Athens Journal of Technology & Engineering

Quarterly Academic Periodical, Volume 12, Issue 1
Published by the Athens Institute
URL: https://www.athensjournals.gr/ajte Email: journals@atiner.gr
e-ISSN: 2241-8237 DOI: 10.30958/ajte

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Athens Journal of Technology & Engineering
ISSN NUMBER: 2241-8237 - DOI: 10.30958/ajte
Volume 12, Issue 1, March 2025
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Athens Journal of Technology & Engineering

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The current issue is the first of the twelfth volume of the *Athens Journal of Technology & Engineering (AJTE)*, published by the Engineering & Architecture Division of Athens Institute.

Gregory T. Papanikos
President
Athens Institute

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- Submission of Paper: **26 May 2024**

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The U.S.-China Innovation Gap: The Chinese Advantage of Backwardness[1]

By Gregory T. Papanikos[±]

Latecomers in the economic development process can leverage existing innovations and technologies available globally. This paper examines China's "advantage of backwardness" using data on innovation provided by the Global Innovation Index (GII), published by the World Intellectual Property Organization (WIPO). I develop a simple theoretical framework to explain the advantage of backwardness and apply this to analyse China's innovation gap with the United States. The analysis assumes that the United States represents the leading country in innovations. This assumption enables a comparison between the two large economies and tests a hypothesis with not only economic but also purported political and military implications. According to the theory of backwardness, China's innovation level is converging with that of the United States. This raises the question: can China's innovation level eventually surpass that of the United States? In other words, if China is developing by capitalizing on its technological backwardness relative to the United States, can it, at some point, become the global leader in innovations? This paper explores this question by analysing 18 observations spanning the period from 2007 to 2024, offering a speculative perspective on whether China can surpass the United States in innovation leadership.

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Keywords: *Advantage of Backwardness, GII index, WIPO, US, China, Innovation, Technology, Leadership, Development*

Introduction

Countries and societies vary significantly across time and space. However, what matters most for the economic well-being of their citizens is the ability to develop innovative solutions to their most pressing challenge: scarcity. Hesiod, writing in the 8th century BCE, was the first to observe that scarcity compels people to work hard to meet their basic needs. Without scarcity, he noted, it would be possible to produce in a single day everything required for an entire year.[2]

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[1]An earlier draft of this paper was presented at the 18th Annual Conference on Global Studies, held on December 18–19, 2024, in Athens, Greece. The author is grateful for the insightful comments provided by conference participants and two anonymous reviewers of this journal. Any remaining errors are the sole responsibility of the author.

[2]As I have argued in Papanikos (2023, 2022a, 2022b, 2022c), Hesiod can be considered the first economist, and his book *Works and Days* the first economics textbook. In Hesiod's work, economic development is described as a technological process characterized by the use of metals: gold, silver, bronze, and iron. He also narrates the beautiful story of Prometheus. He also provides an excellent

What Hesiod believed to be impossible could become reality if an unbounded Prometheus were to steal the gods' well-kept secrets—secrets that would enable humans to apply new knowledge to their daily lives, allowing them to produce more goods with less effort and fewer resources. When a society unleashes its Prometheus, new ideas drive discoveries and inventions, some of which may prove invaluable when applied to various production processes.

At a certain point in time, the accumulation of discoveries and innovations constitutes the stock of innovations, which may vary from country to country. The portion of these innovations applied to production processes to enhance people's welfare defines technology—that is, useful innovations. In this context, we use the terms *innovations* and *technology* interchangeably.[3]

Some countries are leaders in discoveries and innovations, while others lag behind. This paper raises the question of whether countries that lag behind can take advantage of the innovations produced by leading countries. In today's world, innovations resemble pure public goods: it is very difficult to exclude someone from using them (the non-excludability principle), and one country's use of an innovation does not prevent another from using it as well (the non-rivalry principle). If this is the case, the stock of innovations in a relatively technologically backward country can increase if it is able to copy the innovations developed in other countries and apply them to its own economy and society at large. After all, there is no point in 'reinventing the wheel' or 'rediscovering the Americas.' These things have already been done, and all of humanity—both current and future—can benefit from them.

We apply the concept of innovation gaps to the US-China case. Given that the US has historically maintained a higher level of innovation compared to China, how has China taken advantage of its technological backwardness by absorbing innovations created in the US? To explore this, I use the Global Innovation Index (GII), published by the World Intellectual Property Organization (WIPO) since 2007, to investigate the extent of innovation absorption by China. According to WIPO (2024, p. 14), "The goal of the Global Innovation Index (GII) is to be a holistic and flexible measure of the innovation happening all around the world today." It is this concept of *holistic performance* that is the focus of this paper.

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description of how to construct a plow, a remarkable innovation that greatly enhanced the productivity of labor.

[3]It is interesting to note that in Plato's *Protagoras*, *techne* was considered a practical profession, learned through hands-on experience under the guidance of a master. Generalizing this concept, we can say that technologically backward countries can acquire *technes* by being trained by more technologically advanced countries. Applied to China, this idea is exemplified by the many Chinese students who have pursued advanced studies and conducted research at leading U.S. educational institutions. On the other hand, the production of new ideas is more complex and seemingly cannot be taught. Socrates, for instance, explains that his ideas stem from an inner *daimon*. In ancient Greek, the word *daimon* (δαίμων) did not carry the negative connotations it does today. One of its meanings was "spirit," and it was associated with the gods. Thus, Socrates' ideas could be seen as a form of divine revelation. It also implied good fortune. Interestingly, the process of discovery and innovation often requires not only a good spirit (idea) but also a stroke of luck. Many discoverers and innovators have acknowledged that, in addition to having a great idea, they also benefited from a stroke of luck. Those who are religious might refer to this luck as a miracle.

While China has the capacity to discover, innovate, and develop new technologies, this paper focuses on its overall performance in innovation. A simple theoretical model is employed to empirically test this hypothesis, as discussed in the next section. Subsequently, I provide a more descriptive and narrative analysis of the data to evaluate whether China could ever produce as many top innovations as the United States. This section is more speculative than the previous one. The final section offers concluding remarks.

A Simple Theoretical Model Applied to China

Gerschenkron (1962) introduced the term "Advantage of Backwardness," referring to the idea that countries lagging in creating innovations and transforming them into new technologies can benefit from the advancements of leading nations, thereby accelerating their economic growth. He specifically had in mind his native Russia and other less-developed European countries of the 19th and 20th centuries, such as Italy and Bulgaria. Although he does not mention China in his book, his framework is highly applicable to China's remarkable economic growth in the early 21st century.

A Simple Theoretical Model[4]

This section develops a simple theoretical model to analyse the level of innovation of a country (i) in period (t) for a latecomer nation, denoted as (A_{it}). Backwardness, represented as B_{it}, is measured as the gap between the world's available innovations in period t, A_t, and the country's level of innovation denoted by A_{it}:

$$B_{it} = A_t - A_{it} > 0 \quad (1)$$

Catching up implies that B_{it} tends toward zero as (t) increases, meaning the country progressively closes the innovation gap. This can be done in a linear or nonlinear way. In each time period, it is assumed that the country (i) can absorb a certain portion of the world's available stock of technology (A_t). This absorption rate, denoted as (α) is assumed to depend on (a) the country's ability to absorb and (b) the foreign country's willingness to allow it. For simplicity, it is assumed that absorption depends on time. Thus, at time (t), the country adds the following amount to its stock of innovation, derived from the existing global stock of innovation:

$$A_{it}^{f} = \alpha(t) \cdot B_{it} \quad 0 \leq \alpha(t) \leq 1 \quad (2)$$

Where A_{it}^{f} is the foreign country's innovations stock which is absorbed by country (i). Notice that if the innovation gap is zero, then A_{it}^{f} is also zero. Here

[4]In Papanikos (1993), I present an economic model of aggregate supply and aggregate demand, explicitly modelling technical progress as both an endogenous and exogenous process.

(α) is treated as a function of time and is greater or equal to zero. If (α) is zero, then country (i) is either entirely unable to absorb any foreign innovation, or the foreign country is both capable and willing to prevent other countries from copying its innovation. The country (i) is also capable of producing its own innovation, contributing to its total stock of innovation by an amount A_{it}^{d}. This amount is assumed to be exogenously determined primarily by government policies. Here it is assumed that it depends on time given an initial level of innovations and grows at a rate *g*:

$$A_{it}^{d} = A_{i0}(1+g)^{t} \tag{3}$$

A_{i0} represents the initial stock of total innovation in country (i). The total available stock of innovation in country (i) at period (t) is the sum of foreign-absorbed innovation and domestically produced innovation at period (t):

$$A_{it} = A_{it}^{f} + A_{it}^{d} \tag{4}$$

By substitution we obtain:

$$A_{it} = \alpha(t)\cdot B_{it} + A_{i0}\cdot(1+g)^{t} = \alpha(t)\cdot(A_{t} - A_{it}) + A_{i0}\cdot(1+g)^{t} \tag{5}$$

Equation 5 indicates that, in period (t), country i's level of innovation is determined by its ability to absorb internationally available innovation (α). As mentioned, this absorption rate is assumed to depend on time, forming a testable hypothesis about whether the country's ability to absorb international innovations increases or decreases over time.

The total innovation level also depends on the country's ability to produce its own innovations. These domestically produced innovations are assumed to grow at a constant rate (*g*), conditioned by the initial stock of innovations which is constant. Notably, it is highly likely that a country's ability to produce its own innovations increases with the stock of foreign-acquired innovations. Thus, this ability can be considered a function of the given stock of foreign innovations.

In the literature, domestically produced innovations are often modelled as a function of population growth, an argument made earlier by Kremer (1993). A larger population increases the likelihood of producing innovators, which in turn enhances the country's capacity to generate its own innovations, absorb internationally available innovations, or both. We also test this hypothesis.

Developing an Empirical Model to Estimate China's Innovations

The simple theoretical framework outlined above can help determine whether a country can leverage its backwardness. A backward country is defined as one where $A_{it} < A_{t}$. Given that this index is a composite index, it is quite possible that in some areas, innovations may exceed those in the leading country.[5] This issue,

[5]The GII index comprises 78 indicators. According to the 2024 report (WIPA, 2024, p. 22), China ranks first in 8 of these indicators, the US in 9, and Singapore in 14. However, what ultimately matters is the overall index. In 2024, in the overall index the US ranked 3rd, while China ranked 11th. Notably, China's position in the institution's indicator is 44th, and it ranks 22nd in the human capital and

while very important, is not examined in this paper, as it falls within the scope of the literature on industrial clusters.

In its general form, the A_{it} function to be estimated is given by:

$$A_{it} = \Phi_i(A_{i0}, A_t, g, n, t) \quad (6)$$

The empirical specification of the above general function takes the following form:

$$A_{it} = \beta_o + \beta_1 \cdot A_t + \beta_2 \cdot A_t^2 + \beta_3 \cdot t + \beta_4 \cdot t^2 + \beta_4 \cdot n_{it} \quad (7)$$

Where:

β's: constant/parameters to be estimated
A_{it}: the innovation level of country (i) at period (t)
A_t: the innovation level of the leading country in the world at period (t)
t: time
n_{it}: population growth in country (i) at period (t)

The above equation is estimated using data from the GII for the period 2007 to 2024. We approximate the world's available level of innovation with the U.S. level of innovation, while A_i represents the total level of China's innovations.

Table 1 presents two specifications of the model. We report only the specifications for which the parameter estimates were statistically significant, and for which there is a theoretical background justifying the variables used and the functional form (i.e., quadratic). Additionally, we present first the equation with the highest coefficient of determination and the smallest Akaike Information Criterion, even though the differences are small.

Before discussing the findings, it is important to note a potential limitation due to the low degrees of freedom. The dataset includes only 18 observations. While this is sufficient to estimate the parameters, the small sample size should be taken into consideration when interpreting the results. One key consequence is the potential underestimation of the statistical significance of the parameters, leading to a false assumption that they are insignificant. However, this does not appear to be an issue here, as all our parameters are statistically significant. To enhance the robustness of the estimation, heteroskedasticity and autocorrelation-consistent (HAC) standard errors were used to obtain more reliable parameter estimates. The reported t-statistics are based on HAC standard errors.

Another concern arising from the small sample size is the stationarity properties of the variables. Testing for stationarity and cointegration becomes more challenging with a small sample. I used the Augmented Dickey-Fuller (ADF) test to assess stationarity. The results indicate that China's innovation variable

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research indicator. This may explain why, at this stage of its development, China is better positioned to replicate other countries' innovations, as illustrated in Figure 1 below.

is stationary. This is not the case for the U.S. innovation level, which may be due to a structural break that occurred in 2010 following the Great Recession of 2007-2009. In that year, the index dropped significantly to 45 from an average of 58 but quickly returned to its long-term value of around 60. This was further tested using an ADF test with a break, which failed to reject the hypothesis of stationarity.

Table 1. *Regression Results*

Variables	**(1)**	**(2)**
Constant	-199.50** (2.34)	-226.88** (2.54)
US Innovation Level (A_t)	8.33* (3.20)	9.17** (2.69)
US Innovation Level Squared (A_t^2)	-0.07** (2.42)	-0.08** (2.55)
Time (t)	2.69* (10.57)	2.09* (9.89)
Time Squared (t^2)	-0.07* (6.51)	---
China's Population Growth (n_{it})	---	1030* (6.80)
R^2	0.9758	0.9739
R^2-Adjusted	0.9683	0.9659
F	131.00*	121.45*
Akaike	3.841	3.915
DW	1.98	2.19
Observations	18	18

* Significant at 1% level; **Significant at 5%.
Note: In parentheses, absolute values of t-statistics based on HAC standard errors & covariance (Bartlett kernel, Newey-West fixed bandwidth of 3).

Additionally, a Johansen cointegration test was applied. The hypothesis that the two variables have one cointegration vector could not be rejected when a quadratic deterministic trend was included. The growth rate of China's population growth rate was found to be stationary after differencing twice, integrated of order two I(2).

The Durbin-Watson statistic suggests no issues with autocorrelation. The null hypothesis that the independent variables as a group have no effect on China's innovation level is rejected by the F-statistic for both empirical specifications reported in Table 1. Finally, the coefficient of determination indicates that 97% of the variation in the dependent variable can be explained by the predictors.

I will use only the first specification to explain the effect of the independent variables. The most important variable is the effect of the US's innovation level on China's innovation level. This effect is non-linear and is best approximated by a quadratic specification. China's innovation level increases at a decreasing rate as the US innovation level rises. Evaluating at the mean values of China's and the US's innovation levels, the marginal effect is given by:

Marginal Effect = $\partial Ai/\partial A = \beta_1 + 2\beta_2\bar{A}$ = 8.33 – 0.14·58.58 = 0.1289 (8)

Where $\bar{A}$ is the mean value of US's innovation level. China's elasticity of innovation with respect to U.S. innovation is estimated as follows:

Elasticity = $(\beta_1 + 2\beta_2 \cdot \bar{A})(\bar{A}/\bar{A}\iota)$ = 0.1289·(58.58/47.35) = 0.1595 (9)

If the U.S. innovation index increases by one unit, China's innovation index will increase by 0.1289 units. The elasticity of China's innovation with respect to the U.S. innovation level is 0.1595. A 10% increase in the U.S. innovation index—from an average value of 58.58 to 64.64—will result in a 1.6% increase in China's innovation index. This represents an estimate of China's absorption rate. It is likely that this effect unfolds over a period of years.

The effect of the trend variable is quadratic: China's innovation increases over time, but at a decreasing rate. The trend variable can be interpreted as the impact of domestically produced innovations on China's overall innovation level. As before, we can estimate both the marginal effect of time and its elasticity. The marginal effect is 1.36, and the elasticity is 0.273. Thus, each year, China's innovation index increases by 1.36 units.

The empirical findings reveal that China's innovations depend on U.S. innovations in a nonlinear fashion. Absorption is positive and increases with U.S. innovations, but at a decreasing rate. Ultimately, China cannot absorb all U.S. innovations in one year. Similar results are observed for the trend variable.

Population growth exhibits the expected positive sign, but its interpretation is problematic because the hypothesis of stationarity was rejected. A positive association was also found by Kremer (1993), though stationarity and cointegration of the two variables were not tested. There may be a third factor causing the two variables to move together.

Technological change implies an increase in per capita income, which, at early stages of development for populations living at or below subsistence levels, translates into higher population growth. The demographic transition suggests a negative effect on the size and growth of the population over time. Countries in the post-industrial modern world are able to achieve high levels of innovation, resulting in higher per capita incomes and wealth. As suggested by the demographic transition, this leads to a reduction in population growth. However, the mechanism driving this effect may differ and requires more careful analysis and interpretation, which lies beyond the scope of this research.

The next section delves further into this issue, focusing primarily on the political question of whether China will overtake the U.S. in innovation. For this to happen, China must generate its own innovations and leverage its position of relative backwardness. This argument is explored in the following section.

Can China Overtake the US?

This section adopts a different approach from the previous one. It is more journalistic and political. In both the popular and less mainstream press, there is significant concern—often lacking evidence—about China potentially overtaking the U.S. in innovation. Drawing inspiration from Socrates, who saw himself not as Athenian or Greek but as a citizen of the world, I question: what would truly be wrong if China were to surpass the U.S. in innovation at some point in the future?

Some argue the issue lies in military superiority. The fear is that we would all be subjugated to the Communist Party of China. According to this narrative, they are the "bad guys," and we, in the West and pro-U.S., are the "good guys." It is claimed that Western military strength will prevent such an outcome. Yet, U.S. superiority in innovation has not necessarily translated into a better or more democratic world. When the U.S. has attempted to "liberate" the world from its so-called bad guys, it has often failed miserably. Why, then, would China succeed in imposing its political system globally, even if it were to achieve overall innovation superiority?

I believe the underlying animosity stems from vested interests that benefit from such antagonisms. This is partly because discoveries and innovations and their successful transformation into technologies are primarily driven by government policies. In many countries—especially authoritarian regimes—people are not free to discover and innovate unless approved by the state. Historically, many pioneering innovators migrated to freer environments, such as the U.S., to fully develop their talents. However, the most critical government policy in the democratic world is financing innovation. I do not address government policy issues in promoting innovation here. Katz (2025) provides an excellent overview of government policies aimed at fostering innovation in a global context, emphasizing the role of technological supremacy in driving innovation.

In the U.S., researchers and institutions often struggle to secure funding for Research & Development (R&D). Being an academic does not automatically ensure ethical behaviour in any country, US and China included.[6] Thus, many academics, researchers and institutes capitalize on the perceived 'threat' of China to secure funding from U.S. government agencies and other resources.

I will not delve further into these issues here, but they are crucial for understanding the widespread concern about China—similar to past concerns about the Soviet Union and, to some extent, Japan or even the 'Asian Tigers' of the 1960s to 1990s (Hong Kong, Singapore, South Korea, and Taiwan). In the 21st century, the tigers have become domesticated pussy cats.

Instead, this section focuses on two specific issues. First, I compare the innovation models of the U.S. and China, arguing that as long as China's model relies on the advantage of backwardness, it cannot surpass the U.S. This possibility is excluded by definition: one cannot simultaneously be backward and an overall leader. Second, I analyse data often presented by journalists,

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[6]For a discussion on academic virtue and integrity, see Papanikos (2025a).

politicians, and researchers with vested interests to demonstrate how the (deliberate) misuse of data can support false claims—such as the argument that China's discoveries and innovations will soon surpass those of the U.S.

US and China's Innovation Models Compared

The United States maintains a technological advantage over China primarily due to its factor endowments,[7] which enable it to excel in new ideas, discoveries and innovations. Once something is discovered or invented, new technologies are developed. If these technologies offer an economic advantage over existing ones, they are adopted to produce new or improved goods and services. As production progresses, iterative improvements often lead to further advancements and new (improved) products.

The car and the airplane are excellent examples. The car, for instance, was invented only once but has undergone countless improvements. By the early 21st century, it had become a completely different product from its original form. China is now a leader—or is on the verge of becoming one—in producing cars that incorporate the most advanced technology to date. Part of this technology was created in China. This serves as a prime example of how an invention can be continually improved through technological advancements by a country other than the one that originally invented it. It is also an excellent example of how the discovery of a new tool can evolve into technology that is improved exponentially and used extensively. If one compares this process with the invention of the fork, which was initially invented by the Egyptians, Greeks, and Romans, but was first used for eating by the Byzantines in the 10th century, its use expanded to Europe in the 17th century, where it was technologically improved in both design and practicality (with four tines) in the 19^{th} century.

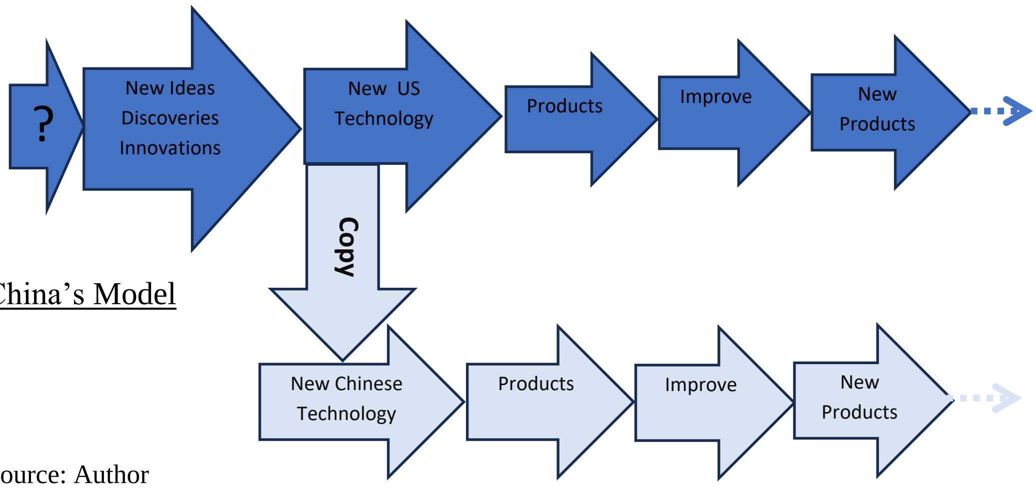
Figure 1 compares the innovation models of the U.S. and China. The process described above characterizes a leading nation in discoveries and innovations, such as the U.S. In contrast, China is portrayed as a latecomer that capitalizes on its position of innovation backwardness. China often imitates the discoveries and innovations of the U.S. However, this does not imply that China lacks the capacity for innovation or discovery. On the contrary, China is capable of producing a wide range of goods and services. Nonetheless, its current factor endowments—particularly in terms of human and institutional capital—restrict its ability to generate more innovations and technologies than the United States. We do not illustrate this dynamic in Figure 1 to avoid complicating the visual representation. However, the theoretical and empirical model presented in the previous section explicitly accounted for these limitations.

[7]The most important factor endowment is human capital, as many economists have pointed out (Papanikos, 1994). It is noteworthy that one of the specific factor endowment comparative advantages of the U.S. is the large migration of the best minds from around the world to the country. This trend has been ongoing throughout the 20th century, resulting in a significant global brain drain. Some of these 'brains' were, and still are, Chinese. While some of these Chinese individuals have returned to China, most have remained in the U.S. However, this important issue is not discussed in this paper.

The U.S. innovation model in Figure 1 begins with a big question mark, reflecting the mystery of how certain nations advanced in ways that produced new ideas, expanded knowledge, and fostered wisdom. For instance, why were the Ancient Athenians the first to achieve such progress, rather than the Ancient Persians, Ancient Chinese, or Ancient Indians? Although these civilizations existed simultaneously, their remarkable achievements had minimal influence on the broader world.

Figure 1. *The Interaction Between the Innovation Models of the U.S. and China*

US's Model



Source: Author

It is noteworthy that in Hesiod's great work, the gift of fire was credited to one man, Prometheus, who stole it from the gods and suffered for his act until another ancient hero, Hercules, freed him from his torment. From what we know, nobody financed Prometheus' endeavor. Prometheus symbolizes talent. Thus, the answer to the question mark is an unbounded Prometheus. Today, individuals form businesses that drive innovation. Governments should craft industrial policies that unbind modern businesses, enabling them to innovate freely.[8]

Why was England the first to lead the innovations that gave rise to the Industrial Revolution? Why was the U.S. the first to pioneer the post-industrial revolution? I believe the primary cause of these advancements is democracy. It is not an accident that, for centuries, democracy had disappeared as a political system. Many great—and not-so-great—empires did not have democracy, including the Byzantine Empire, the Ottoman Empire, and all the European kingdoms from the fall of Rome until the Magna Carta (1215) in England. These years are called the Dark Ages, and rightly so—not because there was no progress, but because they did not embrace the

[8]This critical issue is not addressed here. The GII index includes two of its seven pillars related to market and business in its holistic measurement of innovation. Van der Duin et al. (2016) and Boer & Ihlenburg (2020) explore the topic of business innovation. The former examines the Dutch government's policies to support top innovative industries, while the latter focuses on business collaboration in fostering innovation.

light of democracy. It took many years for the world to discover this light. Democracy began to spread to Europe and the U.S. by the end of the 18th century. Coincidentally, or perhaps because of this, the 19th and 20th centuries saw revolutions in discoveries, innovations, and, most importantly, their applications—what we now call technology. It is no coincidence that electricity was discovered in the 19th century.

It seems that the causality runs from democracy to discoveries, innovations, and technologies. Democracy is required for this to happen. Many countries made discoveries and innovations in the past, going back to the ancient civilizations of Mesopotamia, but it was democracy that enabled these advancements to benefit humanity at large. China, too, made many important discoveries and innovations in the 15th century, but it was the democratic West that transformed them into technology.

The Ancient Athenians are credited with the discovery of democracy, which later evolved into a *techne*—a practical art—in the hands of politicians, effectively transforming it into a form of technology, i.e., the technology of ruling.[9] Over time, the rest of the world adopted this model, creating variations such as parliamentary democracy, presidential democracy, liberal democracy, constitutional democracy, social democracy etc. As it is the case with good brands, for the brand-name democracy there exist today very bad and cheap imitations such as the so-called people’s democracy, illiberal democracy, authoritarian democracy etc.

While I will not delve further into this issue here, I firmly believe that no country can excel in discoveries and innovations if its citizens lack freedom of thought. This is distinct from freedom of speech in general. The issue of democracy and freedom of speech and thought have been discussed extensively in my series of publications; see Papanikos (2016, 2017, 2020, 2022d, 2022e, 2022f). Even in societies that held great respect for freedom of thought and speech, they did not always make the right decision. Socrates was very democratically sentenced to death by a jury of 501 jurors, who were randomly selected from a pool of 5,000 potential jurors on the day of the trial. And what a trial it was! Socrates' *Apology* (defence) during his trial is a masterpiece of what freedom of thought and freedom of ideas are all about. Despite this, he was sentenced to death by a very small margin. Living in a democratic and free society, and despite the offer to escape, Socrates gave another lesson that humanity cherishes: respect for the law is the duty of every citizen in a democratic and free society. Compare Socrates' trial with the next famous trial of a free mind: Galileo Galilei, who was tried in 1633 for his belief in the heliocentric model. Who tried him? The Roman Catholic Inquisition. This is a difference between a democracy and a theocracy or a democracy and a kleptocracy in our times.

Figure 1 provides a descriptive answer to the question, “Can China overtake the U.S.?” The answer is no—unless China adopts characteristics similar to

[9]According to Herodotus, the war between the Greeks and Persia was a conflict between Europe and Asia. Aeschylus's tragedy *The Persians (Perses)* contains a beautiful discussion on the military superiority of Ancient Athens over the Persian Empire. Aeschylus, however, framed it as a war between democracy and authoritarian regimes. It seems, both then and now, that democracy demonstrates superiority over non-democratic regimes.

those of the U.S. While this is a necessary condition, it is not sufficient. At the same time, for China to become a sustained leader in innovation, the U.S. would need to adopt a model characteristic of an authoritarian regime and enter a period of regression. This would constitute the sufficient condition for China's ascendancy.

As it stands, over the long term, the gap between the two countries is expected to narrow, though at a decreasing rate. At some point, China will likely reach a limit in its capacity to absorb internationally produced technologies, as other countries continue to remain one step ahead. This issue is further examined below, with a focus on the use—or rather misuse—of descriptive statistics, a practice frequently employed by the mass media, politicians, and government-funded institutions.

Misusing Descriptive Data

The proposition to be examined here is whether the limited evidence from 18 annual observations can provide insights into the declining trend of the innovation gap between the U.S. and China, eventually reaching a point where further reductions in the gap are no longer possible. These data are reported in Table 2. It is argued that the gap will remain positive as long as the U.S. model and China's model remain unchanged. Not only must China modify its model to encourage more discoveries and innovations within the country, but the U.S.—and, more broadly, the so-called Western world—would need to abandon their successful model of continuous encouragement of discovery and innovation. There is no apparent reason why the U.S. and other leading countries would adopt such a policy.

A small sample size has not stopped the mass media, politicians, researchers, or institutes from drawing sweeping conclusions based on even smaller datasets, as I will demonstrate below. For them, a timeframe as brief as ten years—or even less—often suffices to generalize and validate their concerns about an issue. Similarly, I will use this approach to illustrate how misusing data can lead to absurd conclusions.

Examples of such claims abound in mass media and reports. A notable instance is the 2022 report by Ian Clay and Robert Atkinson. The second author, Robert Atkinson, is a member of the advisory committee for the Global Innovation Index and serves as the president of the Information Technology and Innovation Foundation (ITIF) in the United States. Their report, titled *"Wake Up, America: China Is Overtaking the United States in Innovation Output,"* exemplifies this trend. 'Overtaking' implies that China has not yet surpassed the U.S., but such a title is effective at grabbing attention in the media and I guess funding from tax-payers money.

But why should the rest of the world care if China overtakes the U.S. in innovations? The authors argue that this shift would undermine U.S. security, implying that if China becomes a leader in innovation, it could translate these advances into military supremacy, potentially enabling it to attack and win a war against the U.S. They do not explicitly state this, but it is clearly implied, and such statements are universally understood in this way.

Table 2. *US and China's Innovation Data*

Year (1)	**A** (2)	**A_i** (3)	**$A-A_i$** (4)	**2007-2024** $A_i = -0.8t+19$ (5)	**2007-2011** $A_i = -3.6t+27$ (6)	**2013-2018** $A_i = -1.7t+28$ (7)	**2019-2024** $A_i = -0.005t+7$ (8)
2007	58	32.1	25.9	17.93	23.21	26.01	6.97
2008	52.8	35.9	16.9	17.14	19.62	24.29	6.96
2009	49.25	34.55	14.7	16.35	16.03	22.57	6.96
2010	45.7	33.2	12.5	15.56	12.44	20.85	6.95
2011	56.57	46.43	10.14	14.78	8.84	19.12	6.94
2012	57.7	45.4	12.3	13.99	5.25	17.40	6.94
2013	60.31	44.66	15.65	13.20	1.66	15.68	6.93
2014	60.09	46.57	13.52	12.41	-1.93	13.96	6.93
2015	60.1	47.47	12.63	11.62	-5.52	12.23	6.92
2016	61.4	50.57	10.83	10.84	-9.12	10.51	6.92
2017	61.4	52.54	8.86	10.05	-12.71	8.79	6.91
2018	59.81	53.06	6.75	9.26	-16.30	7.07	6.91
2019	61.73	54.82	6.91	8.47	-19.89	5.35	6.90
2020	60.56	53.28	7.28	7.68	-23.48	3.62	6.90
2021	61.3	54.8	6.5	6.90	-27.08	1.90	6.89
2022	61.8	55.3	6.5	6.11	-30.67	0.18	6.89
2023	63.5	55.3	8.2	5.32	-34.26	-1.54	6.88
2024	62.4	56.3	6.1	4.53	-37.85	-3.27	6.87
			$A_i>A$	2030	2014	2023	3298

Source: Annual publications of the Global Innovation Index from 2007 to 2024, published by WIPO, and the author's calculations. The Global Innovation Index and Report for 2008 was not released due to unprecedented economic shifts in the global economy (INSEAD, 2009, p. 3). In 2010, WIPO's reports referred to the periods 2008–2009 and 2009–2010. I used the first dataset as the 2008 figure and the latter as the 2010 figure, calculating the 2009 value as the average of the two. Of course, the authors correctly report on p. 6 that «This has translated into slower but still significant progress in indicators accounting for the size of each country's economy or population, where China still lags behind the United States».

This, to me, represents a prime example of a ridiculous conclusion. Furthermore, why should the rest of the world care about this hypothetical scenario? And if the authors' premise is correct, why doesn't the U.S. pre-emptively attack China now, while it supposedly holds an innovation-driven military advantage? The U.S. has had military supremacy since World War II but has failed to impose its will in many countries where its military might has been used.[10] Why would a Chinese military supremacy be any better?

[10]Actually, when it comes to choosing between a U.S.-type democracy and a theocracy of any denomination, I will definitely choose and fight for the former. However, this is not the issue. The United States believed it could enforce democracy from the outside, which is a contradiction in terms. People, and only the people of a country, must decide on this; otherwise, it is not democracy. A good example of massive failure was the Arab Spring, which, despite all the support given by the U.S., miserably failed. Why? Because, in Egypt, for example, people very democratically decided not to

Additionally, what evidence do the authors provide? They compare innovation capabilities between 2010 and 2020. While the U.S. still leads, China has narrowed the gap, moving from 58% of U.S. capabilities in 2010 to 75% in 2020. Data from Table 2 tells the same story: China's innovation level in 2010, as a percentage of the U.S. was 73%. By 2020 it rose to 88%. But is this sufficient for China to overtake the U.S.? The answer is no, as I will demonstrate in this section. Nevertheless, the authors misuse the data to predict that *"if this relative growth continues apace, China will surpass the United States by 2035"* (p. 6).

While this prediction may seem plausible, it assumes a linear reduction in the gap between the two countries. However, if a non-linear trend—arguably the more realistic scenario—is applied, China may never overtake the U.S. This is evident in Table 2, where Columns 2 and 3 show the Global Innovation Index scores for the U.S. and China, respectively. Column 4 highlights the innovation gap between the two countries. The final four columns provide forecasts based on linear trends in the data, revealing how substantial differences in outcomes can arise depending on the time periods and assumptions considered, as will be discussed further below.

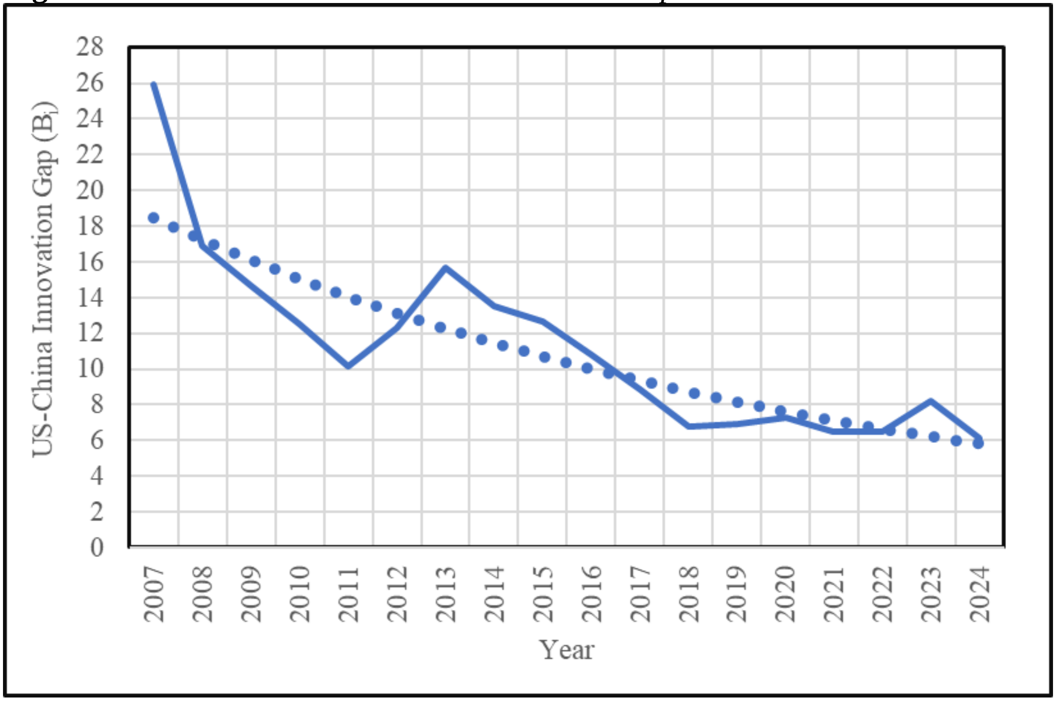
Figure 2 illustrates the gap between the US innovation level and China's innovation level ($A-A_i$) from 2007 to 2024. It is evident that a linear approximation is not appropriate, as demonstrated in the previous section. The innovation gap depends nonlinearly on the US innovation level and follows a quadratic trend. What is noteworthy here is that, over the 18 years for which the index is available, the difference has undergone four distinct phases: three negative phases and even one positive phase (started in 2011 and ended in 2013).

The negative phases are outlined in Table 2, corresponding to the periods 2007–2011, 2013–2018, and 2019–2024. Table 2 also provides parameter estimates for a fitted trend during the three periods where the relationship could be approximated by a linear equation. It is important to note that while 2012 and 2013 were the primary years during which the innovation gap widened, increases were also observed in 2019, 2020, and 2023. However, these increases in the gap were relatively minor.

Linear projections can lead to absurd conclusions. For example, if we assume a linear trend for the entire period (2007–2024), China is predicted to surpass the U.S. by 2030. However, as noted in the previous section, the relationship is not linear but quadratic. I'll come back to that. Using data from the first phase (2007–2011), China would have been projected to overtake the U.S. by 2014. In contrast, using data from the second phase (2013–2018), the projection suggests China would have been ahead of the U.S. by 2023. However, the last six years present a different picture. If the U.S.-China innovation gap continues to close at the rate observed between 2019 and 2024, China would not surpass the U.S. until the year 3298.

have a democracy, but a theocracy. Hamas in Gaza was elected to power once very democratically and then decided to abolish democracy.

Figure 2. *US-China Innovations Backwardness Gap*



At first glance, this may seem like an absurd conclusion. However, considering that China's first known dynasty—the Xia Dynasty of the 2nd millennium BCE, whose existence is still debated—and many others that followed, none of which played a leading global role comparable to that of the Hellenes after Alexander the Great or the Romans thereafter, discussing the 2nd and 3rd millennia CE makes perfect historical sense.

The long-term perspective is also evident in the best-fit line of the innovation gap shown in Figure 2. A log-linear (exponential) function provided the best fit[11], with parameters estimated using a HAC (Heteroskedasticity and Autocorrelation Consistent) estimation. The results are as follows:

$$\text{Log}(B_{it}) = \beta_0 + \beta_1 \cdot t = 2.91 - 0.067983 \cdot t \quad (10)$$

HAC standard errors. R2-Adjusted = 0.7826, Obs.=18
t-statistic (β_0) = 25.62 (0.0000). t-statistic (β_1) = -6.75 (0.0000)

Both estimates were statistically significant, as indicated by the t-statistics and the probabilities shown in parentheses. The trend explains 78.26% of the variation in the innovation gap between the U.S. and China.

[11]The Akaike Information Criterion (minimum value) and the adjusted coefficient of determination (maximum value) were used to select the best fit. However, a glance at the diagram makes it clear that a log-linear specification fits the data better. The evidence from segmenting the sample into linear parts, as presented in Table 2, provides additional support for the conclusion that an exponential fit is the best. The slope becomes nearly flat in the last 6 years of the observations.

The mathematical interpretation of the function suggests that for the gap to approach zero, the value of (t) must approach infinity. To illustrate, let us calculate when China will be one unit below the U.S. innovation level. In this case, where log (B_{it})=0, solving equation (10) for time shows that this will occur in 42.8 years. If the gap is reduced to 0.01 (approximately equal but with the U.S. still slightly ahead), then the number of years required for China to reach the U.S. innovation level is 72 years.

These findings make perfect sense and align with theoretical expectations regarding the "advantage of backwardness." As long as China's innovations rely on lagging behind and copying technologies from other countries, it will never surpass the innovation levels of leading nations.

Why, then, is there so much fuss about China becoming a leading country in discoveries and innovations? Based on the evidence presented above, this outcome seems unlikely. The concern is primarily political. Some politicians, researchers, and institutions in the U.S. have a vested interest in persuading society at large that China poses a potential threat if it becomes a leader in innovation. Successfully creating this perception often translates into increased government funding for R&D initiatives aimed at fostering discovery and innovation.[12]

It would be interesting to examine how these institutions and researchers, who portray China as a threat, are financed and by whom. It is also worth noting that the victims of this propaganda, driven by U.S. vested interests, are people around the world who hope to see the U.S. empire collapse and a new superpower emerge. Any superpower would do, even terrorists and other non-democratic regimes, as long as they are opposed to the U.S. All of this serves the interests of those in the U.S. who benefit from such alleged threats. This issue lies beyond the scope of this paper and should be addressed in future research.

Some Final Thoughts and Conclusions

It is very difficult to predict what will happen a thousand years from now, or even just a few centuries into the future. However, even if such predictions were possible, their usefulness might be limited. This is because knowledge of the future could influence the actions and policies of the current generation, potentially altering the predicted trajectory.

For instance, if someone claimed to see in a "magic sphere" that I would die tomorrow in a car accident, I might decide to stay home all day and avoid driving.[13] In doing so, I would effectively falsify the prophecy by taking action

[12]This is not the first time that the U.S. has panicked when another rival country succeeds in something they consider technologically superior. In the 1960s, it was their space program that was boosted to contest the USSR's achievement of sending people to space. They may fear what others would do to them if they ever discovered something like an atomic bomb. In this case, they judge the affairs of others by their own.

[13]Actually, the correct prophecy would have been: *If and only if you go out, then you will die in a car accident.* Similarly, China will surpass the U.S. if and only if adopts a new innovation model that is

today. Similarly, if scientists were to determine that an asteroid would destroy the planet in 1,000 years, they might first innovate and then develop technologies to change the comet's trajectory. By the way, this has already been tested by the U.S. as part of its OSIRIS-REx program, applied to the asteroid Bennu in 2016. This is called the "gravity tractor," which slightly changed the trajectory of Bennu.

Likewise, if the U.S. perceives China as an 'asteroid' about to hit their world, it can alter either its own innovation trajectory (e.g., by spending more on R&D and/or attracting even more of the best researchers to the U.S.), China's trajectory (e.g., by minimizing China's copying of U.S. discoveries and technologies), or, most likely, both. Many Chinese students have studied in the U.S., gaining firsthand experience in discovery and innovation. By doing so, the U.S. has inadvertently reduced China's costs of overcoming its technological backwardness. Never in history has there been such a wide exchange of ideas on scientific matters. The U.S. can reverse that and prevent China from taking advantage of its backwardness. It can stop admitting Chinese students to U.S. universities and research centres. My feeling is that this would cause more harm to the U.S.'s innovation program than to China's.

This is one of the many benefits of globalization, and it is something that should be preserved. One of the byproducts of such collaborations is worldwide peace—another important issue that is not discussed in this paper. Discoveries and innovations are global public goods, and everyone should benefit from them regardless of political entities or ideologies. Actually, this is what has been happening despite all the obstacles that countries like US may want to impose (Papanikos, 2025b). A recent good example is the rapid development of COVID-19 vaccines, which saved millions of lives worldwide.[14] While the US may be credited with the discovery, the entire world benefited. If this collaborative approach continues, the question of who discovers or innovates becomes irrelevant —at least for those who, like Socrates, prioritize wisdom and the greater good over nationalistic concerns.

As I have shown in Papanikos (2025b), globalization is here to stay because it benefits every citizen of the world—or at least the wealth it generates can be used to compensate those who are negatively affected in the short term. This includes the citizens of the US and China. The evidence is overwhelming: globalization reduces absolute poverty (Papanikos, 2024). Hesiod would have been very happy. While scarcity has not been completely overcome, its effects have been drastically diminished. Prometheus is credited for this, and Prometheus has no nationality.

In today's globalized world, Chinese scientists are able to form multinational teams with colleagues from around the globe to discover and innovate. This can take the form of *ad hoc* teams or more formal structures under the auspices of large private multinational businesses, multinational academic institutes, and other organizations. In a few years, it will likely become very difficult to

superior to that of the U.S. Simply reducing the gap by copying the U.S. and other innovation world leaders is not sufficient.

[14]For more on this issue, see Boutsioli et al. (2022a, 2022b).

identify discoveries and innovations by country. Instead, they will be identified by the individuals involved, which will be best for the world. Who leads becomes completely irrelevant if all citizens of the world, especially those living in absolute poverty, can benefit. The eradication of absolute poverty should be the primary objective of any scientific endeavor, rather than determining who leads in discoveries and innovations.

References

Boer P, Ihlenburg D (2020) How do companies engage in cooperation on product and process innovation in the context of the transformation to an industry 4.0? *Athens Journal of Technology and Engineering* 7(1): 51-72. https://www.athensjournals.gr/technology/ 2020-7-1-4-Boer.pdf

Boutsioli Z, Bigelow V, Gkounta O (2022a) COVID-19: A Selective Short Literature Review. *Athens Journal of Health and Medical Sciences* 9(2): 71–86.

Boutsioli, Z, Bigelow, V, Gkounta O (2022b) *Essays on COVID-19 Research*. Athens: Athens Institute for Education and Research.

Clay I, Atkinson R (2022) *Wake Up, America: China Is Overtaking the United States in Innovation Output*. USA: Information Technology and Innovation Foundation (ITIF).

Gerschenkron, A. (1962). *Economic Backwardness in Historical Perspective: A Book of Essays.* Cambridge: Belknap Press of Harvard University Press.

INSEAD (2009). *Global Innovation Index 2008-2009.* France: INSEAD.

INSEAD (2010). *Global Innovation Index 2009-2010.* France: INSEAD.

Katz Y (2025) The Role of Government in Institutional Enhancement of Innovation and Competition. Athens Journal of Politics & International Affairs (forthcoming) https:// www.athensjournals.gr/politics/2024-5986-AJPIA-Katz-02.pdf

Kremer M (1993) Population Growth and Technological Change: One Million B.C. to 1990. Quarterly Journal of Economics 108 (August): 681-716.

Papanikos GT (1994) Macroeconomic Impacts of Endogenous Technical Progress. *Technological Forecasting and Social Change*, 46(1): 17-28. https://bit.ly/3syXuWs.

Papanikos GT (2016) What can we learn about Globalization from Ancient Athens? The Democracy Effect. *Opening speech at the 10th Annual International Conference on Global Studies: Business, Economic, Political, Social and Cultural Aspects, 19-22 December 2016, Athens, Greece.* https://bit.ly/3z11BM9.

Papanikos GT (2017) Democracy in Ancient Athens and in the Contemporary World. *Opening speech at the 4th Annual International Conference on Humanities & Arts in a Global World 3-6 January 2017, Athens, Greece.* https://bit.ly/3ib4PFk.

Papanikos GT (2020) *Democracy in Ten Lessons* [in Greek: *Η Δημοκρατία σε Δέκα Μαθήματα*]. Athens: Athens Institute for Education and Research (ATINER). https://bit.ly/3IrcZUv.

Papanikos GT (2022a) Hesiod's Theory of Economic History. *Athens Journal of History* 8(2): 147-174. https://bit.ly/3sjLRRx

Papanikos GT (2022b) Hesiod's *Works and Days* as an Economics Textbook. *Athens Journal of Business & Economics* 8(4): 385-416. https://bit.ly/3g68gvZ

Papanikos GT (2022c) Hesiod’s Place in the Economics Literature. *Athens Journal of Business & Economics* 8(3): 277-308. https://bit.ly/3arPP5l

Papanikos GT (2022d) The Five Ancient Criteria of Democracy: The Apotheosis of Equality. *Athens Journal of Humanities & Arts* 9(2): 105-120. https://bit.ly/33EmFNk.

Papanikos GT (2022e) The Bright Future of Democracy is in Education. *Athens Journal of Education* 9(2): 353-364. https://bit.ly/3sJGsoN.

Papanikos GT (2022f) Democracy and Politics: An Introduction to the Special Issue of the Athens Journal of Social Sciences. *Athens Journal of Social Sciences* 9(2): 89-94. https://www.athensjournals.gr/social/2022-9-2-Introduction.pdf.

Papanikos GT (2023) Hesiod on Scarcity. *Athens Journal of Business and Economics* 9(2): 179-206. https://bit.ly/3AtIuzh

Papanikos G.T. (2024) The Future of Globalization. *Athens Journal of Business & Economics* 10(2):97-108. https://bit.ly/4cCsKbv

Papanikos GT (2025a) Ethics and Academic Integrity: Lessons from Plato's Protagoras Athens Journal of Humanities and Arts (forthcoming) https://bit.ly/414C5FJ

Papanikos GT (2025b) The Trump Effect on Globalization: If the First Time was a Farce, Would the Second be a Tragedy? *Athens Journal of Business & Economics* 11(2): 1-23. https://shorturl.at/4dzM6

Van der Duin P, Marchau V, Van der Goes L, Scheerder J, Hoogerwerf R, Wilde S (2016) Challenging the future. implications of the horizon scan 2050 for the Dutch top-industry innovation policy. *Athens Journal of Technology and Engineering* 3(1): 7-27. https://www.athensjournals.gr/technology/2016-3-1-1-Duin.pdf

World Intellectual Property Organization (WIPO) (2024). *Global Innovation Index 2024: Unlocking the Promise of Social Entrepreneurship.* Geneva, Switzerland: World Intellectual Property Organization.

Athens Journal of Technology and Engineering - Volume 12, Issue 1,
March 2025 – Pages 29-40

FazBoard: An AI-Educational Hybrid Intelligent Teaching & Learning System

By Fawzi BenMessaoud, Mohamed Habib Agrebi± & Eliza Ash°*

FazBoard, an avant-garde educational platform, seamlessly integrates artificial intelligence with contemporary educational methodologies to foster a dynamic, adaptive, and collaborative learning ecosystem. The platform's linchpin comprises two components: an agile digital canvas that simulates interactive teaching and learning spaces, and an AI Assistant, incarnated as a digital humanoid, available round-the-clock for responsive academic support. The digital canvas is designed to cultivate an immersive and versatile environment, emulating the interactions of traditional classrooms without the constraints of time or location. The AI Assistant excels in providing instantaneous responses to queries, aggregating valuable learning analytics, and streamlining administrative tasks - all of which contribute to curriculum refinement and enhanced pedagogical efficacy. Furthermore, FazBoard is aimed at bolstering student engagement by creating an inclusive learning milieu, through adaptive learning strategies that cater to the diverse educational needs of its users. This paper delves into the architecture, functionalities, and far-reaching applications of FazBoard, heralding it as a quintessential model of integrating AI into education, thereby shaping the trajectory of 21st-century educational practices.

Keywords: *AI assistant, digital canvas, digital transformation, natural language processing, machine learning, instructional design, learning equity, connectedness*

Introduction

With open Ai and so many bot platforms readily available, just about anyone can create a bot. However, to create a good one in education is all about the Bot Framework and the design with infused and aligned Functional Instructional Design/ Technical Instructional Design (FID/TID) to Content Instructional Design/Pedagogical Instructional Design (CID/PID) as shown in Figure 1. This makes good use of the transfer of learning to the bot since they are not born with the same inherently learning brain as humans. In this case any education bot is only as good as its Framework if built based on the alignment between the FID, TID, CID, and PID. This alignment and the human-AI hybrid system integration in an educational context for example, provides a great tool to adjust the content/curriculum in terms of substance, difficulty, or clarity levels (CID) or to the method and style of the delivery (PID), and that is the pedagogical strategy of ensuring the learning is taking place or in other words helping students assimilate the knowledge.

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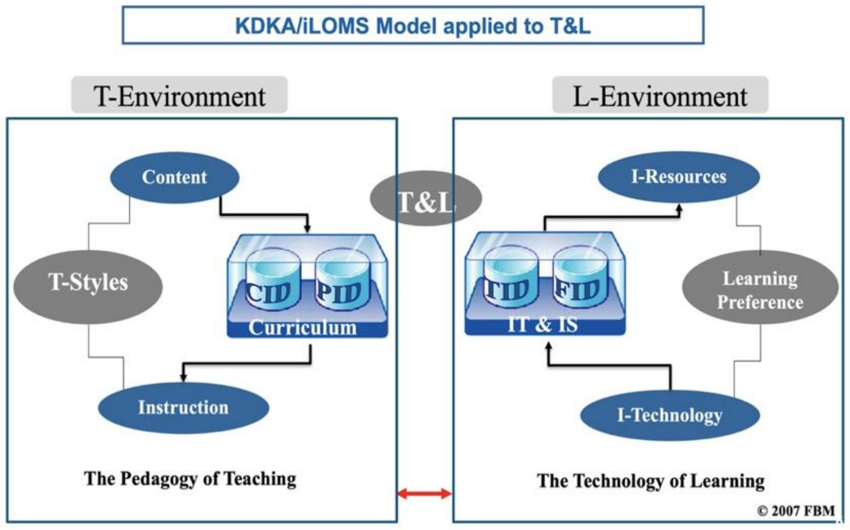
Figure 1. *KDKA/iLOMS Model Applied to T&L*



The advent of technology has dramatically transformed the educational landscape. Contemporary educational systems demand integration with advanced technologies to ensure responsiveness to the evolving needs of students and educators. Among the myriad of technological advancements, Artificial Intelligence (AI) emerges as a crucial instrument for reforming education, and FazBoard stands at the forefront of this evolution.

FazBoard, a pioneering educational platform, amalgamates an Infinite Digital Canvas with an Integrated AI Assistant to foster an adaptive and engaging learning ecosystem. The canvas serves as a dynamic space for educators and students to interact and collaborate, enriched with tools for content delivery and brainstorming. Meanwhile, the AI Assistant harnesses the power of Natural Language Processing (NLP) and Machine Learning (ML) algorithms to understand, process, and respond to human language, automate administrative tasks, and collect data for performance analytics.

This paper delves into the architecture and functionalities of FazBoard, examines its implementation through pilot studies, and evaluates its impact on the educational experience. Furthermore, this paper discusses the potential of AI integration in education, with FazBoard as an exemplary model to achieve the following:

1. Provide all students with 24/7 on-demand instant responses, especially to questions that are frequently asked by most students (like an FAQ).
2. Act as a first line of teaching/learning assistant to provide the on-demand 24/7 connection to the growing number of students taking online classes.
3. Automate the collection and analytics of frequently asked questions by students.
4. Capture most asked questions by students automatically where we can query and organize all questions to make general or class wide announcements with answers/directions/clarifications or adjust my CID or PID. In other words, to help adjust the content/curriculum in terms of substance, difficulty,

or clarity levels (CID) or to the method and style of the delivery and that is the pedagogical strategy of getting the learning to take place or basically helping students assimilate the knowledge.

5. Reduce response time and address belated responses to students, especially with large classes.
6. Integrate with all our teaching material in the class or other supplemental learning materials from other sources outside the CLMS.
7. Provide a fun and engaging personalized messaging experience for our students who as growing digital beings would rather text or chat with a conversational bot than pick up the phone to call, e-mail, or schedule office hour meetings.
8. Students are automatically transferred to live chat with the faculty when they are available if our FazBot cannot give them an answer or at any time they wish to message the faculty instead.
9. Students do not have to have access to any Ai or Bot platform to use our FazBot and can just use any device.

Rationale and Literature Review

The evolving educational landscape, influenced by rapid technological advancements and global events like the COVID-19 pandemic, has emphasized the necessity of integrating Artificial Intelligence (AI) into educational systems. This integration offers transformative possibilities for advancing teaching methodologies, fostering innovative research, and leveraging technological tools. FazBoard represents a hybrid teaching and learning platform designed to bridge the gap between traditional and online education by facilitating seamless and meaningful interactions between students and educators. The disruption caused by the COVID-19 pandemic has highlighted the inadequacies of conventional educational systems and the urgent need for platforms like FazBoard that can ensure educational continuity and excellence in a rapidly changing world.

AI technologies, particularly chatbots, have become integral in modern education by delivering personalized learning experiences and real-time feedback, enhancing the overall teaching and learning process (Bengtsson & Wu 2023). Despite these benefits, existing educational chatbots face limitations, including the lack of flexibility compared to human-to-human interactions (Litman 2016). Addressing these challenges requires leveraging advanced Natural Language Processing (NLP) techniques and machine learning algorithms to facilitate more human-like responses and deeper engagement (Ogawa & Nakamura 2023). This is critical for designing chatbots that create immersive and dynamic educational experiences.

A significant limitation in current educational chatbots is their inability to assess students' emotional states accurately. Research underscores the importance of recognizing and responding to students' affective states, as emotions play a crucial role in the learning process (Abrahams & Regan 2023). An ideal chatbot should identify signs of frustration or confusion and adapt its responses to provide encouragement or clarification. For example, advances in sentiment analysis and affective computing have shown promise in improving the chatbot's capability to engage empathetically with students (Forbes-Riley & Litman 2012).

Another area of improvement is the capacity of chatbots to provide sophisticated feedback on student writing. Traditional systems are limited to surface-level assessments, such as grammar and spelling checks, and fail to address deeper aspects like coherence and organization (Rahimi et al. 2015). Recent studies have explored the use of machine learning models to analyze student essays more holistically, identifying thesis and conclusion statements and offering constructive feedback to improve writing quality (Falakmasir et al. 2014).

Additionally, the integration of learning analytics has emerged as a pivotal tool for enhancing educational outcomes (Ahmad & Chang 2022). By analyzing vast amounts of data generated during the learning process, these tools offer valuable insights into student behavior and performance. When integrated with educational chatbots, learning analytics can enable more personalized and adaptive learning experiences tailored to individual student needs (Wambui & Kirui 2022). For instance, AI systems can use real-time analytics to identify learning gaps and provide targeted interventions, improving both engagement and retention.

The Imperative for AI Integration in Education

The COVID-19 pandemic underscored the need for resilient and adaptive online educational systems, revealing the limitations of traditional tools like video conferencing in fostering engagement and collaboration (Daniel 2020). Platforms such as FazBoard address these gaps by leveraging AI-driven features to bridge the divide between the convenience of digital platforms and the interactive essence of traditional classrooms. FazBoard's integration of tools like Natural Language Processing (NLP) and real-time analytics fosters active participation, personalized learning, and on-demand support, making it a transformative solution for addressing the challenges of both traditional and online educational systems (Abrahams & Regan 2023, Ogawa & Nakamura 2023).

However, the success of AI in education requires addressing critical ethical and societal considerations, including privacy and data security concerns, which are especially pressing when dealing with sensitive student data (Ferreira & Hong 2024). Equitably designed systems like FazBoard advocate for fairness, transparency, and inclusivity to ensure that AI-driven education benefits all learners, particularly marginalized groups (Bengtsson & Wu 2023). By tailoring educational experiences to diverse learning needs, FazBoard not only enhances learning outcomes but also promotes inclusivity, offering a student-centered, responsive model that exemplifies ethical AI innovation in education.

Improving Student-Teacher Interaction

Meaningful interaction between students and educators is vital for effective education, with research highlighting the superior outcomes achieved through personalized human tutoring. Diane Litman (2016) emphasized the importance of natural language dialogues in fostering deeper understanding and engagement. FazBoard addresses this need by integrating an AI-powered teaching assistant (TA) capable of engaging in real-time, natural language dialogues. Using advanced Natural Language Processing (NLP), the system personalizes responses to students, creating an intuitive and conversational learning environment that bridges the gap between traditional human interaction and digital education (Ogawa & Nakamura 2023).

FazBoard’s AI assistant also incorporates adaptive learning capabilities, dynamically evolving to meet individual student needs and learning preferences. By automating routine tasks, it allows educators to focus on complex instructional activities while maintaining high-quality engagement. Recent advancements in conversational AI technologies further enhance this dual approach, combining the strengths of human-centric teaching with the scalability and flexibility of AI. This ensures personalized, immediate, and meaningful academic support for every student, redefining the future of student-teacher interaction (Abrahams & Regan, 2023, Bengtsson & Wu 2023).

Streamlining Knowledge Management

Effective knowledge management is a cornerstone of educational success, facilitating the seamless organization, retrieval, and application of information to enhance learning outcomes. Toshio Okamoto and Mizue Kayama emphasized that knowledge management involves a systematic process of finding, selecting, organizing, and presenting information to optimize learners' comprehension and achievement of educational objectives (Okamoto & Kayama 2015). In alignment with these principles, FazBoard serves as an integrated platform that streamlines knowledge management by providing educators and students with tools to effortlessly share, organize, and access critical information. Building on recent advancements, FazBoard incorporates AI-driven features to further enhance the efficiency of knowledge management systems. By leveraging learning analytics and adaptive learning technologies, FazBoard personalizes the organization of educational content, aligning it with individual learning paths and preferences (Abrahams & Regan 2023). This not only improves information accessibility but also enables real-time feedback and dynamic adjustments to course materials based on student performance and engagement data (Ahmad & Chang 2022).

Transformative Potential of AI in Higher Education

Artificial Intelligence (AI) is reshaping higher education, offering transformative opportunities to integrate innovative technologies into the core design of institutions. Sedigheh Shakib Kotamjani emphasizes that AI’s transformative potential lies not merely in adopting new technologies but in fundamentally reimagining teaching approaches to equip students for a competitive and rapidly evolving global landscape (Kotamjani 2020). FazBoard exemplifies this shift by placing students at the heart of the learning process through its AI-driven facilitation tools. By fostering engagement and active participation, FazBoard creates an adaptive environment where students collaborate, explore, and grow. Moreover, AI enhances instructional methodologies by analyzing student performance data, providing actionable insights to address individual learning needs, and enabling automated grading systems that deliver constructive and timely feedback (Abrahams & Regan 2023).

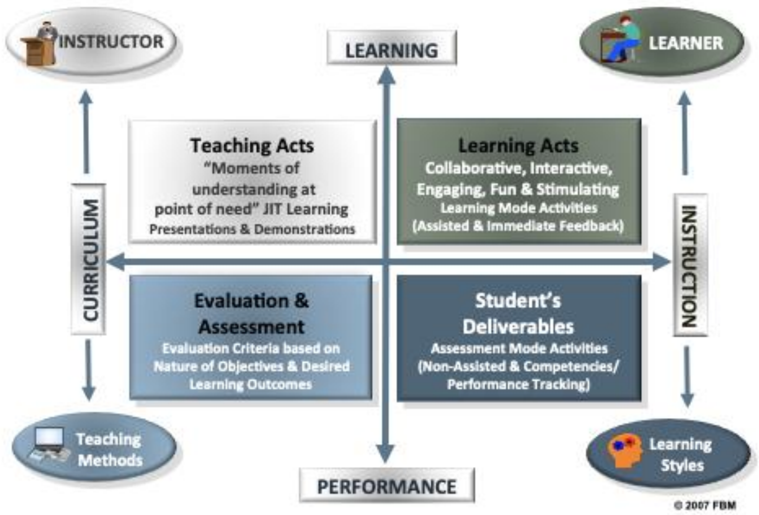
While the promise of AI in education is significant, its implementation is not without challenges. Technologies such as chatbots and adaptive learning systems have shown potential for personalizing education and facilitating real-time interactions. Advances in Natural Language Processing (NLP) and machine learning further enable these systems to mimic human-like interactions, offering a more relatable and effective learning experience (Ogawa & Nakamura 2023). However, the successful deployment of these technologies must address critical ethical and societal concerns. Issues such as data privacy, algorithmic bias, and the potential for unequal access to AI-driven tools pose challenges that require immediate and sustained attention (Ferreira & Hong 2024). Only by addressing these considerations can AI truly realize its promise of democratizing education and fostering equitable learning opportunities.

FazBoard synthesizes the strengths of existing online platforms and transcends their limitations, offering a new paradigm in digital education. Through the integration of an AI assistant and an immersive digital canvas, FazBoard bridges the divide between traditional teaching and modern technological capabilities. By promoting collaboration, adaptability, and inclusivity, it empowers students to navigate the complexities of contemporary education. Especially in the aftermath of the COVID-19 pandemic, which disrupted traditional educational systems, FazBoard provides a robust, scalable, and student-centered approach to online learning. It not only ensures continuity in education but also enhances productivity and focus, positioning itself as a cornerstone of future-ready educational innovation.

FazBoard Applied in Teaching and Learning

As shown in Figure 2, the Knowledge Departed & Knowledge Assimilated (KDKA) Instructional Design (ID) model was employed to develop and evaluate the integration of an infinite digital canvas aimed at emulating the pedagogical spaces of the instructor, individual learner, and collaborative learning groups. The overarching design sought to capitalize on the merits of active learning strategies in tandem with the KDKA model's approaches, which concentrate on knowledge dissemination from the instructor and knowledge assimilation by the learners. This model emphasizes the interdependency between these two aspects throughout the curriculum design, development, and implementation phases, including e-learning content. It is predicated on the understanding that while every teaching activity encompasses a learning component, the converse is not necessarily true. Consequently, the focus shifts toward fostering learning as opposed to merely teaching, and engaging students through active learning via FazBoard.

Figure 2. *The Knowledge Departed & Knowledge Assimilated (KDKA) Instructional Design (ID) Model*



Results

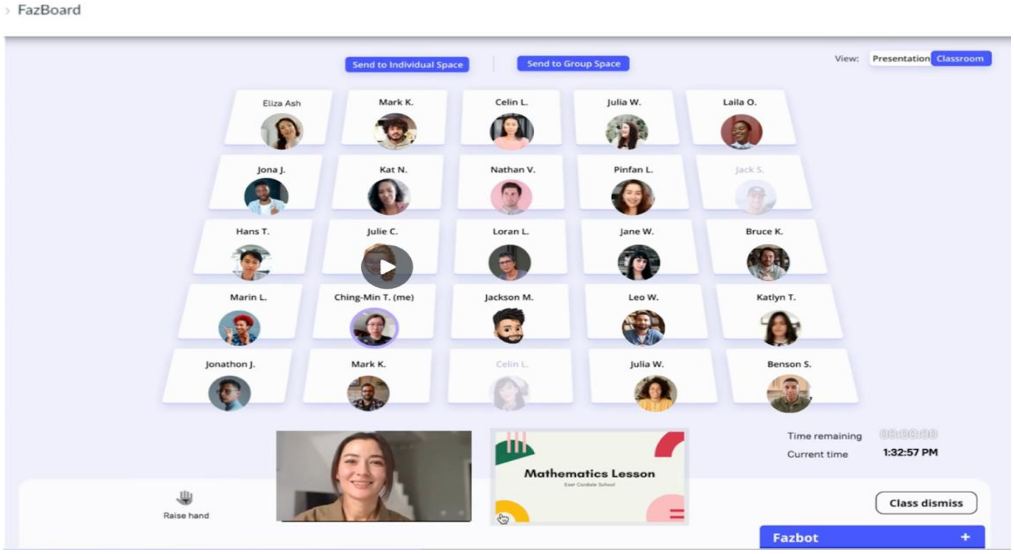
Leveraging the KDKA model, coupled with the digital functionalities afforded by the Learning Management System (LMS) Canvas, emphasis was placed on incorporating active learning pedagogy. This involved a multifaceted approach that encompassed the analysis of learners' backgrounds, identification of content knowledge types, construction of intended learning outcomes, design of interactive teaching and learning activities, and development of relevant assessments aligned with students' deliverables. Furthermore, an AI Teaching Assistant (TA) prototype was integrated to bolster active learning by offering around-the-clock instant responses, thus mitigating the disconnect and delayed replies that often characterize student inquiries.

The three simulated spaces – the teacher's space, the group learning space, and the individual learner's space – each utilized specially-designed KDKA templates:

Teacher's Space

Depicted in Figure 3, this space grants the instructor a comprehensive view of the active participants, complete with video and audio. It also facilitates easy access to and interaction with an AI assistant, as well as a repository of preloaded teaching and learning activities or lesson presentations that can be shared on the class board. Moreover, the instructor can seamlessly share applications, browser sessions, screens, documents, whiteboards, and selected windows with either individual students, the entire class, or collaborative groups. Additionally, content from the individual or group learning spaces can be projected on the class board.

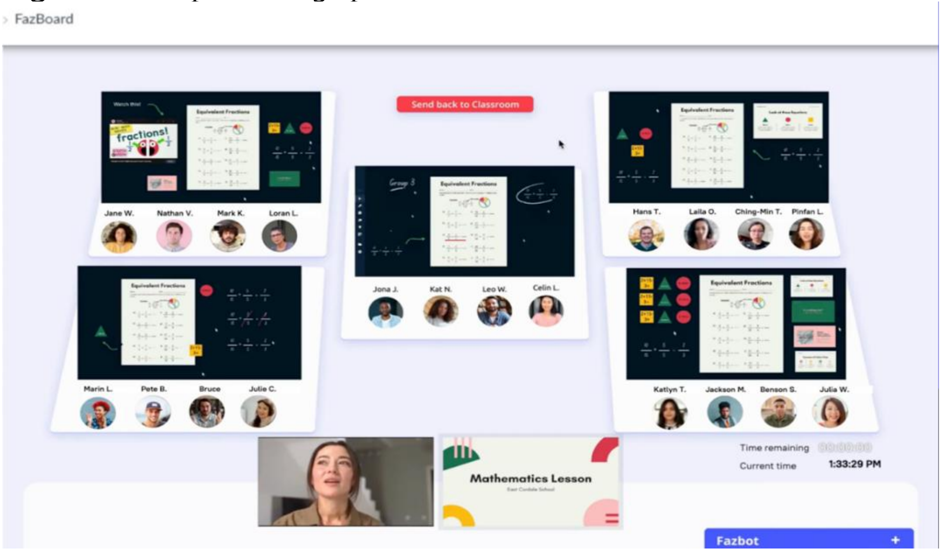
Figure 3. *Teacher's Space*



Group Learning Space (Always Visible to Teacher)

This collaborative environment captured in Figure 4, allows each team member to simultaneously share applications, browser sessions, screens, documents, whiteboards, and selected windows within their individual space or the shared team space. All team members can actively contribute, collaborate, and work synchronously, either within the shared space or their individual spaces. Teams can present to the entire class, and instructors can showcase content from any team's space on the class board. An AI Assistant is readily accessible to answer course-related questions, facilitate communication with the instructor, or engage in conversation.

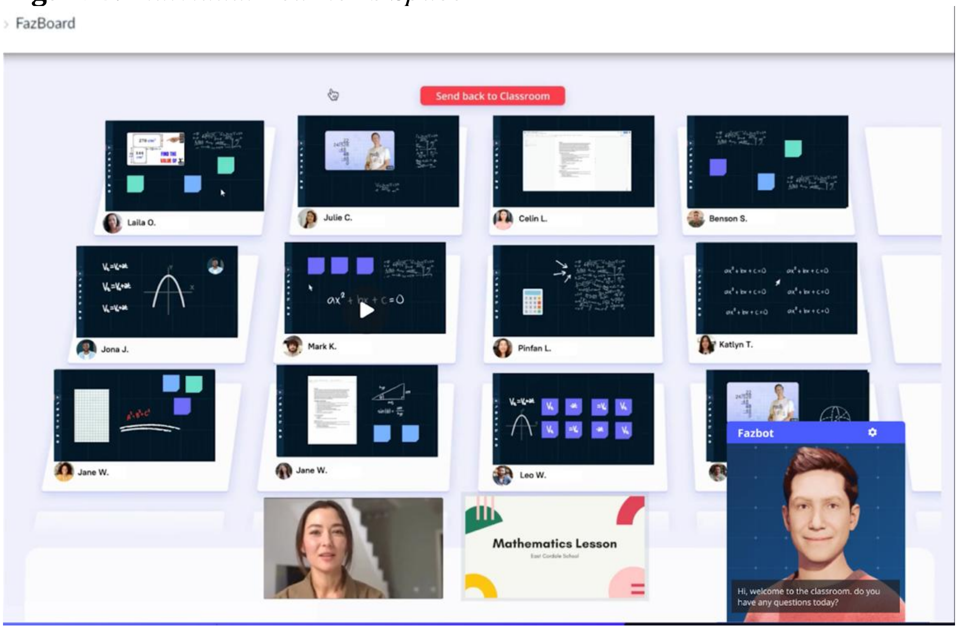
Figure 4. *Group Learning Space*



Individual Learner's Space (Always Visible to Teacher)

As shown in Figure 5, the individual learner's space permits real-time sharing of applications, browser sessions, screens, documents, whiteboards, and selected windows by both the instructor and students. The instructor can enter any student's space to provide assistance or collaborate in real time. Students can present to the entire class, and content from an individual learner's space can be displayed on the class board. Each learner has access to the AI Assistant for course inquiries, instructor communication, or engagement in dialogue.

Figure 5. *Individual Learner's Space*



Pilot Implementation

The pilot implementation involved three classes, and a survey of 17 students yielded the following benefits:

- **Comfort and Immediacy:** The platform alleviated students' anxiety and apprehension, enabling them to seek immediate responses in a comfortable and anonymous setting.
- **Data Quality from Interactions:** FazBoard's AI, unlike human instructors, can maintain a comprehensive record of all questions, challenges, and interactions, thereby facilitating data-driven analysis and targeted interventions for improving learning outcomes.

FazBoard's project was acknowledged as an exemplary innovation by Educause and featured in the 2022 EDUCAUSE Horizon Report | Teaching and Learning Edition. This report surveys critical trends, technologies, and practices that are poised to shape the future of education and contemplates various future scenarios and implications. FazBoard's inclusion in this report as part of EDUCAUSE's Showcase Series underscores its significance in addressing the pressing issues facing higher education.

The Distinctiveness of FazBoard

FazBoard's distinguishing feature is its capacity to immerse students within a simulated teaching and learning environment, suitable for synchronous, asynchronous, or hybrid modalities, augmented with an AI Assistant. By utilizing AI technology and the democratization of Cognitive Computing, including Machine and Deep Learning (ML/DL) and Natural Language Processing (NLP/NLG/NLU), FazBoard bridges the growing divide between learners' readiness and adaptability to innovative technologies, devices, and applications, and the integration of these technologies within instructional practices.

Modern students tend to prioritize achieving desired grades over acquiring a deep understanding of the material, a tendency influenced by education systems that emphasize grades. This has led to a reliance on memorization rather than comprehension. FazBoard, however, guides students through the problem-solving process without directly providing answers, thus placing emphasis on learning rather than memorization.

The adversities faced in teaching and learning have been exacerbated in the wake of COVID-19. The efficacy of technology-assisted instruction, especially in virtual settings, depends not only on the robustness of the Learning Course Management System (LCMS) or virtual meeting tools like Zoom, but significantly on the pedagogical design of the content in terms of rigor, depth, presentation, and style.

Under this perspective, mere Instructional Design sophistication and LCMS are insufficient indicators of educational success in the genuine transfer of information and knowledge between students and educators. Furthermore, contemporary learners, who are growing up in the digital age, do not assimilate information in traditional ways. This divergence is aggravated by the disparity between learners' embrace of technology and educators' adoption of technological instructional methods. FazBoard addresses this challenge through a design that caters to the evolving learning preferences relative to traditional teaching methods.

The system includes an AI Assistant capable of personalized, adaptive instruction based on instructional resources and students' learning preferences. Furthermore, it incorporates the power of automation in teaching and learning, along with cognitive process automation to perform complex actions autonomously, such as identifying missing assignments, attendance, and other key performance indicators. This facilitates faculty tasks, such as the Student Engagement Roster, while also sending periodic reminders to students.

Conclusion and Next Steps

FazBoard's innovation lies in its focus on learning through the combination of an infinite digital board and Artificial Intelligence. It recognizes that the terms “equality” and “equity” in education are differentiated by the letters "A&L," which stand for “All Learn.” All students have the ability to learn, albeit through different means and under varying conditions. FazBoard seeks to realign teaching and learning activities with classroom diversity and ensure equitable access and learning outcomes through Adaptive and Active Learning. Moreover, it tackles the challenge of delayed responses to students’ inquiries by providing 24/7 on-demand instant responses through an engaging AI Teaching Assistant.

The next phase of the FazBoard project will expand its focus on AI Assistant (FazBot) learning, including:

- Intelligent Tutoring & Mentoring/Coaching: Enabling FazBot to reach out to a broader spectrum of knowledge sources and adapt to the individual learner's needs.
- Adaptive Learning Model: Personalizing and adapting instructions based on resources and students’ learning preferences.
- Open Learner Modeling: Allowing students to evaluate their knowledge and reflect on their learning.
- RPA Integration: Integrating automation from cognitive RPA and I4PA to perform complex actions autonomously.
- Sounds More Human: Advancements in speech-to-text, text-to-speech, NLP, and Machine Learning will enable FazBot to conduct more sophisticated conversations.
- Looks More Human: As AI-powered video services and media presentation improve, FazBot may interface with humans in a more human-like manner.

Future scopes of FazBoard will also include more personalized learning and customized teaching through Machine and Deep Learning with NLP. This aims to provide individualized attention accommodating diverse learning preferences and abilities, embodying the essence of inclusivity in education. Additionally, new collaborations between human educators and FazBot will be explored to create more powerful learning environments and achieve stronger learning outcomes.

References

Abrahams C, Regan E (2023) Adaptive learning systems and AI: A systematic review. *International Journal of Educational Technology in Higher Education* 20(3): 145–162.

Ahmad R, Chang M (2022) Learning analytics and student engagement: A data-driven approach to education. *Computers & Education* 191: 104636.

Bengtsson M, Wu J (2023) The role of AI chatbots in remote learning during the pandemic: Challenges and opportunities. *Journal of Computer-Assisted Learning* 39(4): 678–694.

Chen H, Liu X, Yin D, Zhang X (2020) A systematic review of empirical studies on learning analytics in higher education. *Sustainability* 12(7): 2913.

D'Mello S, Craig S, Witherspoon A, McDaniel B, Graesser A (2008) Automatic detection of learner's affect from conversational cues. *User Modeling and User-Adapted Interaction* 18(1–2): 45–80.

Daniel SJ (2020) Education and the COVID-19 pandemic. *Prospects* 49: 91–96.

Falakmasir M, Ashley K, Schunn C, Litman D (2014) Identifying thesis and conclusion statements in student essays to scaffold peer review. *Intelligent Tutoring Systems* 254–259.

Ferreira P, Hong S (2024) The future of AI in education: Ethical implications and student-centered learning. *AI & Society* 39(1): 55–68.

Forbes-Riley K, Litman D (2012) Adapting to multiple affective states in spoken dialogue. In *Proceedings of the 13th Annual Meeting of the Special Interest Group on Discourse and Dialogue*, 217–226.

Gamon M, Gao J, Brockett C, Klementiev A, Dolan W, Belenko D, et al. (2008) Using contextual speller techniques and language modeling for ESL error correction. In *Proceedings of IJCNLP*.

Hutt S, Klahr D (2020) Data-driven education: Approaches and challenges. *Journal of Cognitive Psychology* 32(5–6): 477–495.

Kotamjani SS (2020) The transformative potential of artificial intelligence in higher education. *International Journal of Educational Technology in Higher Education* 17(20).

Litman D (2016) Natural language processing for enhancing teaching and learning. In *Proceedings of the Conference on Empirical Methods in Natural Language Processing*.

Ogawa T, Nakamura H (2023) AI-powered teaching assistants and their impact on educational outcomes. *IEEE Transactions on Learning Technologies* 16(2): 145–153.

Okamoto T, Kayama M (2015) Ontology-based semantic recommendation for context-aware e-learning. In *Proceedings of the International Conference on Knowledge Management and Information Sharing (KMIS),* 77–84.

Piwek P, Hernault H, Prendinger H, Ishizuka M (2007) T2d: Generating dialogues between virtual agents automatically from text. In *Proceedings of IVA/LNAI,* 161–174.

Rahimi Z, Litman D, Wang E, Correnti R (2015) Incorporating coherence of topics as a criterion in automatic response-to-text assessment of the organization of writing. In *10th Workshop on Innovative Use of NLP for Building Educational Applications*, 20–30.

Wambui T, Kirui J (2022) Exploring AI's role in promoting equity in education: A focus on underserved communities. *International Review of Research in Open and Distributed Learning* 23(4): 67–83.

Athens Journal of Technology and Engineering - Volume 12, Issue 1,
March 2025 – Pages 41-54

Equitable Access to the Built Environment for People with Disability

By Claire Flemmer[*] & Alison McIntosh[±]

The overarching goal of the United Nations Convention on the Rights of Persons with Disabilities was to foster inclusivity in all aspects of living. However, equitable access to the built environment is a long way from being reached. This research examines the barriers to inclusive access. It considers the perspectives of people with disability and the sometimes-conflicting constraints that different impairments place on building design. Next it examines the perspectives of building professionals involved in the design and management of public buildings. Finally, it presents case study assessments of the accessibility of shops, libraries and restaurants in New Zealand, and highlights features that need improvement. The results show that accessibility remains limited, particularly in small restaurants and shops. The attitude and awareness of building professionals and employees is a barrier to improving accessibility, indicating the importance of training programs. In addition, accessibility legislation needs to be improved and enforced. Finally, the government should subsidize accessibility features in buildings and people with disability should be involved in the building design process in order to move closer to genuinely inclusive access for everyone.

Keywords: *accessibility, disability, inclusivity, built environment*

Introduction

A person with disability (PWD) is someone who has one or more impairments related to cognitive, mobility, vision, hearing and other functions. The World Health Organisation (WHO) estimates that PWDs make up an estimated 16% of the world's population (WHO 2023). Population census data reports 26% of Americans live with some type of disability (CDC 2020). In New Zealand, about 24% of the population are PWDs and 59% of this demographic are elderly (aged 65 or over) (MacPherson, 2014). In 2006, the United Nations drafted the Convention on the Rights of Persons with Disability, which included the rights of PWDs to 'live independently and be included in the community' (Article 9, UNCRPD 2006, Watene, et al. 2023). As such, PWDs should be able to access a wide range of buildings including government buildings, shops, restaurants, residences, schools, hospitals, offices, theatres, churches, libraries, gyms, heritage buildings, airports, stations, and recreational places/parks. The concept of Universal Design (UD) of buildings and spaces is based on the same principle, namely that the built environment (BE) should be designed to provide equitable

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access to people of all abilities and ages (Zallio and Clarkson 2021). There is a definite obligation to provide good access but the reality of providing such access is difficult. Firstly, different types of impairment place different and sometimes conflicting constraints on building design (Carlsson et al. 2022). For example, a wheelchair user prefers smooth paths with gentle transitions while a person with vision impairment needs distinct tactile changes, high-contrast signs and bright lights and a person with autism is distracted by colours and lights. Secondly, the mandatory legislation on provision of accessible features needs to be unambiguous, comprehensive and backed up by regular compliance monitoring. Thirdly, current methods for measuring accessibility are very variable and difficult to compare. Finally, the party responsible for providing and maintaining equitable access needs to be identified. The consequence is that public buildings today fail to provide PWDs with their fundamental right to equitable access (Charitakis 2018).

The aim of this work is to research the accessibility of New Zealand's public buildings for PWDs from a range of perspectives. It has the following objectives:

1. To review the international findings on the perspective of PWDs in accessing the BE.
2. To compare accessibility legislation internationally and in New Zealand to identify ways to improve accessibility.
3. To assess the perspective of New Zealand building professionals on the provision of accessible features in buildings.
4. To examine the accessibility of three types of public buildings in New Zealand using case studies on shops, libraries and restaurants and to provide the perspective of people working in those buildings on their interaction with PWDs.

The first two objectives are considered in the literature review section. The article then looks at public building accessibility in the New Zealand context. Firstly, questionnaire responses are used to present the perspective of 61 building professionals. Next, case studies are presented for three different types of public building (shops, libraries and restaurants). In each case, there is an assessment of the accessible features of the buildings, followed by the opinions of people working in the buildings. The findings are then contrasted with those from the literature, with concluding remarks and recommendations for improving building access.

Literature Review

Barriers to inclusive access in the built environment for PWDs

People live with a wide range of impairments. Most of the research into building access for PWDs focuses on physical impairments (especially those related to mobility, vision and hearing) with relatively little information on cognitive impairments such as autism (Ijadunola et al. 2019). For people with mobility impairment, particularly those using wheelchairs, the main challenges in accessing the

BE include narrow entrances, stairs, inaccessible toilets, steep entrance ramps, narrow aisles, missing or inadequate kerb cuts on pavements, rough pathways, inadequate accessible parking, and shelves/counters positioned too high to be useable (Bromley et al. 2007, Torkia et al. 2015). People with visual impairment find that navigating the BE is the main challenge, particularly when learning a new building layout. They often use a white stick or a guide dog, but both aids will only find floor-based objects. Therefore, one of their main risks in a building is being hit by body-level and head-level obstacles, such as wall-mounted fire extinguishers and signs. Moving people and shopping trolleys are additional hazards. Other problems include transparent doors, unmarked/smooth transitions to building entrances, lifts, elevators and stairs, furniture, and poor signage. Libraries are singularly problematic, being silent environments with abundant furniture and inadequate Braille signage (Ayoung et al. 2021, Jeamwatthanachai et al. 2019). Many types of building use sound to communicate information to the occupants; the fire alarm rings loudly; the lift chimes to announce its arrival and the public announcement system uses speech played through loudspeakers. People with hearing impairment do not get this information. Coupled with this, it is difficult for them to get help since customer service is mostly verbal (Ayoung et al. 2021, Keerthirathna et al. 2010).

In addition to the physical impairments discussed above, there are people who have more than one physical impairment and/or cognitive impairment. This includes the elderly who report access barriers in the BE that include trip hazards, poor lighting, uneven paths, steep paths, stairs and lack of seating (Perry et al. 2021). They also report that accessible features are often unusable, either because they are poorly designed, broken, or already being use by someone else (Mao and Chen 2022). People with cognitive impairment, such as autism, have access needs that are completely different from those with physical disabilities. They can be overwhelmed by sensory inputs such as noise, lighting, touch and smells in buildings (Kinnaer et al. 2016).

It is clear that people with different types of impairment have very different requirements and that achieving UD in buildings is challenging. Burns et al. (2023) review access in a range of public spaces and make several recommendations, including the use of Braile, high-contrast large font signage, text captioning, sound and vibration to communicate important information such as key navigation points (entrances, lifts, corridors) and public messages within buildings. In addition, Malcolm (2022) suggests that quiet spaces with dim lighting will help people with sensory challenges.

Finally, there is a common perception amongst PWDs that one of their chief barriers to visiting public places is the negative attitude of other people in the building. Heylighen et al. (2016) stress the importance of improving public awareness on the problems faced by PWDs in order to address this barrier. Fisher and Purcal (2017) suggest that awareness and training programs are needed not only at the individual level (i.e., the general public), but also at the organisational level to modify the attitudes of people working in public places such as workplaces, education and health facilities, and government buildings.

Legislation on accessibility in the Built Environment

Key factors in achieving equitable access to the built environment for PWDs are the overarching accessibility legislation and the enforcement of mandated accessibility features. Most countries have legislation protecting the rights of PWDs and mandating accessibility in public buildings. However, the legislation detail and the enforcement of compliance is very variable. The US and the UK have very detailed mandatory standards, and these are stringently enforced (Arditi 2017, Friaz-Lopez and Queipo de Llano 2020). By comparison, New Zealand has fewer specific requirements and limited enforcement. The country's Building Act 2004 merely specifies that buildings access must be 'reasonable and have adequate provision' for people with disability (Stewart 2021). The New Zealand Building Code (NZBC), Clause D1 outlines the minimum requirements for access facilities in public buildings but only applies to places with more than 10 employees and has differing requirements for new buildings and modifications to heritage buildings (Bell et al. 2015). The New Zealand standard NZS4121:2001 'Design for Access and Mobility – Buildings and Associated Facilities' provides comprehensive specifications on accessible features, but these standards are not mandatory and exceed the minimum requirements in the NZBC (Calder et al. 2018). The result is legislation that is confusing, has many loopholes and minimal enforcement. There is an urgent need to make it more comprehensive and to implement stricter monitoring and penalties (Foster et al. 2021).

Alongside legislation and enforcement of inclusive accessibility features, is the need to educate building professionals about the practical implementation of inclusive design (Carlsson et al. 2022, Mulligan et al. 2018). Several studies recommend that building practitioners should be trained on the needs of PWDs and that PWDs themselves are the most effective educators/consultants in this area (Jackson 2018, Nijs and Heylighen 2015). It is also necessary to consider the cost overhead of providing accessible features. Construction companies are competitive and building owners/managers are reluctant to bear the extra cost (Yau and Lau 2016, Zallio and Clarkson 2021).

Methodology/Materials and Methods

An online questionnaire was used to collect data from 61 building professionals involved in the design and management of public buildings in New Zealand. The questionnaire was divided into the five topics relating to building accessibility: New Zealand legislation and policy; comparison between New Zealand and international legislation; application of inclusive access; the state of accessibility; awareness and training. In each topic, the respondents selected their response to statements based on a 5-point Likert scale with responses of 1: strongly disagree; 2: disagree; 3: neutral; 4 agree; 5: strongly agree. The demographics of the respondents are summarised in Table 1.

Table 1. *Demographics of the 61 Building Professionals*

Characteristic	Demographic
Primary job role	Quantity Surveyors (31%); Site Managers/Engineers (25%); Project Managers (23%); Architects (15%); Commercial Managers (3%); Other (3%)
Experience (years)	Over 15 (41%); 11 to 15 (31%); 6 to 10 (21%); 1 to 5 (5%); less than 1 (2%)
Primary project type	Buildings (80%); Infrastructure (15%); Services (2%); Other (3%)

The accessibility of a range of public buildings in New Zealand was assessed for compliance with the country's standard (NZS4121: 2001 Accessibility and Mobility Design) using three case studies comprising ten shops, ten libraries and eleven restaurants. In addition, a small sample of people working in the buildings was asked about their experience in dealing with people with disability.

Data was collected by students enrolled in the Master of Construction degree from the School of Built Environment at Massey University as part of their research course requirements. Data collection took place from August 2023 to January 2024 with low-risk ethics notification lodged under identification numbers: 4000027946, 4000027970, 4000027973 and 4000027981.

Results

Perspectives of Building Professionals on Inclusive Accessibility

The responses of 61 New Zealand building professional with the demographics shown in Table 1 are listed in Table 2.

Table 2. *Perceptions of 61 New Zealand Building Professionals on Accessibility*

Topic	Percentage of respondents agreeing with the statement
New Zealand legislation and policy	59%: legislation sufficiently mandates accessible requirements
	61%: NZ disability strategy policy has influenced the construction practices in the industry
	74%: NZBC accessibility requirements were considered in their projects
	67%: stricter accessibility legislation is needed
	52%: accessible features should be regularly audited and enforced
Comparison between New Zealand and international legislation	54%: did not know how NZ accessible standards compared with international standards
	53%: construction industry should play a role in improving accessibility standards
	49%: did not know if international benchmarking has helped identify gaps in NZ accessibility standards
	51%: did not know whether there was international collaboration on accessibility standards
	53%: did not know whether NZ construction industry was proactive in adopting international accessibility innovations

Application of inclusive access	71%: NZ buildings are designed with features that cater to people with mobility impairments
	23%: NZ buildings have adequate provision for individuals with vision and hearing impairments
	35%: NZ buildings have adequate provision for individuals with cognitive and age-related impairments
	15%: NZ construction industry often seeks feedback from PWDs to improve building designs
State of accessibility in NZ buildings	62%: most NZ buildings constructed in the last 5 years are easily accessible for PWDs
	53%: modern NZ construction projects prioritise accessibility features as a central design element
	56%: did not know whether the NZ built environment facilitated independence and participation for PWDs
	75%: newer NZ building have significantly better accessibility features than older NZ buildings
	54%: did not know whether the NZ built environment adequately met the diverse needs of all people, including PWDs
Awareness and training	52%: construction professionals do not receive adequate training on the importance of building accessibility for PWDs
	61%: did not know whether accessibility training modules were regularly updated to include the latest requirements
	48%: neutral on whether accessibility awareness campaigns were frequent in the construction industry
	41%: on-site personnel were not given adequate training on how to maintain accessibility features

NZBC: New Zealand Building Code; NZ: New Zealand; PWD: person with disability.

Additional comments from building professionals showed that they did not know where to get information and updates on accessibility requirements and on technological advances related to supporting PWDs, where to find PWD representatives for collaboration, and where to find training opportunities. Further, they felt that this support should be provided to them at no cost.

Case Study One: Accessibility of Shops

The sample of ten shops consisted of four large grocery stores and six small stores (corner grocery stores or stores attached to fuel stations), all located in Auckland, New Zealand. The outdoor and indoor accessibility features (Table 3) of each shop were measured and compared with the specifications of NZS4121:2001. Some features, have several sub-features, all of which had to meet the standard. For example, there are five sub-features for accessible car parks. If any one of these sub-features failed to comply with NZS4121:2001, then that shop was deemed to have failed compliance for its provision of accessible car parks. Table 4 shows the assessment of the ten shops.

Table 3. *Outdoor and Indoor Accessibility Features Used in Assessment of Shops*

Outdoor features	
Feature	**Number and type of sub-feature**
Car parks	5: location; signage; number; dimensions; surface
Foot paths	3: clear width; transverse gradient; longitudinal gradient
Ramps	7: clear width; transverse gradient; longitudinal gradient; edge-rail; safety rail; handrail; landing
Kerb ramps	3: gradient; dimensions; distance from top of ramp to any obstruction
Indoor features	
Feature	**Number and type of sub-feature**
Entrances	2: level approach space; threshold
Doorways	2: clear opening; automatic door
Passing space	1: clear width
Shelf	1: height
Checkout counter	2: height; aisle width
Lifts	1: available/not required (single story building)
Toilets	3: dimensions; toilet door clear opening; washbasin position

Table 4. *Compliance of Ten Case Study Shops with NZS4121:2001*

Outdoor features											
Feature	**Large shops**				**Small shops**						**Compliance (%)**
Car parks	✓		✓								20
Foot paths	✓		✓		✓						30
Ramps		-	-	-		-	-	-	-	-	0
Kerb ramps	-		✓			✓	-				25
Indoor features											
Entrances	✓		✓	✓	✓	✓	✓	✓	✓	✓	90
Doorways	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	100
Passing space				✓		✓					20
Shelf											0
Checkout counter											0
Lifts	-	-	-	-	-	✓	✓	-	-	-	100
Toilets	✓	-	✓	✓	-	-	-	-	-	-	100
Compliance (%)	56	13	67	44	33	56	38	25	25	25	

Key: ✓Compliant - not required

Perceptions of Shop Employees

Seven shop employees (two shop owners, three shop managers and two customer service representatives) provided their perspectives on accessibility for people with disabilities. The findings can be summarized as follows:

- Awareness of the legislation, policies and standards relating to accessibility in public buildings for people with a range of needs (including children, the elderly, the pregnant, people with various dimensions of disability, and people of different cultures) is greatest for people working in management roles, in large shops.
- Large shops are better than small shops in providing accessible features such as handrails, lower counters, wheelchair accessible trolleys, benches (for people wanting to rest) and quiet and dim shopping hours (for people with sensory impairment). They are also more likely to have staff who are

trained to assist shoppers with special needs and to have a system in place for collecting feedback from all of their customers.

- In small shops, the main barriers to providing more accessible features include the cost, the lack of space, and uncertainty on how to provide features such as Braille signage.
- One shop offered a delivery service (for a fee) and the employee felt that this compensated for inaccessible features since customers "did not have to visit the shop to get their groceries". However, this is an ableist attitude which ignores the right of everyone to access public buildings and which excludes the provision of goods to only those customers who can afford the delivery cost.

Case Study Two: Accessibility of Libraries

The outdoor and indoor accessibility features of ten public libraries, located in Auckland, were measured and compared with the specifications of NZS4121:2001. The results are summarized in Table 5.

Table 5. *Compliance of Ten Case Study Libraries with NZS4121:2001*

Location	Feature	Sub-feature	Compliance (%)
Outdoor	Car parks	Number	100
		Length	40
		Width	40
		Slope	60
		Average	60
	Foot paths	Clear route	100
	Ramps	Width	100
		Transverse gradient	100
		Longitudinal gradient	90
		Average	97
	Kerb ramps	Length, width, slope	100
Indoor	Entrances	Level approach space	90
	Doorways	Clear opening	100
	Passing space	Aisle width	70*
	Counter	Height, width	100
	Lifts	Interior space, door width	100
	Toilets	Clear area (toilets and washbasins)	100

**In 3 of the 10 libraries the aisle width was compromised by furniture.*

Case Study Three: Accessibility of Restaurants

The eleven case study restaurants were located in Tauranga, New Zealand, with six in the central business district and the remainder in the coastal suburb of Papamoa. Table 6 shows the level of provision of facilities for PWDs.

Table 6. *Provision of Accessible Features in Eleven Case Study Restaurants*

Impairment type	Accessible features	Provision (%)
Vision	Pathway marking, braille signage, braille menus	0
Hearing	Visual display of special menu items	0
Mobility	Accessible parking	100
	Accessible ramps	73
	Accessible entrances	100
	Accessible dining tables	82
	Accessible toilets	91*

**In one of the eleven restaurants the accessible toilet was elsewhere in the same building.*

Perceptions of Restaurant Managers

Eleven restaurant managers provided the following perspectives on accessibility for people with disabilities:

- Seven of them had never encountered PWDs in their restaurants. Those who had catered to PWDs found that the main challenges arose from flooring and from split level steps. Hard, smooth flooring is easiest to clean but could be a slip hazard for some patrons. The cost of installing an alternative route with a ramp and handrail to access dining space on a different level was prohibitive.
- Communication with PWDs was limited. They received occasional pre-booking phone calls enquiring about the availability of accessible tables and clear pathways. Three restaurants had websites for customer feedback. The remainder had no formal feedback system, although six managers said they got regular feedback from talking to their customers.
- Their knowledge of inclusive accessibility was limited; only one had collaborated with a vulnerable group and three had some training on the accessibility requirements of PWDs.
- They all understood the importance of offering inclusive access to their restaurant but did not know where to get information about accessibility requirements and training opportunities.
- In small restaurants, the managers felt that their profit margins were too low to allow them to allocate more space between tables for wheelchair access.

Discussion

The perceptions of New Zealand's building professional on various aspects of building accessibility are mixed and sometimes contradictory. For example, the majority feel that existing mandatory New Zealand legislation is adequate, but a similar majority feel that stricter legislation is needed. Just over half of the respondents feel that the regulations should be regularly audited and enforced. Most respondents know little about international accessibility legislation. There is consensus that newer buildings are more accessible than older buildings and that buildings have access features that accommodate mobility impairments but lack provision for those with vision and hearing impairment. They did not know whether the current state of building access met the needs of PWDs. Most respondents felt that they did not receive adequate training on providing access for PWDs. They did not know where to get training and felt that the construction sector should not be solely responsible for the costs associated with improving access in buildings.

The ten case study shops all complied with the NZS4121:2001 accessible design standard for doorways, lifts (when required) and toilets and nine complied with the entrance requirements. None was fully compliant with the requirements for ramps, shelves and checkout counters. Very few shops were fully compliant with the standard for car parks, foot paths, kerb ramps, and passing space. On average over all features, the large shops were compliant with 45% of the features, while the small shops were compliant with 34% of the features. These findings are similar to those reported for shops in malls in Saudi Arabia which users rated at an average accessibility of 53% (Peterson 2021). Large shops provided more accessible features such as handrails, wheelchair accessible counters and benches. They also had weekly "quiet periods", during which the lighting was dimmed, and the music turned off, to provide a better environment for customers with sensory impairment. Employees in the larger shops were more likely to be aware of New Zealand's legislation and policies relating to inclusive access for PWDs and had staff who were trained to assist shoppers with special needs. Staff in smaller shops felt that the cost of providing better accessibility was prohibitive and that wider aisles would reduce the area available for their merchandise. All the employees in the case study shops were willing to provide help to PWDs on request.

Compliance was much higher for the ten case study libraries than for the shops; the libraries had an average of 92% compliance over both outdoor and indoor accessible features. However, improvements could be made to the dimensions of the accessible parking, the slope of access ramps and the level approach space at the entrance door. It is also important to note that aisles need to be kept clear of furniture to maintain an adequate clear passage. The reason for the better accessibility might be that libraries have municipal funding.

Accessibility in the eleven case study restaurants was mostly focused on features for people with mobility impairments, while ignoring the needs of those with vision and hearing impairment. All the restaurants provided accessible parking, entrances and toilets, but were deficient in providing adequate access ramps and accessible dining tables. Restaurant staff had limited knowledge of inclusive accessibility and little experience or training in meeting the needs of PWD patrons. They felt that the main barriers to improving accessibility features were cost and space; increasing the clearance between tables to facilitate wheelchair users would reduce the number of seats for customers. They were receptive to learning more about inclusive access but did not know where to get the information and training.

A limitation of the research is the small sample size of each type of building in the three case studies. A further limitation is that the assessments are based on NZS4121:2001 standards relating to mobility impairment; no assessment has been made on the accessibility for people with other types of impairments.

Conclusions

The United Nations laid out the desired goal of providing inclusive and equitable access for everyone. The case studies on accessibility in public buildings in New Zealand confirm the findings in other countries, namely that accessibility falls far short of the goal. Some progress has been made in providing access for people with mobility impairments but provision for people with vision, hearing, cognitive and multiple impairments is severely limited. In New Zealand, the accessibility legislation is vague, with many loopholes, and there is little enforcement.

In considering a solution to the problem in New Zealand, this work examines the perspectives of several stakeholders. The PWDs experience accessibility problems firsthand and are frustrated by the inefficient and dilatory attitude of legislators and municipal officers. The building practitioners are aware of the need to improve building accessibility but are very aware that any unenforced expenditure in mitigation of the problem will come out of their pockets and are consequently rather passive. Managers in the buildings regard the issue as a nuisance that interferes with their other duties and threatens to be an extra financial burden. However, our research shows that they are generally willing to improve but know little about problems faced by PWDs, how to find out about these and what resources are available to them.

New Zealand legislators also recognise that the problem exists but do not know what aspects of accessibility are in most need of improvement or what steps to take. Research such as this hopes to answer those questions. Unambiguous legislation can then be enacted, together with clear and enforceable penalties for non-compliance.

This brings us to the question of which party should bear the cost of providing equitable access in buildings. The answer lies in the last stakeholder, who is not generally recognized, namely the New Zealand public. The government, through taxpayer revenue, provides many excellent schemes to provide citizens with resources such as pensions and health care. The citizens are aware of and support this use of their taxes. If they were more aware of the needless trials suffered by PWDs in trying to access buildings and more aware of the likelihood that as they age, they will probably become a PWD, they would support the use of their taxes to improve accessibility. Therefore, the burden of providing access to all public buildings should properly rest upon the taxpayer. If the government mandates provision of access in the building design and provides subsidies to implement accessible features, the building professionals would be pleased to comply. The final step in improving accessibility is monitoring and enforcement. In order to operate, New Zealand's public buildings are required to have a Building Warrant of Fitness (BWOF), with critical features, such as the fire protection facilities and emergency lighting checked annually as a condition of the BWOF renewal. If the accessible facilities were added to the BWOF list, the problem of maintaining compliance would be solved. New Zealand would then be closer to achieving equitable access for everyone as envisaged by the United Nations.

Acknowledgments

This project is funded by the Building Research Levy provided by the Building Research Association of New Zealand (BRANZ). The authors gratefully acknowledge this support. Additional thanks go to the masters students at Massey University's School of Built Environment who helped collect the data as part of their research projects.

References

Arditi A (2017) Rethinking ADA signage standards for low-vision accessibility. *Journal of Vision* 17(5): 8–8.

Ayoung DA, Baada FNA, Baayel P (2021) Access to library services and facilities by persons with disability: Insights from academic libraries in Ghana. *Journal of Librarianship and Information Science* 53(1): 167–180.

Bell S, McGregor J, Wilson M (2015) The convention on the rights of disabled persons: A remaining dilemma for New Zealand? *New Zealand Journal of Public and International Law* 13(2): 277–296.

Bromley RD, Matthews DL, Thomas CJ (2007) City centre accessibility for wheelchair users: The consumer perspective and the planning implications. *Cities* 24(3): 229–241.

Burns SP, Mendonca RJ, Smith RO (2023) Accessibility of public buildings in the United States: a cross-sectional survey. *Disability and Society*, 1–16.

Calder A, Sole G, Mulligan H (2018) The accessibility of fitness centers for people with disabilities: A systematic review. *Disability and Health Journal* 11(4): 525–536.

Carlsson G, Slaug B, Schmidt SM, Norin L, Ronchi E, Gefenaite G (2022) A scoping review of public building accessibility. *Disability and Health Journal* 15(2): 101227.

CDC (Centers for Disease Control and Prevention) (2020) Disability and Health Promotion: Disability Impacts All of Us. Available at: https://www.cdc.gov/ncbddd/disabilityandhealth/infographic-disability-impacts-all.html.

Charitakis S (2018) *Access Denied: The Role of the European Union in Ensuring Accessibility under the United Nations Convention on the Rights of Persons with Disabilities.* Doctoral thesis. Maastricht University https://doi.org/10.26481/dis.20181011sc.

Fisher KR, Purcal C (2017) Policies to change attitudes to people with disabilities. *Scandinavian Journal of Disability Research* 19(2): 161–174.

Forster W, Barraclough T, Barnes C (2021) *Making New Zealand accessible: a design for effective accessibility legislation*. New Zealand Law Foundation report, 1–160 https://apo.org.au/node/314411

Frías-López E, Queipo-de-Llano J (2020) Methodology for 'reasonable adjustment' characterisation in small establishments to meet accessibility requirements: A challenge for active ageing and inclusive cities. Case study of Madrid. *Cities* 103: 102749.

Heylighen A, Schijlen J, Van der Linden V, Meulenijzer D, Vermeersch P-W (2016) Socially innovating architectural design practice by mobilising disability experience. An exploratory study. *Architectural Engineering and Design Management* 12(4): 253–265.

Ijadunola MY, Ojo TO, Akintan FO, Adeyemo AO, Afolayan AS, Akanji OG (2018) Engendering a conducive environment for university students with physical disabilities: assessing availability of assistive facilities in Nigeria. In *Disability and Rehabilitation: Assistive Technology* https://doi.org/10.1080/17483107.2018.1449017.

Jackson MA (2018) Models of disability and human rights: Informing the improvement of built environment accessibility for people with disability at neighborhood scale? *Laws* 7(1): 10–41.

Jeamwatthanachai W, Wald M, Wills G (2019) Indoor navigation by blind people: Behaviors and challenges in unfamiliar spaces and buildings. *British Journal of Visual Impairment* 37(2): 140–153.

Keerthirathna WAD, Karunasena G, Rodrigo VAK. (2010) Disability access in public buildings. In *International Research Conference on Sustainability in Built Environment*, 94–104.

Kinnaer M, Baumers S, Heylighen A (2016) Autism-friendly architecture from the outside in and the inside out: an explorative study based on autobiographies of autistic people. *Journal of Housing and the Built Environment* 31(2): 179–195.

MacPherson L (2014) *Statistics New Zealand Disability Survey: 2013*. Available at: https://webapps.ilo.org/surveyLib/index.php/catalog/957/related-materials.

Malcolm M (2022) Environmental accessibility for autistic individuals: Recommendations for social work practice and spaces. *Aotearoa New Zealand Social Work Review* 34(3): 103–115.

Mao X, Chen L (2022) "To go, or not to go, that is the question": perceived inaccessibility among individuals with disabilities in Shanghai. *Disability and Society* 37(10): 1659–1677.

Mulligan K, Calder A, Mulligan H (2018) Inclusive design in architectural practice: Experiential learning of disability in architectural education. *Disability and Health Journal* 11(2): 237–242.

New Zealand Standards (2001) *NZS4121:2001 Design for Access and Mobility – Buildings and Associated Facilities*. Available at: https://www.standards.govt.nz/shop/nzs-4121 2001/?utm_source+MBIE

Nijs G, Heylighen A (2015) Turning disability experience into expertise in assessing building accessibility: A contribution to articulating disability epistemology. *Alter* 9(2): 144–156.

Perry M, Cotes L, Horton B, Kunac R, Snell I, Taylor B, Wright A, Devan H (2021) "Enticing" but not necessarily a "space designed for me": experiences of urban park use by older adults with disability. *International Journal of Environmental Research and Public Health* 18(2): 552.

Peterson HP (2021) Built environment accessibility in the eastern province of the Kingdom of Saudi Arabia as seen by persons with disabilities. *Journal of Accessibility and Design for All* 11(1): 115–147.

Stewart B (2021) Legislative Recognition of the Human Right to Accessible Housing in Aotearoa New Zealand. *Public Interest Law Journal of New Zealand* 8: 128–150.

Torkia C, Reid D, Korner-Bitensky N, Kairy D, Rushton PW, Demers L, Archambault, PS (2015) Power wheelchair driving challenges in the community: a users' perspective. *Disability and Rehabilitation: Assistive Technology* 10(3): 211–215.

UNCRPD (2006) *United Nations 2006 Convention on the Rights of Persons with Disabilities —Articles*. Available at: https://www.un.org/development/desa/disabilities/convention - on-the-rights-of-persons-withdisabilities/convention-on-the-rights-of-persons-with-disabili ties-2.html.

Watene RF, Mirfin-Veitch B, Asaka U (2023) Disabled person-led monitoring of the UNCRPD in Aotearoa New Zealand: maximising the potential of civil society in the implementation of Article 33.3. In S Robinson and KR Fisher (eds.), *Research Handbook on Disability Policy*, 85–99. Edward Elgar.

WHO (2023) *World Health Organization Disability: Key Facts*. Available at: https://www. who.int/news-room/fact-sheets/detail/disability-and-health

Yau Y, Lau WK (2016) Property management, disability awareness and inclusive built environment. *Property Management* 34(5): 434–447.

Zallio M, Clarkson PJ (2021) Inclusion, diversity, equity and accessibility in the built environment: A study of architectural design practice. *Building and Environment* 206: 108352.

Athens Journal of Technology and Engineering - Volume 12, Issue 1, March 2025 – Pages 55-74

Structural Design of Tall Mass Timber Buildings

*By Görkem Arslan Kılınç**

Following the Industrial Revolution, the construction of tall buildings has surged as a means of utilizing dense urban lands more efficiently. Previously, iron/steel and reinforced concrete were the primary structural materials used in tall buildings. However, the use of engineered mass timber as a structural material for tall buildings is steadily increasing due to its numerous benefits compared to its steel or reinforced concrete counterparts. These benefits include a lower carbon footprint, biophilic effects on occupant well-being, high-quality products due to reduced on-site manufacturing and labor, and shorter construction periods. Nevertheless, there are structural design considerations for tall mass timber buildings. This study first briefly examines the development of industrialized mass timber and investigates mass timber products. Mass timber encompasses a range of timber products, including glued laminated timber (GLT), cross-laminated timber (CLT), nail-laminated timber (NLT), dowel-laminated timber (DLT), laminated strand lumber (LSL), laminated veneer lumber (LVL), parallel strand lumber (PSL), and mass ply panel (MPP). It then explores the types of framing systems created with mass timber. These framing systems can be categorized according to their material usage as all-timber or hybrid systems and, according to load-bearing element usage, as post and beam, point-supported panels, wall and panel, and modular. Later, structural design considerations for tall mass timber structures are explained. After conducting case studies for the five tallest mass timber buildings worldwide, current approaches and research areas were identified for tall mass timber building structures.

Keywords: *tall buildings, mass timber, structural system, framing system*

Introduction

Wood is a natural and environmentally friendly material that humans have used as a building material for thousands of years. Traditionally preferred for smaller structures, advancements in technology and sustainability efforts have made wood an increasingly attractive option for high-rise construction. This rediscovery of wood has sparked excitement among architects and engineers, opening new horizons in the construction sector.

There are several reasons why wood is chosen for high-rise buildings. Firstly, its high strength and durability make it ideal for constructing long-lasting and safe buildings. Additionally, wood's natural beauty and aesthetic value provide aesthetic richness and warmth in modern architectural designs. Wood also stands out as an environmentally friendly option; it reduces carbon emissions and is easily

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recyclable. These features make it particularly desirable for sustainability-focused projects.

However, using wood for high-rise buildings comes with challenges. The risk of fire and wood's susceptibility to external factors such as moisture and insects require careful design and maintenance. Moreover, the technical complexity and cost of large-scale wood structures are among other factors that need attention during the design process.

Impressive high-rise buildings constructed using wood can be found worldwide. These structures represent significant achievements both technically and architecturally.

This article will examine the development and usage of mass timber in high-rise buildings, supported by examples from around the world. It will explore how wood could play a role in the future construction industry and discuss its potential.

Industrialized Mass Timber Products

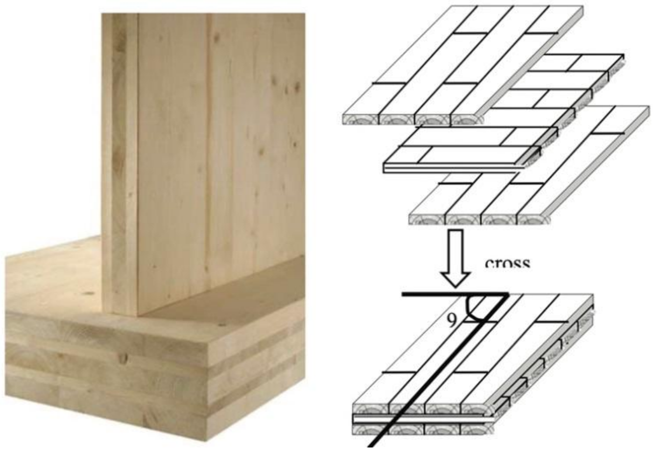
The development of the engineered mass timber began with the discovery of the cross-laminated timber (CLT) in the mid-1990s. While multi-layered wood products like plywood had been used before, they did not play a primary role in the load-bearing systems of structures. In 1994, a doctoral thesis titled "Elastic Analysis of Flexibly Jointed Laminated Timber Plates" was completed at Graz University of Technology in Austria. Existing mechanical theories were applied to multi-layered wood. Following this, collaboration with industry leaders led to the development of marketable structural panels. Initially produced as three-layer panels, they later evolved into five-layer panels and more (Wood et al. 2023).

Today, a variety of laminated timber products are manufactured in the construction industry. The main types of mass timber used in construction industry are Cross-Laminated Timber (CLT), Glued Laminated Timber (Glulam), Nail Laminated Timber (NLT), Dowel Laminated Timber (DLT), and Structural Composite Lumber (SCL) (Abed et al. 2022).

Cross-Laminated Timber (CLT)

CLT panels are created by stacking timber boards perpendicular to each other and bonding them together with a structural adhesive (see Figure 1). The moisture content of the timber used is reduced to around 12% through a kiln-drying process. Any knots or other defects in the panels are removed or cleaned. Once the dimensions of the panel are determined, they are pressed together under pressure using a press machine. After coming out of the press, the panels are cut to their full dimensions, edge profiles are applied using Computer Numerical Control (CNC) machines, and they are prepared for assembly.

Figure 1. *Picture and Lay-up of Cross Laminated Timber*



Source: Kulien et al. 2011.

These panels are typically produced with an odd number of layers, with three, five, and seven layers being the most common. CLT panels can vary in size depending on the manufacturer, but they can be as large as 18 meters in length, 5 meters in width, and up to 500 mm in thickness. They are ideal for use in floors, walls, and roofs (Harte 2017, Kuilen et al. 2011).

Glued Laminated Timber (Glulam)

Glued Laminated Timber (GLT) is created by bonding shaped timber pieces together with the grain directions parallel to each other using adhesive. Glulam elements can vary in size from manufacturer to manufacturer, but they are typically produced in thicknesses ranging from 180 to 630 mm, widths from 66 to 200 mm, and lengths up to 50 meters. This makes them suitable for use as beams and columns. The length of the element is generally limited due to transportation and handling constraints.

One of the significant advantages of GLT is its ability to be produced in large sizes and complex shapes, thereby meeting both architectural and structural design requirements (Abed et al. 2022).

Nail Laminated Timber (NLT)

Nail Laminated Timber (NLT) involves bonding shaped timber pieces together with their long edges placed side by side using nails. This engineered wood material, created through mechanical lamination, is suitable for use in floors, roofs, and walls of buildings.

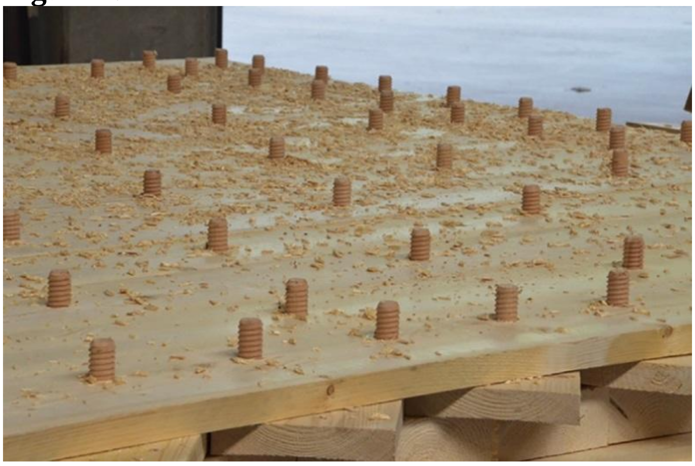
One significant advantage of NLT, compared to other types of laminated wood, is that it does not require specialized production facilities or equipment. NLT systems can be assembled on-site using basic carpentry techniques and locally sourced wood species. Another advantage of NLT is its long history of use in buildings for over a century, which means that engineering requirements and details are well supported by building codes and standards (Abed et al. 2022).

NLT offers a versatile and accessible solution for structural applications, leveraging traditional carpentry skills and readily available wood types to meet construction needs effectively.

Dowel Laminated Timber (DLT)

Dowel Laminated Timber (DLT) is a layered wood product that is widely used in Europe but is slowly gaining acceptance in North America and other countries. The manufacturing of DLT employs a concept similar to NLT, but instead of nails or screws, wooden dowels are used (see Figure 2). In the production of DLT panels, multiple boards of softwood lumber are placed edge-to-edge and joined together using hardwood dowels. These hardwood dowels expand into the surrounding lumber to achieve moisture equilibrium, creating a tight friction fit that enhances the dimensional stability of the panel.

Figure 2. *Dowel Laminated Timber Panels*



Source: Soyato et al. 2020.

DLT panels are typically manufactured using CNC machines, automating the process and producing a highly consistent product that is safer than traditional manufacturing methods (Sotayo et al. 2020).

Unlike layered wood products such as CLT and GLT that use adhesives, which can emit toxic gases like formaldehyde and Volatile Organic Compounds (VOCs), DLT products do not use these chemical compounds. This absence of chemicals improves indoor air quality, reduces the risk of allergic reactions, and creates a healthier indoor environment. Furthermore, by eliminating adhesives and metal connectors, DLT facilitates easier recycling and reuse of wood materials (Sotayo et al. 2020).

Structural Composite Lumber (SCL)

Structural Composite Lumber (SCL) is obtained by combining small wood pieces to create a single structural member. The two main types of SCL products widely used in construction projects are Laminated Veneer Lumber (LVL) and Laminated Strand Lumber (LSL) (Stark et al. 2010).

LVL was developed in the 1970s and is manufactured by bonding thin sliced wood veneers under high heat and pressure. Before lamination, the wood is dried and the grains are oriented parallel to the member's length. LSL is very similar to LVL but uses timber strands instead of veneers (Stark et al. 2010).

These SCL products are suitable for residential construction and can be used in various structural applications including beams, columns, and roof joists. However, they are not suitable for tall buildings and are generally more appropriate for low-rise construction projects.

Mass Timber Structures & Design Considerations

Buildings constructed with mass timber can be categorized based on the types of structural materials (timber, concrete and steel). According to the structural material, mass timber structures are classified under four headings:

- All-timber structures.
- Concrete-timber hybrid structures.
- Steel-timber hybrid structures.
- Concrete-steel-timber hybrid structures.

In all-timber structures, all horizontal and vertical structural elements are made of wood. Non-wooden connection elements can be used at the joints of these wooden load-bearing elements.

A single-material tall building, whether made of steel, concrete, or timber, primarily uses one material for its main structural components. Secondary flooring materials do not affect this primary structural classification. This approach aligns with current guidelines for defining tall buildings, such as those with concrete floors on steel beams in steel structures (Foster et al. 2017). Alternatively, concrete floor slabs can be used in an all-timber structure. One of the most well-known examples of this type of structure is the Treet Building in Bergen, Norway (see Figure 3) (Safarik et al. 2022).

Figure 3. *Treet building, Bergen-Norway*

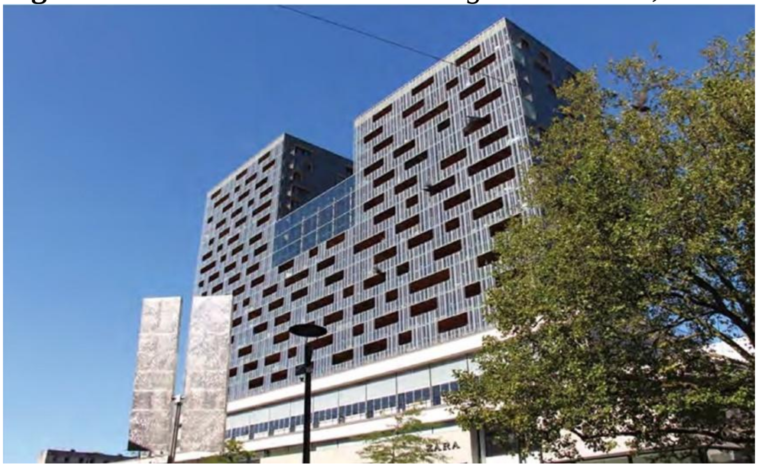
Source: Foster et al. 2017.

In Concrete-Timber Hybrid Structures, building structure combine concrete and timber elements to form the primary structural framework. Typically consisting of a wooden frame and a reinforced concrete core. Another type of these structures involves concrete slabs being constructed as wood. Currently, the tallest concrete-timber hybrid building is the 84-meter tall, 24-story HoHo Building located in Vienna, Austria.

In Steel-Timber Hybrid Structures, the vertical and horizontal load-bearing elements are steel. These steel elements are typically combined with steel-frame cores or perimeter frames, complemented by wooden floor and wall systems. Currently, the tallest steel-wood hybrid building is the Sara Kulturhus mixed-use building located in Skelleftea, Sweden (Safarik et al. 2022).

Concrete-Steel-Timber Hybrid Structures, utilize a blend of all three materials for primary load-bearing purposes. A common configuration includes a concrete core supported by steel beams and columns, along with timber flooring and partition walls, although numerous variations are possible. The tallest known concrete-steel-timber hybrid building is De Karel Doorman in Rotterdam, Netherlands, standing at 71 meters and 22 floors. This structure predominantly comprises a lightweight hybrid tower erected atop an existing department store from 1951 (see Figure 4) (Safarik et al. 2022).

Figure 4. *De Karel Doorman Building in Rotterdam, Netherlands*



Source: Safarik et al. 2022.

Using mass timber structural elements, different framing systems can be created. The typical timber framing options are post and beam, point-supported panels, wall and panel, and preassembled/modular systems. Each system has its own strengths and weaknesses. Therefore, designers need to thoroughly evaluate the specific requirements and limitations of their project to decide on the most advantageous framing system for their application (see Table 1).

Table 1. *Each Framing System is Suitable for Various Building Types. Pros and Cons are Outlined to Highlight Crucial Design Considerations.*

Framing Systems			
Post and Beam	**Point-Supported Panels**	**Wall and Panel**	**Modular**
Applications			
High-end, multi-unit residential Commercial office Amenity floors, conference rooms, lobbies	Cellular, multi-unit residential (student residences, hotels, small apartments)	Multi-unit residential	Small room, multi-unit residential (student residences, hotels, small apartments)
Examples			
2150 Keith Drive, Vancouver 25 King, Brisbane Mostarnet, Brumunddal, Norway	Brock Commons Tallwood House, Vancouver	Dalston Works, London Stadthaus, London	Sara Kulturhus, Skelleftea Treet, Bergen, Norway
Pros			
Commonly used, design/analysis/ construction is well understood due to practitioners' prior experience on low- to mid-rise buildings Enables large grid spacings	Very quick installation time Thin structural floor assembly Uncluttered soffit for easy service distribution	Partition walls are utilized as structural elements Thin structural floor assembly	Quick installation Prefabrication leads to high degree of quality control

Cons			
Deeper structural floor assembly requires greater floor-to-floor heights Routing services through/under/ around beams can be a challenge•	Narrow column spacing constrains programming Requires stacked floor plans Very dependent on supplier panel dimensions Lack of structural redundancy Gaps in code guidance on punching shear for CLT panels	Generally, not suitable for buildings in seismic regions, as wall elements behave as shear walls, which is not ideal Difficult detailing to accommodate shrinkage due to platform framing	Limited suppliers Custom connection detailing Integration with lateral systems is challenging

Source: Wood et al. 2023.

During the design of timber systems, minimizing the number of components where possible, planning simply assembled connections in advance, and ensuring premanufactured parts are accurately prepared are crucial for saving time. In other words, production and assembly details should be predetermined.

Vertical movement in the structural frame is one of the most important considerations in the design of tall timber structures. Factors such as moisture fluctuation, elastic shortening, creep, joint slip, and fabrication tolerance all need to be taken into account. Vertical movements within the structure can lead to differential settlements, causing issues at door and window alignments or even cracks in the structure.

Case Studies

In this section of the study, the highest 5 mass timber buildings of today, namely Ascent (2022), Mjostarnet (2019), HoHo Wien (2020), Haut (2022), Sara Kulturhus (2021) have been examined.

Table 2. *Case Study Buildings*

Building	Location	Completion Year	Building Function	Height (m)	Number of Floors	Structural Material	Structural Classification	Total Mass Timber Volume
Ascent	Milwaukee USA	2022	Residential	86.6	25	Mass Timber Concrete	Concrete-Timber Hybrid over Concrete	7,371 m^3
Mjostarnet	Brumunddal Norway	2019	Mixed-Use	85.4	18	Mass Timber Concrete	All-Timber	2,654 m^3
HoHo Wien	Vienna Austria	2020	Mixed-Use	84.0	24	Mass Timber Concrete	Concrete-Timber Hybrid	4,633 m^3
HAUT	Amsterdam Netherlands	2022	Residential	73.0	22	Mass Timber Concrete	Concrete-Timber Hybrid	-
Sara Kulturhus	Skelleftea Sweden	2021	Mixed-Use	72.8	19	Mass Timber Concrete Steel	All-Timber over Steel-Timber Hybrid	12,022 m^3

Ascent Building, Milwaukee-USA, 2022

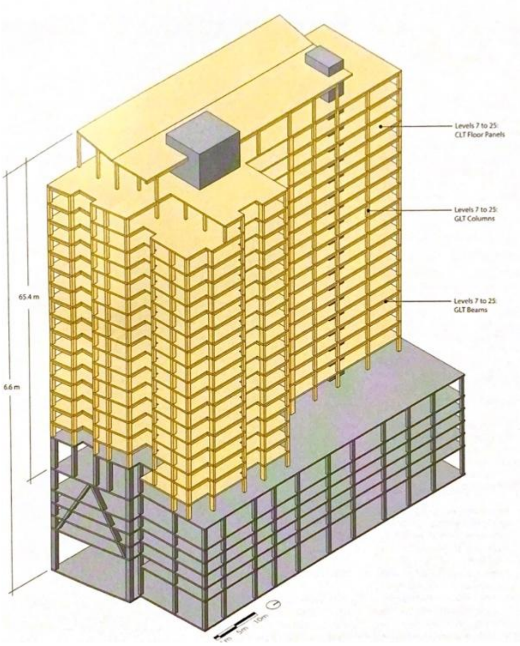
Completed in 2022, Ascent in Milwaukee, United States, is a 25-story residential building. It stands at a height of 86.6 meters and is currently the tallest timber structure (see Figure 5). The ground floor of the building includes a lobby, rental spaces, offices, a bicycle park, storage, and mechanical rooms. Floors 2 through 6 are dedicated to vehicle parking. The 7th floor features a swimming pool, a health center, and some residential units. Residential units occupy floors 8 to 24, with the 25th floor serving as the rooftop.

Figure 5. *Ascent Building. Ascent Building, Milwaukee-USA, 2022*

Source: Gokhman 2021.

In this concrete-timber hybrid structure, the first 7 floors feature a reinforced concrete structural system, while floors 8 to 24 use mass timber. The building incorporates a reinforced concrete core, which provides horizontal load resistance throughout. Mass timber structure begins at the 8th floor, where each floor features 64 GLT mass timber columns (see Figure 6).

Figure 6. *Isometric Diagram Illustrating the Structural System, Depicting the Interplay among the Concrete Structure, GLT Columns and Beams, CLT Floor Panels, and Concrete Core*



Source: Wood et al. 2023.

The primary mass timber structure, featuring glulam beams and columns along with one-way spanning Cross-Laminated Timber (CLT) slabs made from Austrian spruce, extends above the reinforced concrete podium starting at level 7. For high-rise projects, efficiency in structural design across multiple floors is crucial for cost-effectiveness.

In mass timber construction, one-way spanning framing systems typically require column grids spaced approximately 4.5-6.1 meters x 6.1-7.6 meters to achieve economical design. While mass timber can span even larger distances, exceeding these dimensions results in deeper beams and thicker floor panels, significantly increasing costs. Therefore, Ascent opted for a standard residential column grid of around 5.2 meters wide with alternating lengths of 6.1 meters to 7.6 meters, ensuring efficient floor assemblies with 5-ply CLT floor panels while maintaining structural integrity and cost-effectiveness (Fernandez et al. 2020). Column dimensions range from 361x480 mm to 701x678 mm, decreasing in size as the vertical load decreases with increasing floor height. GLT mass timber is also used for beams, with beam heights varying based on load distribution. CLT panels are used for the building's floors (see Table 3).

Table 3. *Ascent Structural System Details*

Ascent Structural System		Structural System Material	Mass Timber Product Thickness/Height/Lenght	Mass Timber Product Dimensions
Concrete-Timber Hybrid over Concrete	Core System	Levels 1 to 25: Concrete		
	Floors	Levels 1 to 7: Concrete Levels 7 to 25: CLT	Floors: 5-ply 180-230 mm Roof: 5-ply 140 mm	2.3x10.5 m
	Columns	Levels 1 to 7: Concrete Levels 7 to 25: CLT	Height: 3.2 m	No typical column size; 16 different columns per level
	Beams	Levels 1 to 7: Concrete Levels 7 to 25: CLT	Lenght: 6.1 m	No typical beam size; 29 different beam sizes per level

Mjostarnet, Brumunddal-Norway, 2019

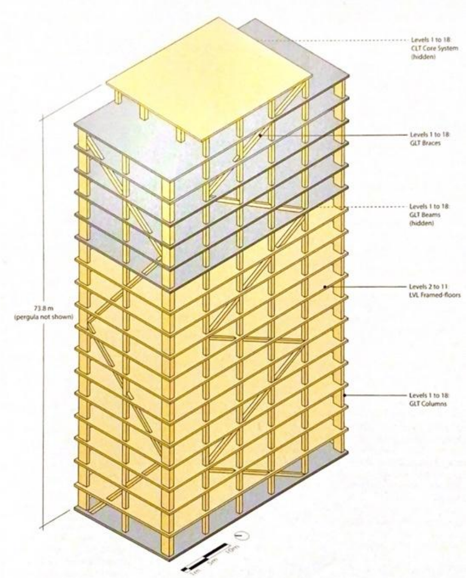
The Mjøstårnet, standing at 85.4 meters tall with 18 floors, is the tallest all-timber structure. It was completed in 2019 and is located in Brumunddal, Norway. This mixed-use building includes restaurants, offices, a hotel, apartments, a conference center, and a rooftop terrace. The footprint of the building, measured from the outer corners, is 16.3 meters by 36.9 meters (Liven and Abrahamsen 2023).

Figure 7. *Mjostarnet, Brumunddal-Norway, 2019*

Source: Safarik et al. 2022.

The primary structure consists of GLT columns and beams with diagonals in the building perimeter. Between the 2nd and 11th floors, a cassette system is used where GLT beams and laminated veneer lumber (LVL) panels are glued together. Between the 12th and 18th floors, a floor slab is created by pouring 300 mm of concrete into precast wooden molds. This composite floor, combining wood and concrete, increases the building's weight to limit swaying under wind loads. CLT panels are used in the core of the structure, and balconies are formed with CLT panels on floors 12 to 17.

Figure 8. *An Isometric Diagram of Mjøstårnet's Structural System Illustrates the Relationship between the Foundation, Pre-Assembled Timber Frame System, and tra8*



Source: Wood et al. 2023.

The GLT column-beam frame forms the primary system providing strength against vertical and horizontal loads. CLT is used for secondary load bearing in the staircases and elevator shafts, and is not structurally connected to the GLT frame. The maximum horizontal deflection at the 18th floor level of the building is 140 mm.

Column spacing is 6.5 m in the short direction and 7.1 m in the long direction. Column dimensions vary throughout the building: 725x810 mm on floors 1-4; 675-720 mm on floors 5-13; and 625-630 mm on floors 14-17. Beam lengths are 3.9 m around the perimeter of the building and 5.8 m in interior spaces. Beam sizes also vary across the structure: 395x675 mm for interior beams on floors 1 and 10, and 625x439 mm for perimeter beams; 625x720 mm for interior beams on floors 11-17, and 625x585 mm for perimeter beams. The typical cross-sectional dimension is 625x990 mm (see Table 4).

Table 4. *Mjostarnet Structural System Details*

Mjostarnet Structural System		Structural System Material	Mass Timber Product Thickness/Height/ Lenght	Mass Timber Product Dimensions
All-Timber Structural System	Core System	CLT Core		
	Floors	Level 1: Cast-in-place concrete Levels 2 to 11: Tra8 casette system Levels 12 to 18: 300 mm concrete	-	Module lenght: 6.5 to 7.3 m
	Columns	Level 1-18: GLT columns	Height: 15-19 m	Levels 1 to 4: 725x810 mm Levels 5 to 13: 675x720 mm Levels 14 to 17: 625x630 mm
	Beams	Level 1-18: GLT beams	Lenght: 5.8 m (inner) 3.9 m (perimeter)	Levels 1 to 10: 395x675 mm (interior) 625x429 mm (perimeter) Levels 11 to 17: 625x720 mm (interior) 625x585 mm (perimeter)
	Walls	Cross-Laminated Timber (CLT)	Panel Thickness: 120-240 mm	Panel dimensions: Walls: 1.4 to 2.9 x6.8 to 11.3 m Balconies: 2.3 x 5.4 to 7.6 m

HoHo Wien, Vienna-Austria, 2020

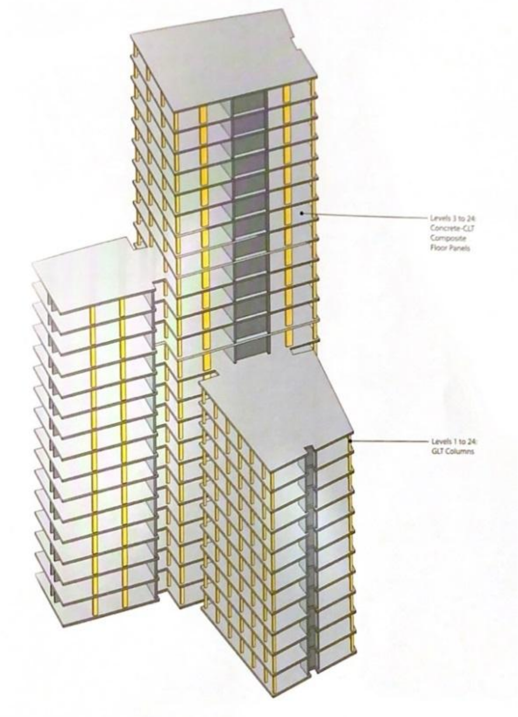
HoHo Wien, completed in 2019 in Vienna, Austria, consists of a 24-story tower reaching 84 meters in height, along with two adjacent towers measuring 57 meters and 40 meters in height (see Figure 9).

Figure 9. *HoHo Wien, Vienna-Austria, 2020*

Source: Safarik et al. 2022.

HoHo Wien utilizes a concrete-timber hybrid system comprising a concrete core, shear wall system, and timber frame.

Figure 9. *An Isometric Diagram of HoHo Wien's Structural System Illustrates the Interplay between the Concrete Core, Shear Walls, and Prefabricated Floor Panels*



Source: Wood et al. 2023.

On the 1st to 5th floors of the building, there are a lobby, restaurant, wellness center, and beauty center. The 6th to 10th floors are used as offices; the 10th to 19th floors function as a hotel. The 20th to 23rd floors house serviced suites, while the 24th floor is dedicated to technical facilities. The aim of the system design was to create a flexible, simple, and repeatable module that facilitates relatively easy transformation and modification of programs. One of the main motivations in the project was to showcase wood prominently. GLT columns, CLT walls, and ceilings are left uncovered throughout all units. In addition, some small details such as the inner edges of window jambs are also made of wood.

The building's floors use prefabricated panels. These panels are 2.4 meters wide and 7 meters long. They are composed of a combination of 160 mm CLT panels and a 120 mm concrete layer. These floor panels are supported by concrete beams located on top of GLT columns. The height of the GLT columns is 3.5 meters, with varying dimensions (see Table 5). The concrete beams of the structure are precast, providing both time savings and ease of manufacturing. The longest distance between the structure's perimeter and the core is 7 meters.

Table 5. *HoHo Wien Structural System Details*

HoHo Wien Structural System		Structural System Material	Mass Timber Product Thickness/Height/Lenght	Mass Timber Product Dimensions
Concrete -Timber Hybrid	Core System	Cast-in-place reinforced concrete		
	Floors	Levels -2 to 1: cast-in-place reinforced concrete Levels 2 to 24: X-Lam Concrete (XC) system (concrete over CLT system)	Panel Thickness: 160 mm	Panel dimensions: 2.4 x 7 m
	Columns	Levels 1 to 24: GLT columns	Height: 3.5 m	400 x (320-1080) mm
	Beams	Levels 2 to 24: Precast concrete edge beams	-	-
	Walls	Concrete shear wall system	Wall Thickness: 140 mm	4.8 x 3.5 m

CLT panels used on the walls had waterproof membranes applied to their outer surfaces before being transported from the factory to the construction site. Additionally, all exposed surfaces of the timber elements were wrapped in plastic before being lifted into place by crane, with the plastic removed just before lifting.

In this project, a total of 4000 cubic meters of wood was used, including open ceilings, columns, and exterior walls. Compared to a similarly scaled traditional concrete structure, choosing wood resulted in approximately 3000 metric tons of carbon dioxide equivalent saved.

HAUT, Amsterdam-Netherlands, 2022

Haut is a residential building located in Amsterdam, standing 21 stories tall with a height of 73 meters. Situated alongside the Amstel River on the edge of Amsterdam city center, the design process prioritized providing residents with expansive views and vistas (see Figure 10). The architectural concept of Haut focuses on transparency in its façade, aiming to offer ample sunlight and unobstructed urban and natural views to its residents (Linders 2024).

Figure 10. *HAUT, Amsterdam-Netherlands, 2022*

Source: Linders 2024.

During the structural system design, braced frames or CLT panels were not preferred to ensure facade transparency and the active role of perimeter walls in load distribution. Load-bearing walls were chosen instead, positioned within the structure to also act as partitions between residential units. GLT beams were used along the building perimeter (see Figure 11). The floors consist of prefabricated timber-concrete composite (TCC) panels. (Verhaegh et al. 2020).

Figure 11. *An Isometric Diagram of HAUT Structural System*

Source: Verhaegh et al. 2020.

In the building, most of the floor slabs are supported on one side by a reinforced concrete shear wall and on the other side by a timber wall or beam.

Concrete and timber are two materials with different mechanical properties. The difference in these properties will lead to differential movements between the two materials. Therefore, detailed studies/analyses have been conducted regarding potential differential movements in the structure. The maximum calculated differential shortening between the reinforced concrete core and the CLT wall is 20 mm. This value can also be observed in other buildings of similar height where mass timber is not used (Verhaegh et al. 2020).

Table 6. *HAUT's Structural System Details*

HAUT Structural System		**Structural System Material**	**Mass Timber Product Thickness/Height/Length**	**Mass Timber Product Dimensions**
Concrete-Timber Hybrid	Core System	Cast-in-place reinforced concrete	-	-
	Floors	CLT	Panel Thickness: 160 mm 80 mm concrete top layer	-
	Columns	GLT	-	-
	Beams	GLT	-	-

Sara Kulturhus, Skelleftea-Sweden, 2021

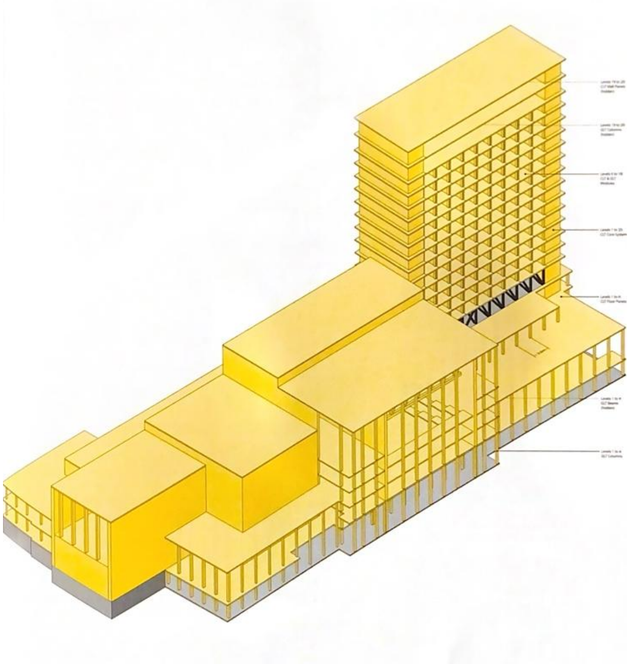
Sara Kulturhus is a 20-story, mixed-use building located in Skelleftea, Sweden. The usage purposes of the spaces within the building vary significantly. The ground floor of the building includes the lobby of the hotel section and the entrance to the cultural center. The 2nd and 3rd floors house a theater. The 4th floor accommodates a conference center, while technical spaces are located on the 5th floor. Floors 6 to 18 are dedicated to the hotel, and the 19th and 20th floors are used for a restaurant and spa.

Figure 12. *Sara Kulturhus, Skelleftea-Sweden, 2021*

Source: Safarik et al. 2022.

The structure is complex due to the diversity in the structural system of the program. The hotel section, which rises above conference and performance centers requiring large spans without vertical supports within the space, is a significant design point in determining the structural system. The structure's system is created by combining 2 different primary wood systems. In the low-rise podium section of the structure, GLT columns and beams are used in conjunction with CLT cores and shear walls. The high-rise section of the structure consists of prefabricated CLT modules positioned between cores containing vertical circulation elements (see Figure 13).

Figure 13. *An Isometric Diagram of HAUT Structural System*



Source: Wood et al. 2023.

The reinforced concrete basement floor houses the service areas of the theater. Floors 1 to 4 accommodate the spaces of the cultural center, including the theater and conference center. This section of the building, which requires large spans, has a structural system consisting of columns, beams, and platforms. GLT columns, beams, trusses, and CLT shear walls ranging from 140 to 160 mm in thickness. GLT columns of varying dimensions form a 3.6x7.2 m grid plan (excluding the theater and lobby sections). The largest columns measure 845 mm x 645 mm.

On Level 2, lattice beams composed of GLT and steel tension and compression rods allow spanning of 13.5 m openings. The upper chords and columns of these flat lattice beams are GLT, while the diagonal rods and lower chord are steel. The connection points of the steel elements are concealed within the GLT columns.

Level 5 is constructed from steel truss boxes. The beams of these steel boxes are H-section steel beams, and the columns and diagonals are various sizes of box columns. This floor accommodates mechanical spaces and serves as the base for the hotel floors.

From Levels 6 through 18, prefabricated hotel modules made from CLT panels are positioned within the GLT column-beam frame system located between cores at the two short edges of the plan. The prefabricated modules consist of GLT columns and 140 mm thick CLT panels. The CLT panels used in the flooring include two layers of 20 mm thick mineral wool for fire protection, a 13 mm thick double-layer gypsum board panel, 22 mm thick particle board, and an 8 mm thick floor covering. Ceilings feature a 100 mm insulation layer and a 100 mm CLT panel (See Table 7).

On the 19th and 20th floors where the hotel restaurant and span are located, a combination of steel columns, GLT columns, GLT shear walls, and concrete flooring is used. This allows for larger spans compared to the hotel floors.

Table 7. *Sara Kulturhus Structural System Details*

Sara Kulturhus Structural System		**Structural System Material**	**Mass Timber Product Thickness/Height/Lenght**	**Mass Timber Product Dimensions**
Steel-Timber Hybrid	Core System	CLT	Thickness: 5-ply CLT 255 mm	
	Floors	Levels -1 to 1, 5, 19 to 20: concrete floors Levels 2 to 4, 6 to 18: CLT floors	Cultural Center floors: 140 mm Hotel ceiling: 5-ply CLT 100 mm Hotel floors: 5-ply 140 mm Roofs: 5-ply 160 mm	
	Columns	Levels 1, 5, 19 to 20: steel columns Levels 1 to 4, 19 to 20: GLT columns	Height: 3.2 m	Hotel: 215 x 400 mm
	Beams	Levels 1 to 4, 19 to 20: GLT beams Level 5: Steel box truss Level 19 to 20: Steel beams	-	-
	Prefabricated modules	Levels 6 to 18: GLT and CLT modules		

Discussion

Tallest five timber buildings worldwide reveal significant advancements and trends in the use of timber as a primary construction material for high-rise structures. Timber's strength-to-weight ratio and sustainability attributes have been leveraged to create efficient and aesthetically pleasing structures. Additionally, hybrid systems integrating timber with other materials like steel and concrete have been utilized to enhance structural performance and address specific design challenges such as large spans and vertical loads.

Looking forward, the findings from this investigation suggest opportunities for further research and development in tall timber construction. Innovations in material science, construction techniques, and digital technologies are poised to unlock new possibilities for taller and more sustainable timber buildings. Addressing technical challenges and enhancing industry collaboration will be crucial in realizing the full potential of timber as a viable alternative in high-rise construction.

Moreover, the environmental benefits associated with timber construction are noteworthy. Timber buildings sequester carbon dioxide during their lifecycle, contributing to carbon neutrality and mitigating the environmental impact of urban development. This aspect is increasingly significant in the context of sustainable urban planning and the global effort to combat climate change.

However, fire resistance, legal regulations and economic concerns were left out of scope for this study. Fire safety remains a critical concern, despite advancements in fire-resistant timber treatments and construction techniques. Building codes and regulations often necessitate rigorous testing and certification to ensure compliance with safety standards, adding complexity and cost to timber projects. The economic feasibility of tall timber buildings compared to traditional materials is another area of ongoing research and debate. While timber construction can offer cost savings in certain contexts, initial investment costs and market acceptance may pose barriers to widespread adoption.

In conclusion, the investigation into the tallest five timber buildings highlights both the achievements and the ongoing challenges in advancing timber as a primary construction material for tall buildings. As urban populations grow and environmental concerns intensify, the role of timber in sustainable urban development is poised to expand, driven by continuous innovation and collaboration across disciplines.

References

Abed J, Rayburg S, Rodwell J, Neave M (2022) A Review of the Performance and Benefits of Mass Timber as an Alternative to Concrete and Steel for Improving the Sustainability of Structures. *Sustainability* 14(5570): 1–24.

Fernandez A, Komp J, Peronto J (2020) Ascent – Challenges and Advances of Tall Mass Timber Construction. *International Journal of High-Rise Buildings* 9(3): 235–244.

Foster RM, Ramage MH, Reynolds T (2017) Rethinking CTBUH Height Criteria In the Context of Tall Timber. *CTBUH Journal* 4: 28–33.

Gokhman T (2021) Ascending Timber Aspiration in Milwaukee. *CTBUH Journal* 1: 50-52.

Harte AM (2017) Mass timber – the emergence of a modern construction material. *Journal of Structural Integrity and Maintenance* 2(3): 121–132.

Kuilen JWGVD, Ceccotti A, Xiac Z, Hed M (2011) Very Tall Wooden Buildings with Cross Laminated Timber. *Procedia Engineering* 14: 1621–1628.

Linders J (2024) *ARUP*. https://www.arup.com/projects/ haut/.

Liven H, Abrahamsen R (2023) Mjostarnet: The World's Tallest Timber Building. In *World Conference on Timber Engineering.* Oslo.

Safarik D, Elbrecht J, Miranda W (2022) State of Tall Timber 2022. *CTBUH Journal* 1: 22–31.

Sotayo A, Bradley D, Bather M, Sareh P, Oudjene M, El-Houjeyri I, et al. (2020) Review of state of the art of dowel laminated timber members and densified wood materials as sustainable engineered wood products for construction and building applications. *Developments in the Built Environment* 1: 1–11.

Stark NM, Cai Z, Carll C (2010) Wood-Based Composite Materials Panel Products, Glued-Laminated Timber, Structural Composite Lumber, and Wood–Nonwood Composite Materials. In *Wood Handbook—Wood as an Engineering Material*. Madison.

Verhaegh R, Vola M, de Jong J (2020) Haut – A 21-storey Tall Timber Residential Building. *International Journal of High-Rise Buildings* 9(3): 213–220.

Wood A, Safarik D, Miranda W, Elbrecht J (2023) *Tall Timber: Mass Timber for High-Rise Buildings.* Chicago: Council on Tall Buildings and Urban Habitat.