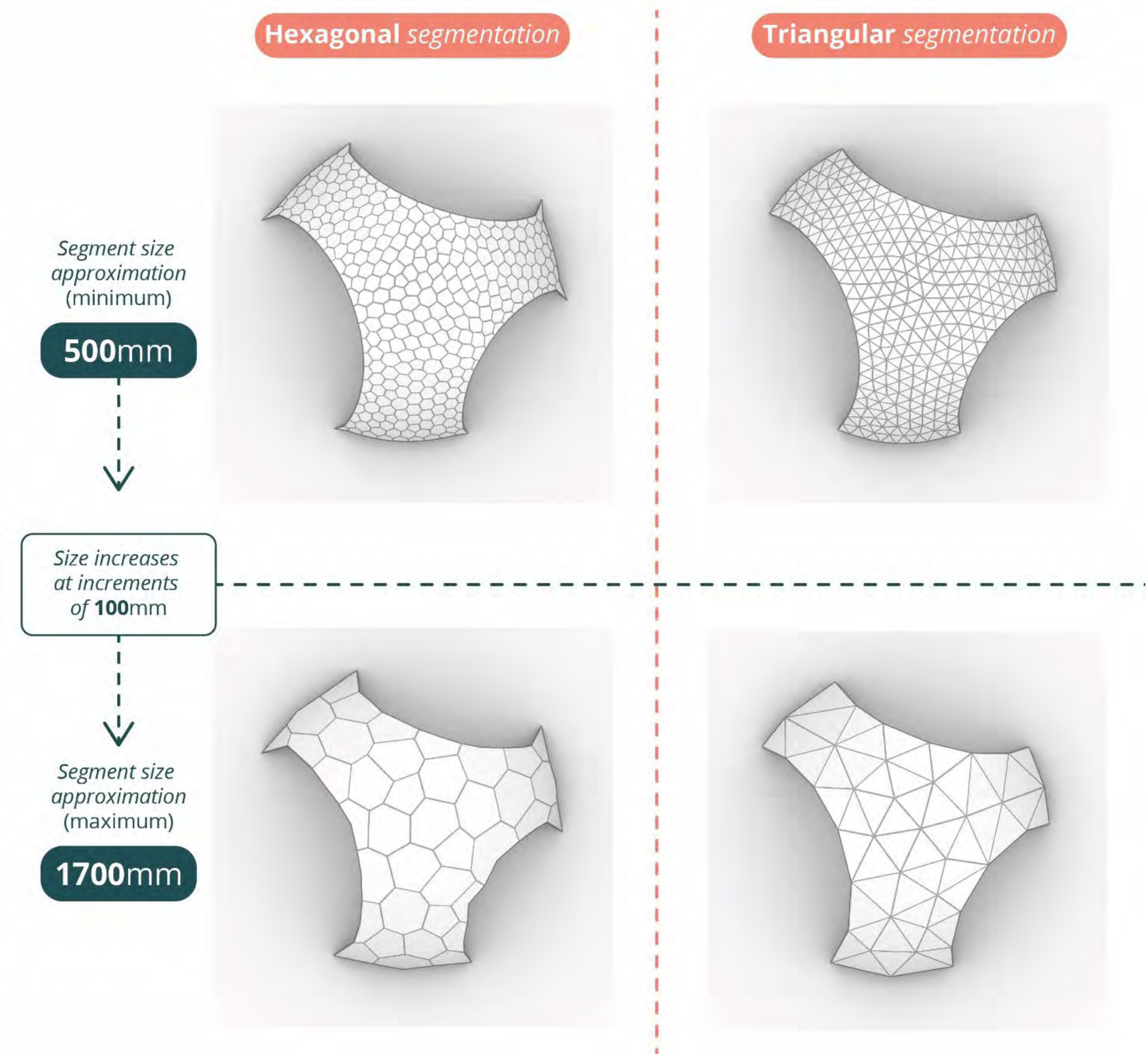


Figure 44: Total segment edge length and quantity generated for different segmentation geometries and sizes (Author 2024)

4.2.2 B) Results for total segment edge length

Referring to figure 45, both segmentation geometry and size influence total segment edge length. Hexagonal segmentation performs better than triangular segmentation as it has a 37% reduced total edge length at 500mm, and a 27% reduced length at 1700mm. The degree to which total edge length can be optimised stagnates as segment sizes increase.

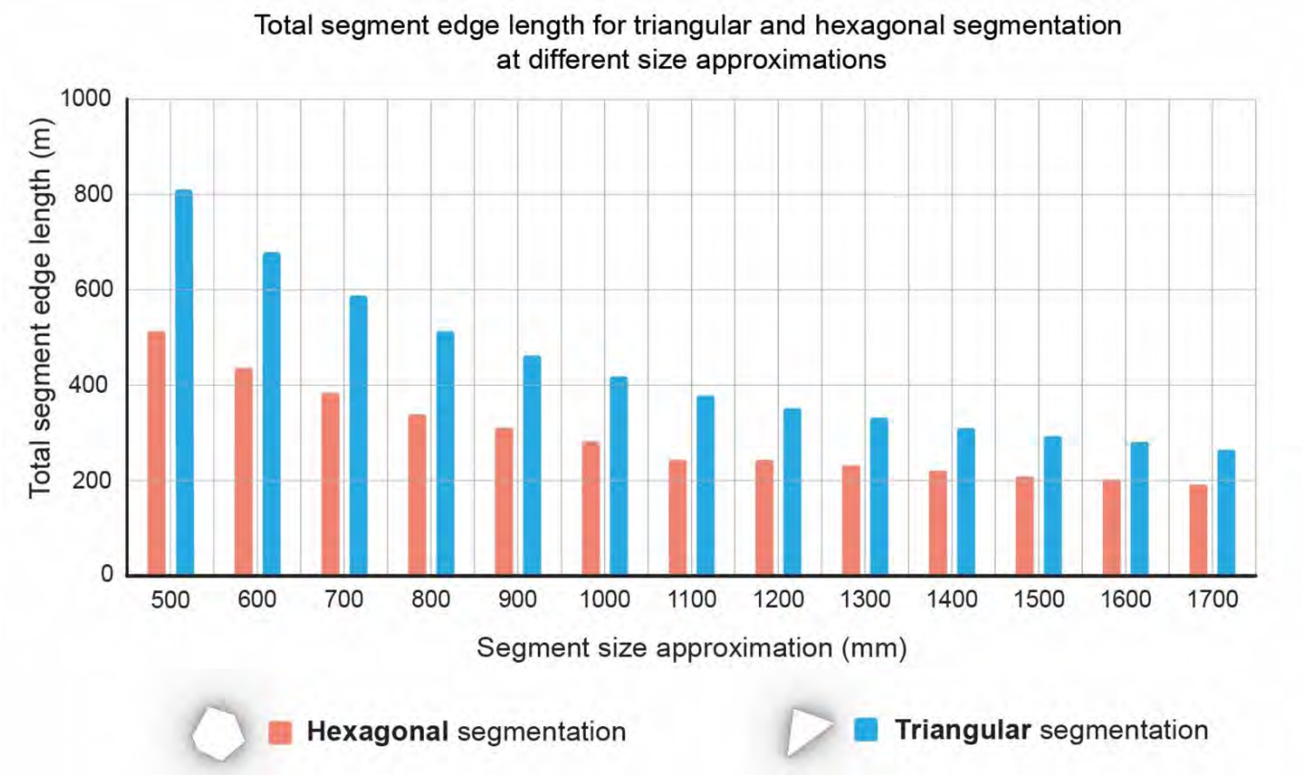


Figure 45: Results for total segment edge length (Author 2024)

4.2.3 Parameter 3: Segment quantity

4.2.3 A) Relevance of segment quantity as a parameter

Internally, segmented shells require load transferral with a minimal disturbance of material continuity. Larger segments reduce the disturbance of material continuity. However, larger segments impact the extent to which low-skilled hand-based labourers can be included, which is a socio-economic necessity in South Africa. The total number of segments generated across triangular and hexagonal segmentation at different size approximations is thus a relevant parameter that intersects these requirements. Regarding structural performance, a lower number of segments, which implies larger segments (figure 44), is more optimal as it reduces disturbance to material continuity and assembly complexity.

4.2.3 B) Results for segment quantity

Referring to figure 46, both segmentation geometry and size influence the total number of segments that must be cut, managed and assembled. Hexagonal segmentation performs better than triangular segmentation as it has a 43% reduced total amount of segments required to cover the same surface area at an edge length of 500mm, and a 26% reduction at 1700mm. The degree to which segment quantity can be optimised stagnates as segment sizes increase.

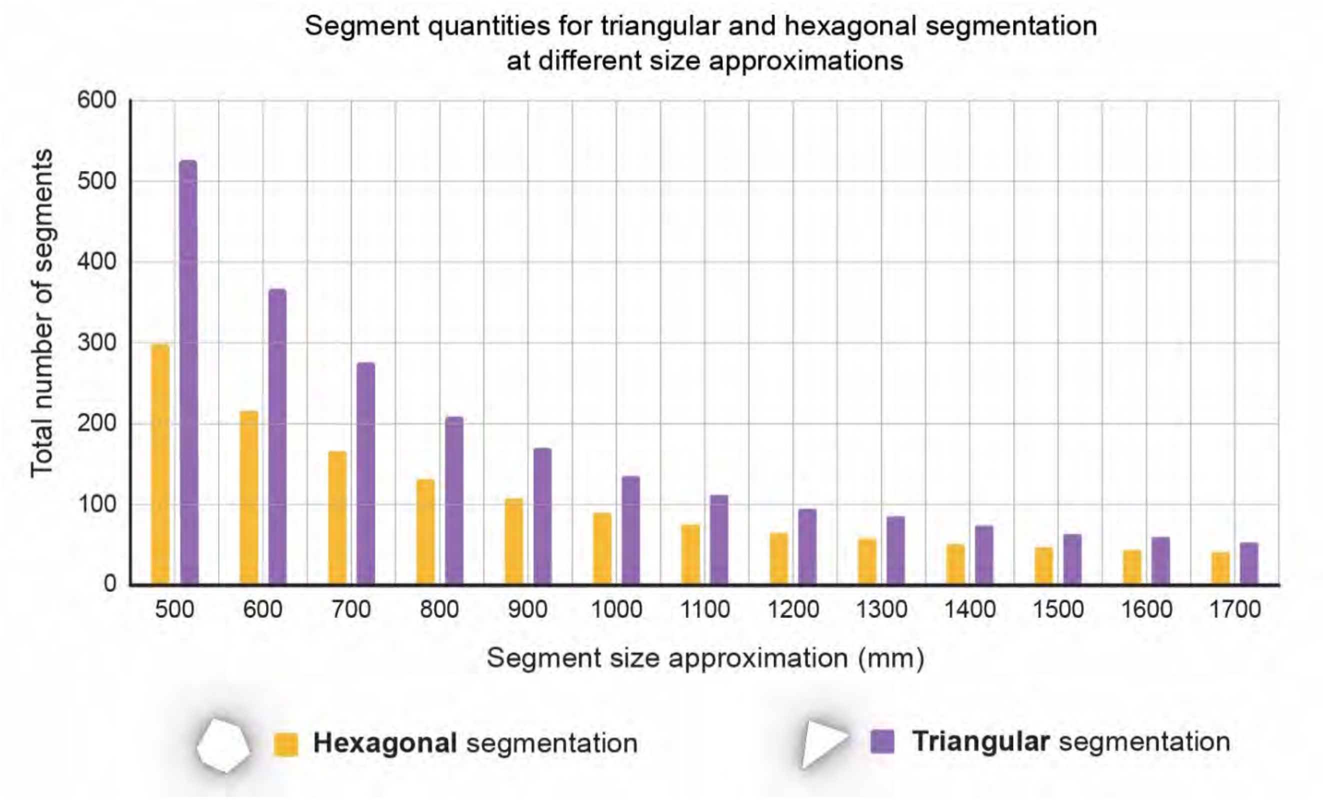


Figure 46: Results for segment quantity (Author 2024)

4.3 SYNTHESIS OF RESULTS FROM DATASET 1 & 2

The simulation case study provides data from three relevant parameters, namely nesting efficiency, total segment edge length and segment quantity. Hexagonal segmentation performs better than triangular segmentation across all three parameters. Therefore, going forward, the investigation will only consider hexagonal segmentation to determine appropriate segment size approximation and the impact of local CLT manufacturers' panel dimensions on overall system performance.

4.3.1 Results differentiation between local manufacturers

The three parameters can be charted onto a multi-dimensional axis to allow for holistic performance assessment. The centre point represents the direction of optimisation of each parameter and can be referred to as the *pole of the optimal*.

Defining the *boundary of the producible* necessitates a consideration of the available panel sizes of the two CLT manufacturers in South Africa. Referring to figure 47, the panel size of the manufacturers influences nesting performance while bearing no impact on the other two parameters. Notably, XLAM exhibits better nesting performance due to having larger standardised panel dimensions. Therefore, going forward, the data for hexagonal segmentation nested onto XLAM panels will be consolidated into the research framework (figure 48).

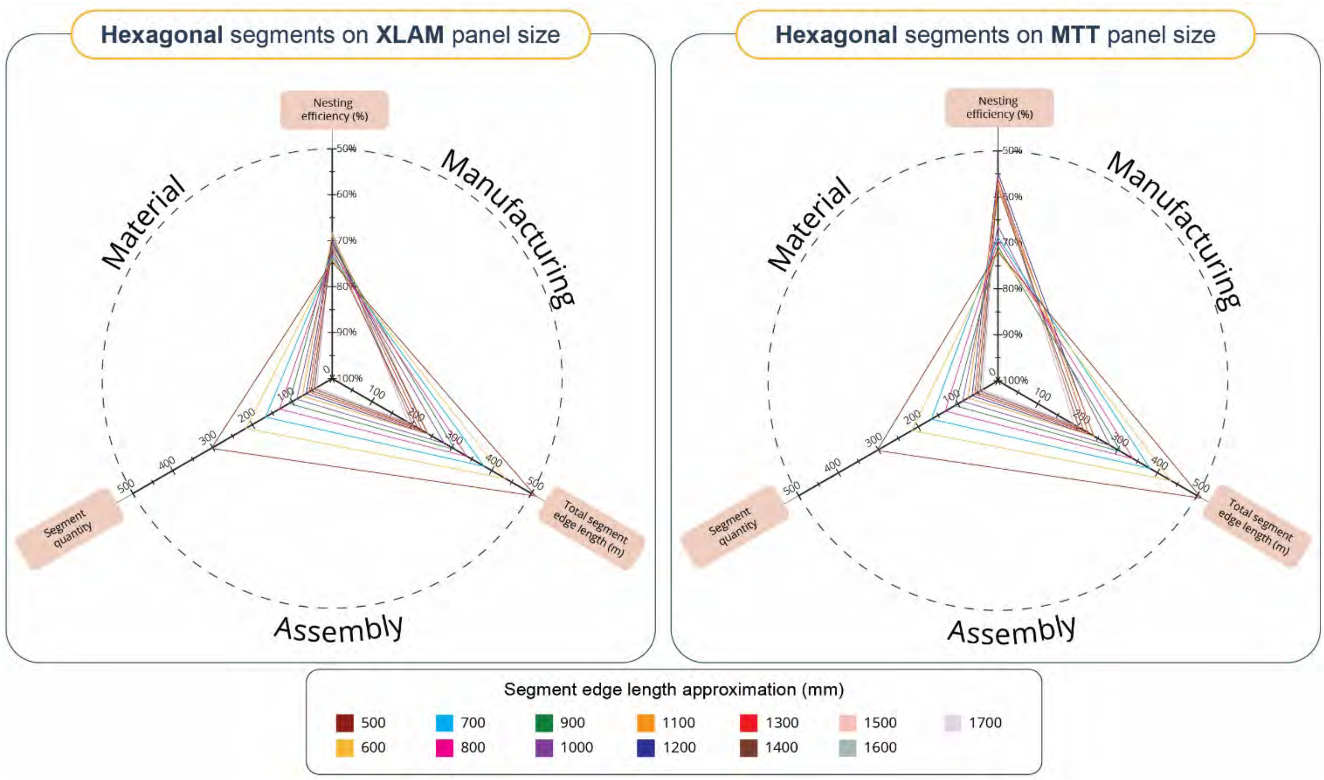


Figure 47: Performance differentiation between local manufacturer's standardised panel sizes (Author 2024)

4.3.2 Consolidation of research framework

The principal aim of this thesis is to create a framework that accounts for how well segmented timber shells will perform within the South African built environment. This chaper presented the qualitative nuances of the nation's construction industry, which was translated into quantitative assessment parameters intersecting the *factors of formation*. The findings from the mixed methodology are consolidated into the research framework (figure 48), leading to a discussion on how the internal and external can be balanced to determine appropriate segmentation size.

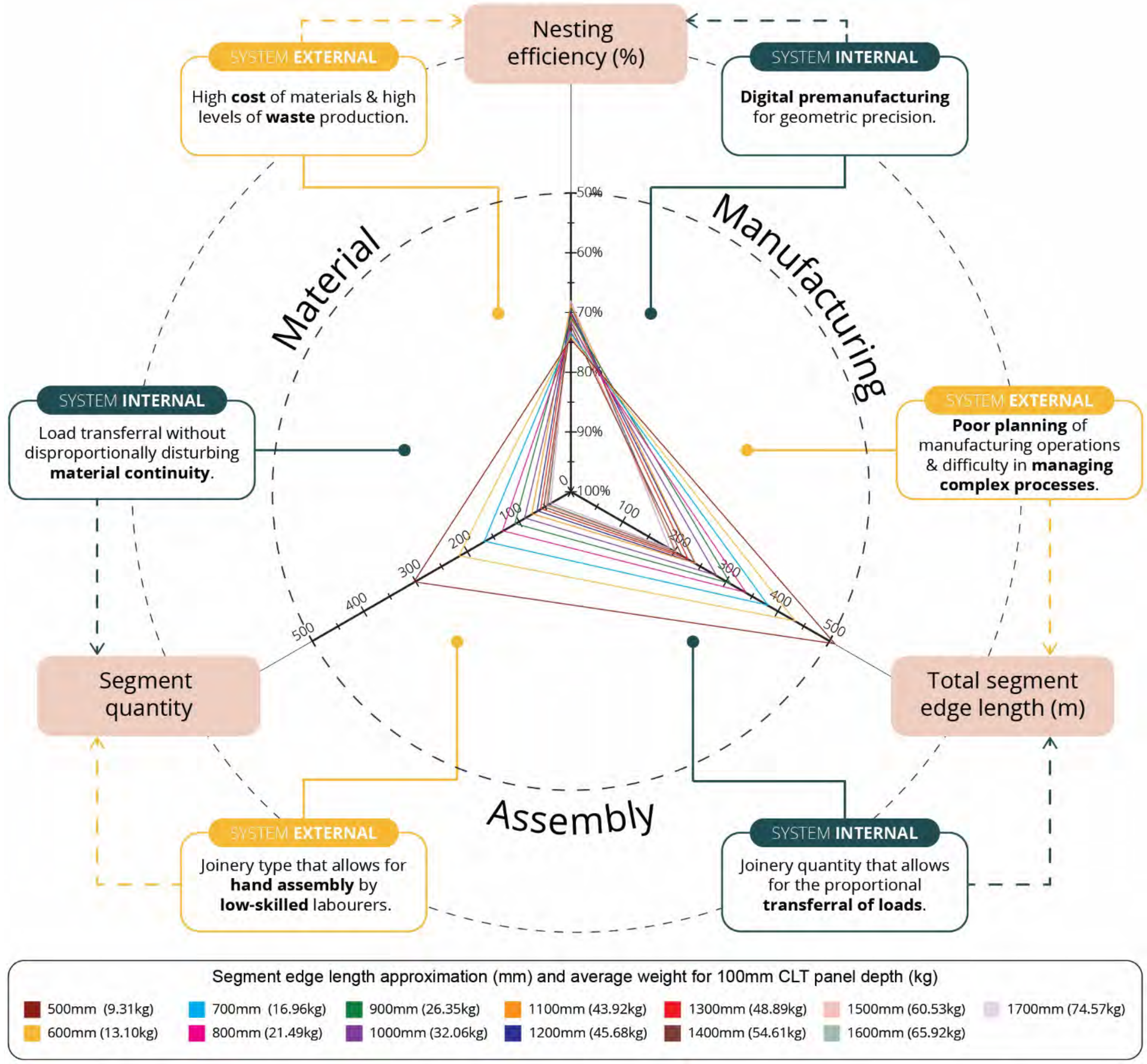


Figure 48: Consolidated research framework to assess relationships between system-internal and system-external requirements for segmented timber shell structures in the South African built environment, based on hexagonal segmentation and XLAM's panel size (Author 2024)

5 DISCUSSION

"The essence of technology is by no means anything technological." (Heidegger 1977: 9)

This research demonstrates that the value of Biomimetic design extends beyond the mere application of advanced digital technologies. Leveraging computational tools is not an end in itself, but a means to achieve deeper, contextually informed insights into how construction performance can be optimised to imbue the resulting architecture with socio-economic and environmental relevance. The AEC sectors of developing economies such as South Africa represent exacerbated performance challenges (figure 5), necessitating innovative and resilient design solutions. The question of technology then becomes how integrative computational design can be elevated to a poetic medium whereby the nation's contextual nuances can be mediated to adopt innovative building systems, such as segmented timber shells, and improve industry performance. In this regard, the research reconciles the computable and the incomputable.

5.1.1 Sub-question 1: The incomputable

What are the key challenges and opportunities for advancing sustainability through technological innovation within the South African construction industry?

Compared to the rest of Africa and its BRICS counterparts, South Africa is positioned relatively well in terms of adopting innovative building practices within the digital paradigm (World Economic Forum 2016). This is underscored by the nation's timber value chain (Grobbelaar & Visser 2021), the presence of CLT manufacturers (MTT n.d.; XLAM n.d.), the opportunity for advanced skill development within its robust tertiary education institutions (Manda & Dhaou 2019: 249), and the availability of people dependent on participating in the AEC sector (Mkhize 2019: 17).

However, reluctance to adopt innovative building practices can be attributed to the cost of building (Dosumu & Aigbavboa 2021: 98), skills deficiencies (Adebowale & Agumba 2023: 12; Department of Science and Innovation 2023: 54), and fear of economic exclusion from the AEC sector (Manda & Dhaou 2019: 250). Thus, socio-economic transformation should be central to the pursuit of sustainability. Bridging the gap between highly skilled fabrication stakeholders and the widespread prevalence of low-skilled assembly workers becomes an opportunity for technological hybridity. Including hand-based assembly within a highly digitised process enables economic participation and an opportunity for on-the-job training. This concurs with Low's (2014: 295) assertion that participatory construction can give

African architecture a strong sense of innovation. Computation is humanised through socio-economic participation in the meaningful act of making state-of-the-art structures, competing in the global discourse of Biomimetic architecture while remaining rooted in the South African context.

These insights build familiarity with regionally specific qualitative assessment proxies, which can be computationally mediated within quantitative data outputs.

5.1.2 Sub-question 2: The computable

What parameters can be used to assess the performance of segmented timber shell structures across material, manufacturing and assembly processes?

Outlining relevant assessment parameters is based on the conception of *natural morphogenesis* whereby the performative capabilities of biological structures result from the negotiation of often opposing requirements between an organism's internal genetic coding and external environmental forces acting upon it (figure 10) (Menges 2007: 727, 2011: 72). Thus, parameters are distilled upon intersecting structural and fabrication requirements of segmented timber shells with the contextual conditions of South Africa's AEC sector. Simply put, relevance is attained by intersecting system-internal and external. The research demonstrates that nesting efficiency, total segment edge length and segment quantity are regionally appropriate assessment proxies (figure 48).

Nesting efficiency intersects the contextual challenge of material cost and waste, with the digital manufacturing process whereby the nesting layouts can be iterated within the Grasshopper interface. Total segment edge length intersects the regional challenge of managing complex manufacturing processes and, by extension, machining intensity of long edge lengths, with the structural requirement of having joinery quantities proportional to segment circumferences. Segment quantity intersects the contextual challenge of including labourers with skills deficiencies and the necessity of carrying individual segments by hand, with the structural requirements of avoiding disruption to material continuity. These parameters represent different ranges and scales of optimisation and stagnation. For example, the range in which nesting efficiency can be optimised is limited compared to the exponential range of total edge length and segment quantity. This underscores the importance of balance.

With a descriptive overview of the two sub-questions, it is now possible to discuss the primary research question holistically:

What are the relationships between system-internal requirements and system-external conditions in optimising the material, manufacturing, and assembly processes for segmented timber shell structures within the South African built environment?

5.2 FACTORS OF FORMATION: THE BALANCE BETWEEN INTERNAL & EXTERNAL REQUIREMENTS

Moving from *natural* to *computational morphogenesis*, the research demonstrates how principles that lend natural systems their regenerative qualities can be transferred into building systems in the South African context. This is achieved through a multi-objective optimisation process across material, manufacturing and assembly processes of segmented timber shells. Each realm will be discussed accordingly.

5.2.1 Material performance

Within the material realm, the findings suggest that there are opposing internal and contextual requirements. These opposing requirements are investigated through the following parameters: segment quantity and nesting efficiency.

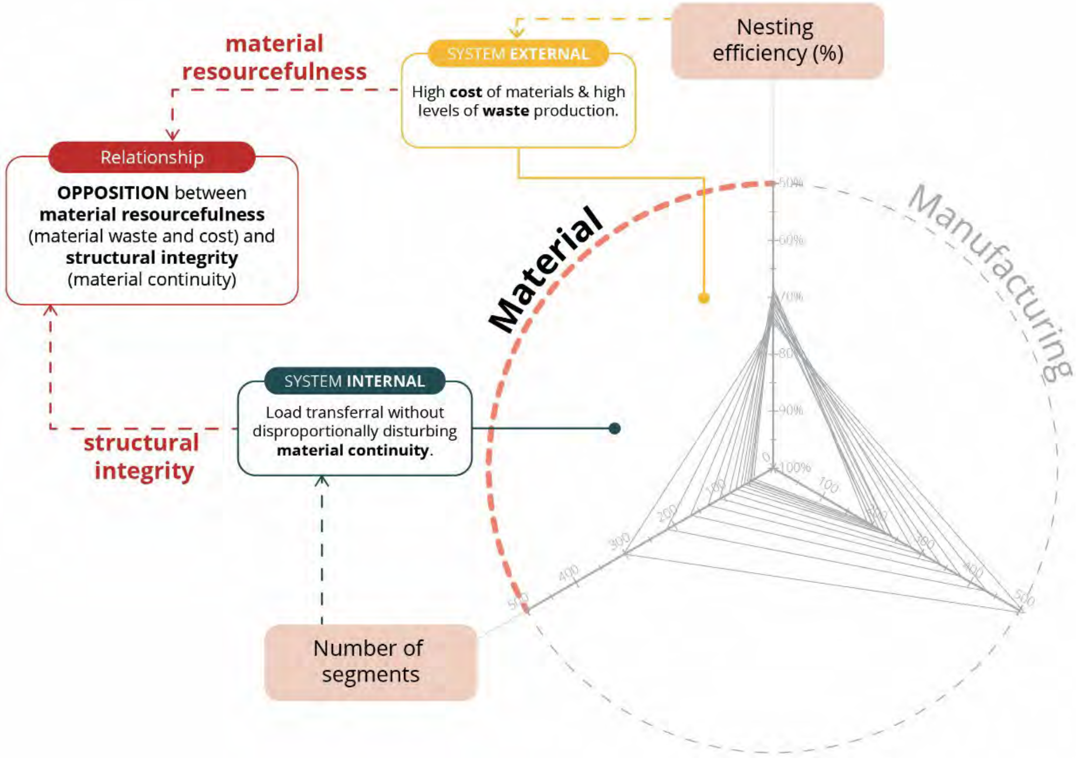


Figure 49: Interplay of parameters for assessment of material performance (Author 2024)

Segmented shells require material continuity for the proportional transferral of compressive forces (Bechert et al. 2018: 1). Small CLT segments imply that there are a larger number of segments (figure 44), disrupting material continuity. Rather, it is structurally optimal for segments to be large, meaning that segment quantity is reduced as fewer are needed to cover the surface area.

This opposes the contextual challenge of material cost and waste (Fitchett & Rambuwani 2022: 106–109; Aghimien et al. 2019: 1122), was assessed through nesting efficiency. Better nesting efficiency implies that fewer CLT sheets are used to cut segments. This results in lower material usage, cost and waste production. Simply put, what is optimal for material resourcefulness opposes what is optimal in terms of structural integrity (figure 49).

However, this opposition does not happen on similar scales. Nesting efficiency of hexagons can only be improved in a range of approximately 6% when nested onto XLAM’s panel size (figure 43). This range remains limited compared to the range of approximately 87%, in which the quantity of hexagonal segments can vary (figure 46). These ranges assist in defining the threshold between what is structurally optimal and what is resourceful.

Concrete shells such as Bosjes Chapel, a South African example, represent one end of this spectrum (figure 24). Its superior structural performance results from the compressive properties of concrete. Yet this internal structural characteristic comes at the cost of a difficult construction process, producing waste and limiting the degree to which a generally unskilled construction labourer in South Africa can be employed in the process (figure 25).

An unbalanced optimisation in the realm of material, structurally efficient but unaffordable and inefficient in its formation process, is argued to represent Heidegger’s *challenging-forth* mode of conceptualising technology. It exemplifies the contemporary tendency of prioritising form over fitness and formation and its association with the multifaceted challenges faced by the global AEC sector (figure 4) (Oxman 2010: 27–28).

The balance between what is structurally optimal, large segment sizes and less in quantity, and what is contextually optimal, small segment sizes at an increased quantity, can only be struck through a holistic assessment across the *factors of formation*. As the next section demonstrates, what is structurally optimal yet less resourceful concurs with what is optimal in terms of manufacturing.

5.2.2 Manufacturing performance

The regional challenge of managing complex construction processes leads to a conflict between internal and external requirements in the realm of manufacturing performance. This opposition is analysed using the following parameters: nesting efficiency and total segment edge length, and segment quantity by extension (figure 44). The inclusion of segment quantity in this analysis, although not initially distilled as an assessment parameter in this specific realm (figure 41), underscores the interrelated nature of the *factors of formation*. The research framework ultimately remains a heuristic representation of a much more associative and integrated assessment process.

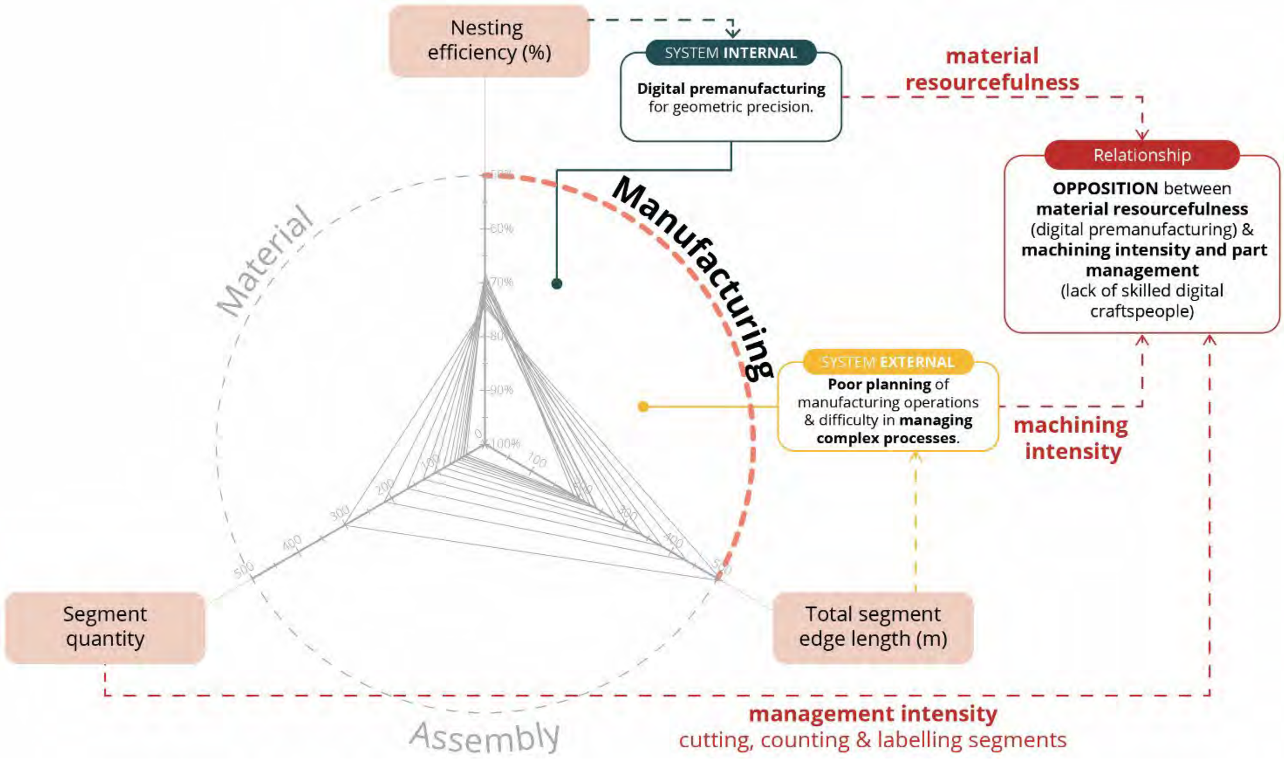


Figure 50: Interplay of parameters for assessment of manufacturing performance (Author 2024)

The high level of geometric precision required to build segmented shells necessitates a digital prefabrication process (Bechert et al. 2021: 4815). A longer total edge length and, by extension, a greater number of segments (figure 44) improves nesting efficiency. Smaller segments can be organised more compactly onto standardised CLT panel sizes (figure 42). Simply put, increased total edge length and segment quantity improve material resourcefulness.

This contradicts the contextual lack of technologically and computationally skilled people who can manage a digital premanufacturing process. This regional constraint can be expressed through the two parameters of total edge length and segment quantity.

Firstly, regarding total edge length, material resourcefulness of hexagonal segments nested onto XLAM panels can only be improved within an approximate range of 6% (figure 43). This comes at the expense at much wider range of 63% in which edge length can vary (figure 45). An exponential increase in total edge length implies much greater machining intensity, which is hindered by the low graduate output of people who can algorithmically instruct and manage fabrication machinery.

Secondly, segment quantity increases symmetrically with total edge length (figure 44). This bears implication yet again to the regional issue of skills deficiencies in construction management. A larger number of segments implies greater management intensity in terms of counting, labelling and keeping track of these parts, both in a factory and on-site scenario.

Notwithstanding, South Africa’s tertiary education institutions has the capacity to produce graduates with the skills to oversee these processes. Thus, the degree to which robotic fabrication intensity and management capabilities can be leveraged to improve material resourcefulness depends on increasing graduate outputs from the nation’s already robust institutions.

However, even if technologically skilled people become more readily available, the implied improvement to nesting efficiency and by extension, material resourcefulness, will still come at the expense of structural performance through a disruption to material continuity (figure 49). These increasingly interrelated and contradictory requirements underscore the importance of creating as much of a holistic view as possible before arriving at any conclusions regarding optimal segment size. As such, the discussion is driven towards the last realm: assembly performance.

5.2.3 Assembly performance

Within this realm, internal and external requirements do not oppose each other and can be optimised symmetrically. This is assessed through the following two parameters: total segment edge length and segment quantity.

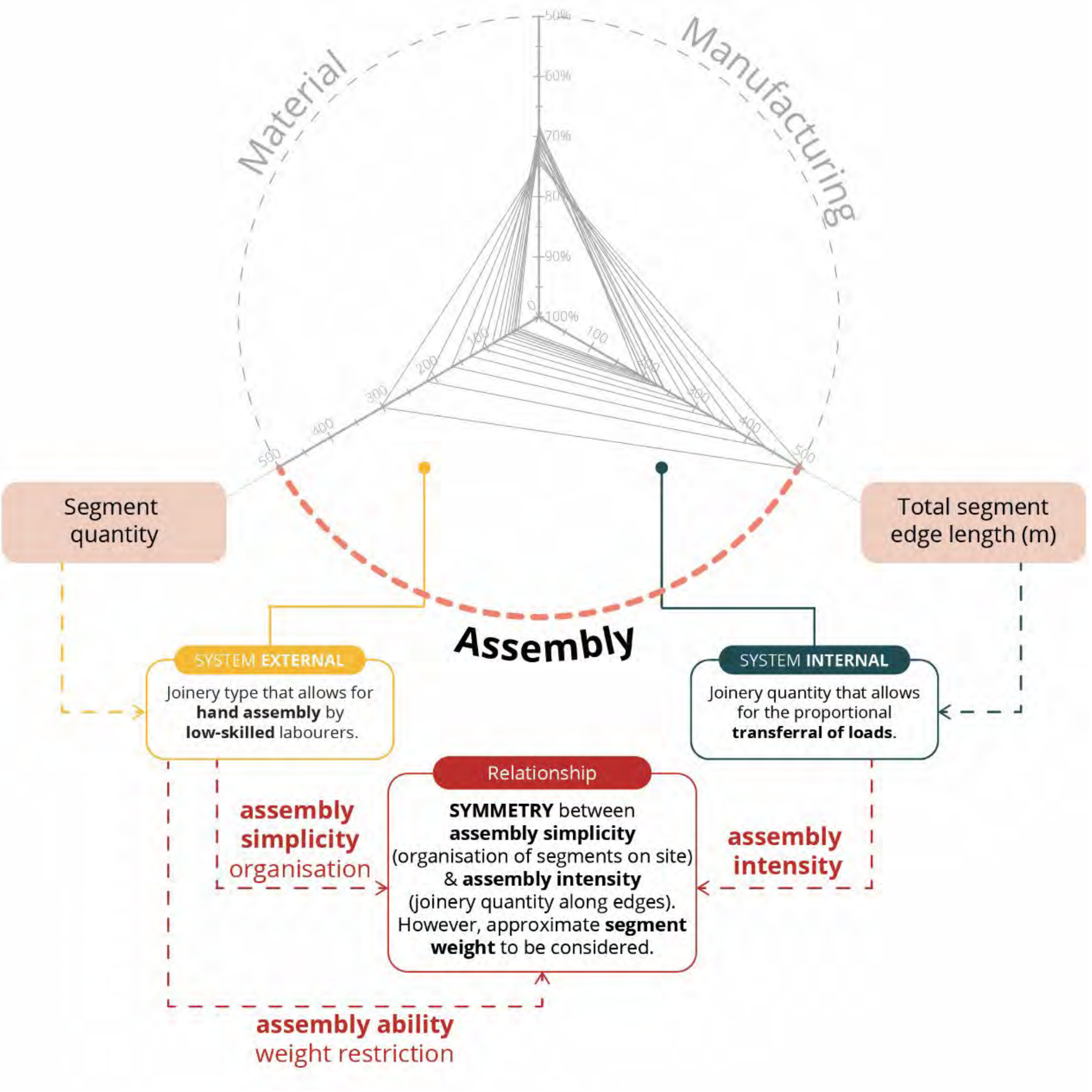


Figure 51: Interplay of parameters for assessment of assembly performance (Author 2024)

Internally, joinery quantity needs to be proportional to the transferral of loads along segment edges, which typically require a large number of connections (Bechert et al. 2018: 1). This internal condition is expressed through total edge length since more connections will be required as this parameter increases. A shorter total edge length implies that fewer connections are required, which reduces assembly intensity and the opportunity for on-site errors. Reduced edge lengths also imply larger segments and a smaller quantities (figure 44), simplifying assembly by reducing the risk of segments going missing or becoming disorganised. Thus, assembly intensity and simplicity considerations can be optimised symmetrically (figure 51).

However, the socio-economic necessity of employing hand-based labourers greatly influences the degree to which segment quantity and total edge length can be minimised and optimised. Large and heavy segments will restrict the degree to which hand-based construction labourers can comfortably carry and safely raise and assemble each segment. Smaller segments are easier to carry. Although smaller sizes disturb material continuity, it will enable better nesting efficiency (figure 42). Yet again, balance is imperative.

5.2.4 Synthesis: material, manufacturing and assembly performance

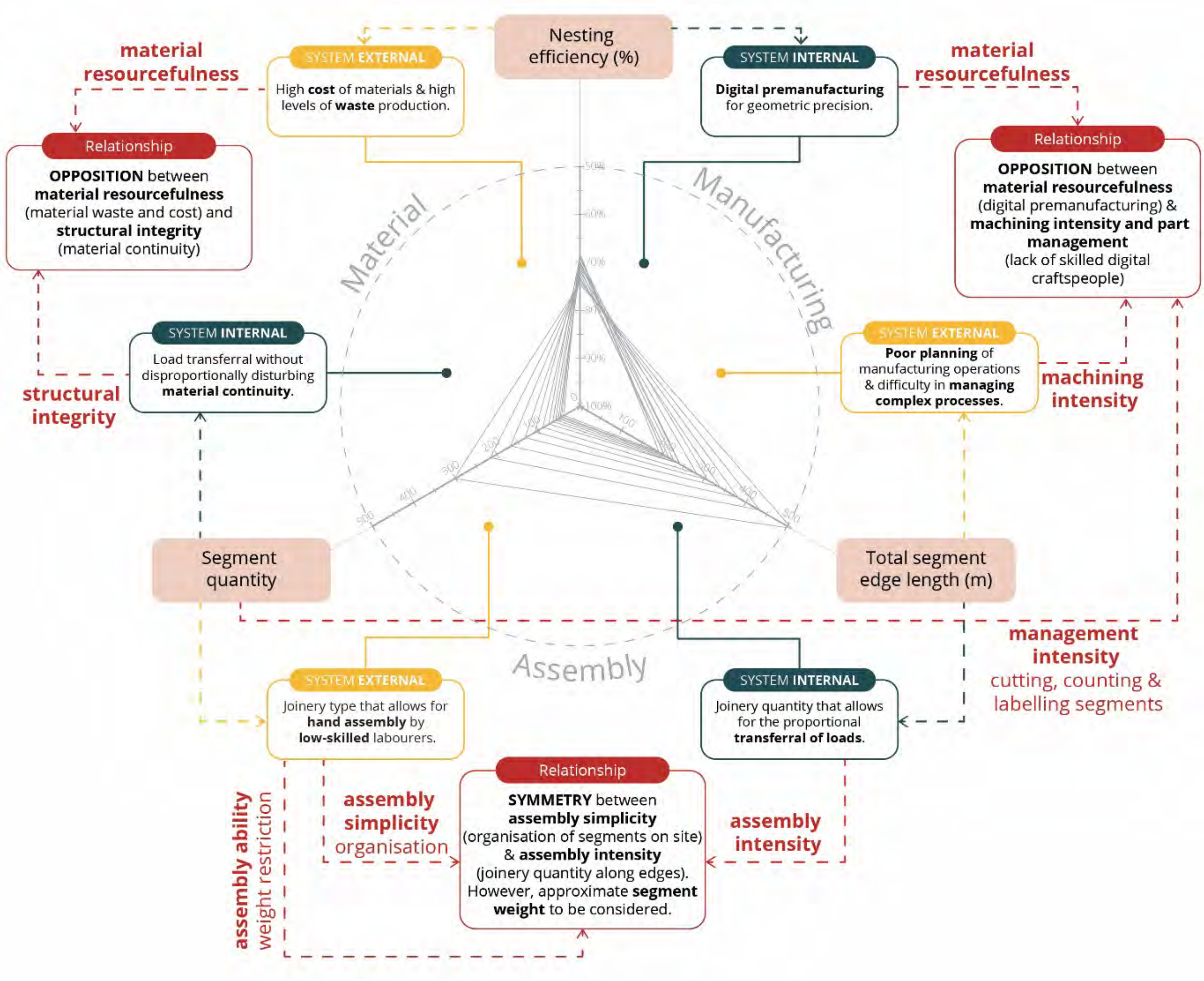


Figure 52: Holistic view of opposing and symmetrical relationships across the factors of formation of segmented timber shells in the South African context (Author 2024)

With a holistic assessment of the contradictions and symmetries encountered across material, manufacturing and assembly processes, it is now possible to discuss specific research outcomes in terms of optimising this building system for its new context.

5.3 OPTIMISING SEGMENTED TIMBER SHELLS FOR THE SOUTH AFRICAN BUILT ENVIRONMENT

"Almost every period of architecture has been linked to research in construction"
(Le Corbusier 1931: 216)

The previous section addresses the primary research question by outlining the complex and opposing relationships between internal and external informants for building segmented timber shells in the South African context. In addition to its theoretical value, a holistic view across the realms of material, manufacturing and assembly leads to outcomes with practical implications for the constructability of this building system. Geometric segmentation, size approximation and impact of local CLT manufacturers' panel sizes represent the *boundary of the producible* as it could be limited to specific outcomes upon situating the *factors of formation* within the nation's construction industry. These research outcomes will be discussed accordingly.

5.3.1 Regionally optimal geometric segmentation

The research considers triangular or hexagonal segmentation methods. This is based on the three-plate principle as found in biological shells (figure 26 & 27) (Bagger 2010: 4). Existing literature indicates that hexagonal segmentation is advantageous due to an increased area-to-edge ratio (Robeller & Von Haaren 2020: 128). The implication is that hexagonal segmentation performs better in terms of total edge length, which is confirmed in this study (figure 45). If triangles nested better than hexagons, then there could have been an opportunity to compromise on an optimal area-to-edge ratio and structural performance in favour of material resourcefulness, a significant contextual challenge. The nesting performance of triangular segmentation is not well documented, especially considering South African CLT manufacturers' unique panel dimensions. However, findings indicate that hexagonal segments nest better on both local CLT manufacturers' standard panel sizes (figure 43). Moreover, hexagons perform better in terms of segment quantity (figure 46). Fewer segments are required to cover the surface area, making it easier to label, count and manage individual parts, another contextual challenge. Hexagons are thus the optimal segmentation geometry within the South African built environment since it performs better across all three parameters. This falls in line with the prevalence of hexagonal segmentation in international case studies (Robeller & Von Haaren 2020; Bechert et al. 2018; La Magna et al. 2013).

5.3.2 Regionally optimal segment size approximation

The different ranges and scales in which optimisation and stagnation can occur across parameters assist in determining an appropriate segment size range. Referring to figure 53, it is concluded that a range between 800mm to 1000mm is optimal for this context. This range represents the *boundary of the producible*. It should be noted that this boundary is flexible, allowing for adaptation towards adjacent ranges when selecting segment sizes depending on specific project conditions. This size range will also depend on segment weight resulting from panel depth, which will be a function of the span based on the specific project's footprint. This flexibility of size mirrors the natural phenomenon where resilience results from the diversity of solutions within a single habitat (La Magna et al. 2013: 27).

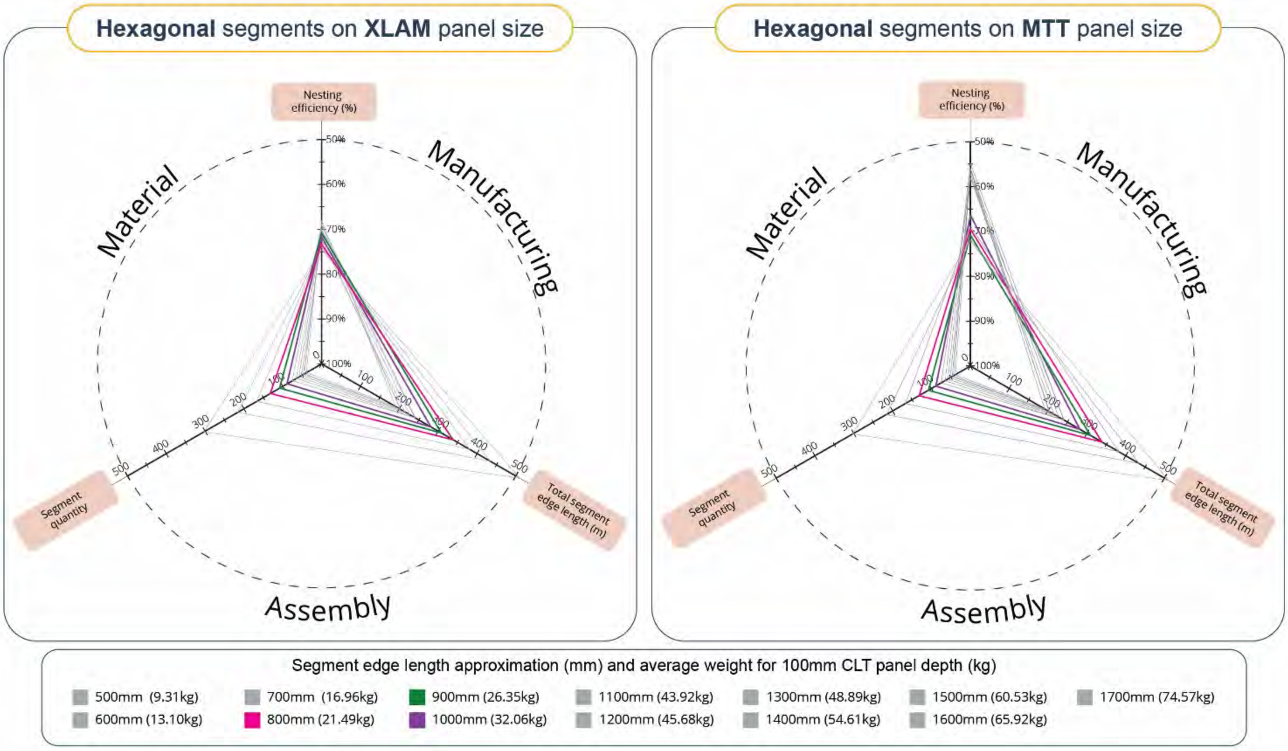


Figure 53: Optimal segment size approximation for segmented timber shell structures in the South African built environment (Author 2024)

5.3.3 Implication for South African CLT manufacturers

When considering nesting efficiency in isolation, findings suggest that using XLAM to manufacture segments is more optimal, as the company's larger panel dimensions reduce material waste by 8% across all sizes for hexagonal segments (figure 43). However, a holistic assessment of all three parameters reveals that the choice of manufacturers does not play a significant role in the overall performance of segmented shells. This insight is based on the appropriate segment size range. Referring to figure 53, there is no significant difference in nesting efficiency between the two manufacturers at a segment size range of 800mm to 1000mm. The implication is that transportation costs and carbon emissions can be reduced by selecting a CLT manufacturer closest to the specific project's location. This insight underscores the importance of holistic multi-objective optimisation.

5.3.4 Reiterating form and formation: next steps in determining segment depth

Distilling the appropriate geometric segmentation and size range concludes the first cycle of optimisation. Going forward, these outcomes can be plugged back into the case study methodology and become assumptions in a new digital form-finding process based on the new building footprint of a specified project (figure 54). In this regard, hexagonal segments within a flexible range of 800mm-1000mm remain relatively constant, while the span of the new footprint will determine segment thickness and associated weight. From here, the process will loop back to formation, where segment depth can be optimised, resulting in either a specified CLT panel thickness or a lightweight cassette buildup (figure 32). Form and formation are finally attuned.

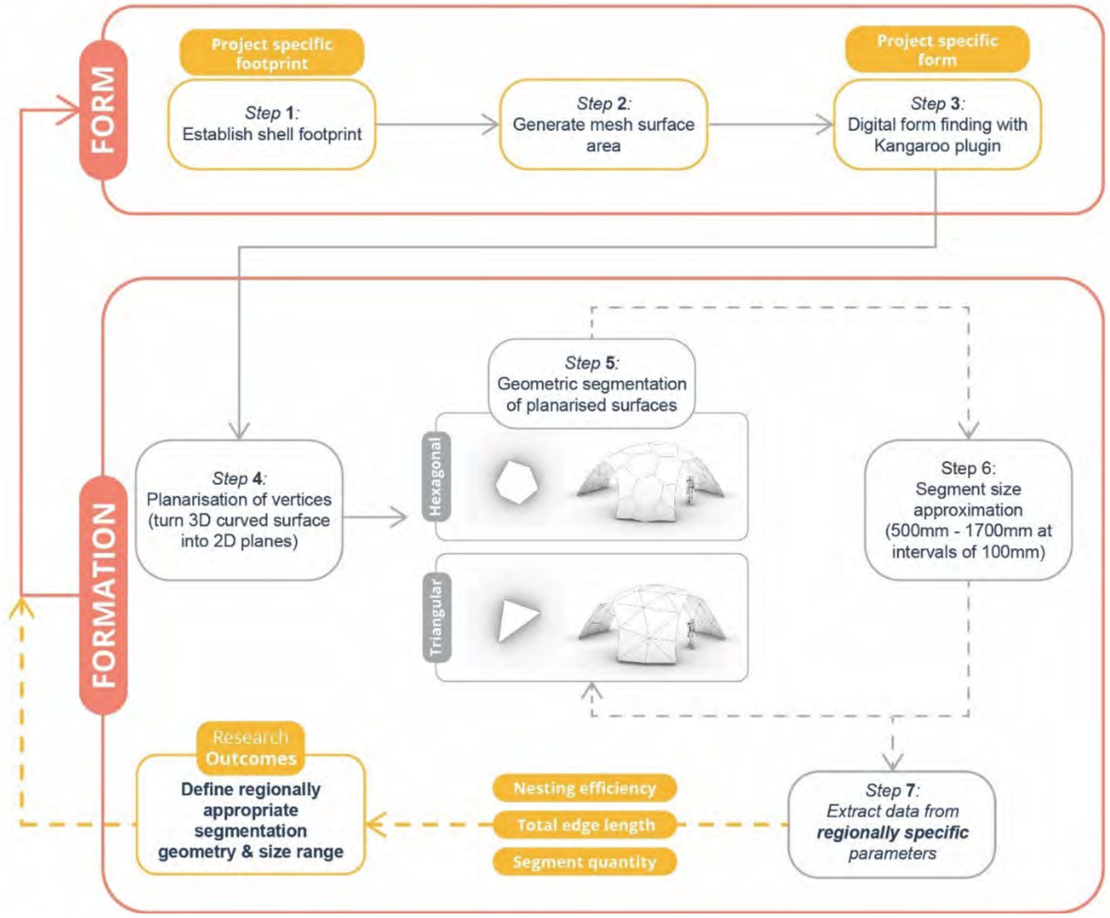


Figure 54: Iteration between form and formation based on research outcomes (Author 2024)

5.4 BEYOND OPTIMISATION: RECONCILING THE COMPUTABLE WITH THE INCOMPUTABLE

This research demonstrates the poetic capacity of computation. The acknowledged difficulty of quantifying sustainability performance (Goh et al. 2020: 2), has led this study to investigate its advancement through proxies in a data-driven design and delivery process (figure 39). Contextual considerations in socio-economic and ecological spheres are algorithmically entangled with material, manufacturing and assembly processes (figure 17). These *factors of formation* are further investigated through parameters that attain relevance through the intersection of internal and external requirements of segmented shell structures in the South African context (figure 41). Observing these opposing relationships, specifically how optimisation in nesting efficiency contradicts optimisation in terms of total segment edge length and segment quantity, implies that it is impossible to reach the centre point of the multidimensional axis. The *pole of the optimal* can be orbited but never reached.

The poetry lies in the pursuit of an elusive target. This understanding represents the fine line between Heidegger's two modes of conceptualising technology (Heidegger 1977). Achieving absolute efficiency in one parameter comes at the expense of other formation processes, representing *challenging-forth thinking*. Conversely, orbiting the *pole of the optimal* reveals a deeper engagement with the intricacies between materiality, resourcefulness, affordability, structural integrity, parts availability, fabrication tools, assembly intensity and skills.

Bringing-forth this engagement is computationally enabled in this study (figure 52), concurring with the assertion that these relationships have always been deeply understood by skilled craftspeople (Menges et al. 2016: 6; Sennet 2009: 26; Klinger 2001: 240). Form and formation are not solely a function of physical force. It is not mono-parametric. Rather, it results from the negotiation between the technicalities of structural and fabrication efficiency, the computable, and the socio-economic forces that define the conditions of its construction, the incomputable. By leveraging integrative computational design tools, architects can reimagine their role in the digital era akin to that of the master carpenter. In this capacity, the architect becomes the master of the data, computationally mediating between the technical and the non-technical, the quantitative and the qualitative to define the *boundary of the producible*. Efficiency and equity converge, casting light on the timeless value of human intuition amidst the evolutionary trajectory of technology.

6 CONCLUSION

The study adds to the general lack of research investigating the advantages of Biomimetics and integrative computational design and delivery processes within the global South. More specifically, segmented timber shell structures are considered within the South African AEC sector as a possible solution to its performance challenges (figure 5).

This building system is analysed across material, manufacturing and assembly processes to understand the relationships between its internal requirements and the external conditions that characterise the nation's construction sector. The findings underscore the importance of aligning socio-economic transformation, specifically skills development and participatory construction, with the adoption of innovative and regenerative construction practices in the digital era. Enriching the research framework with regionally specific conditions (figure 41), leads to practical outcomes in terms of building a segmented shell in South Africa.

Firstly, it is determined that hexagons are the appropriate geometric segmentation method compared to triangles, falling in line with its prevalence in international case studies. Secondly, the size of these segments performs best when individual edge lengths fall within a flexible range of 800mm - 1000mm. Important to note is that this range can be adapted to adjacent numerical inputs depending on specific project requirements, building span, and segment weight resulting from a specific depth. Lastly, the findings indicate that differences in nesting performance across the two South African mass timber manufacturers remain insignificant compared to other assessment proxies. This implies that the manufacturer can be selected depending on project location, reducing transportation costs and emissions.

6.1 RESEARCH VALUE AND CONTRIBUTION

This study builds upon existing international research on shell structures, outlining various considerations regarding their structural and fabrication processes. The value lies in enriching these internal considerations with the contextual influences that define the conditions of building segmented shells in South Africa across formation processes. In essence, the value lies in the regional specificity of this research. Moreover, the research framework (figure 41) can be adapted for other building systems that fall within the field of Biomimetics and integrative computational design. Simply put, the framework's internal considerations can be replaced by that of a different building system.

6.2 RECOMMENDATIONS FOR FUTURE RESEARCH

The research framework aims to create as holistic of a view as possible to understand the oppositions and symmetries between internal and external informants (figure 52). As this framework remains a heuristic representation of a much more integrative process, future research can be directed towards optimisation, automation and detailing within the three *factors of formation*. Each realm will be discussed accordingly.

6.2.1 Material

Currently, the assumption is that the shell is made of a uniform material thickness across its entire surface. This implies two things. Firstly, future research can use the segment edge length range of approximately 800mm – 1000mm to distil the relationship between segment depth and structural span. This leads to the second recommendation, which is to understand how local stresses within parts of the shell can inform thickness variation across the structure. The question then becomes how thickness uniformity can be adapted to reduce material usage, creating a relationship between material placement and local stresses.

6.2.2 Manufacturing

The low graduate output of technologically skilled people who can oversee the construction of a segmented shell necessitates automating the segment management process. Research can be directed towards distilling a part tagging and part management methodology.

6.2.3 Assembly

The framework outlines the importance of including hand-based labourers through appropriate joinery types. Future research should consider regionally relevant joinery techniques to avoid importing patented and typically expensive joinery products for assembly purposes. Moreover, research can be directed to distil an appropriate assembly sequence methodology.

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