

RELATING NON-PHYSICAL WASTE IN LEAN CONSTRUCTION TO CARBON EMISSIONS DURING PROJECT EXECUTION

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ABSTRACT

Lean Construction has been widely applied to improve efficiency and reduce waste in construction projects; however, its relationship with carbon emissions remains predominantly examined from material-based perspectives. This study explores how non-physical waste in Lean Construction such as waiting, downtime, and making-do relates to carbon emissions during project execution. This study employs a structured literature review to synthesize research on Lean–Green construction, focusing on relationships between process-based waste, waste-related outcomes, and carbon-generating activities. The findings indicate that non-physical waste contributes to carbon-relevant impacts through time-based and process-related inefficiencies, including extended activity durations, idle equipment operation, and repeated processes. Rather than causing direct material loss, these waste mechanisms indirectly increase the intensity and duration of carbon-generating activities. As a key contribution, this study proposes a structured analytical framework, including a generalized proxy formulation, to relate non-physical waste to carbon emissions based on additional operational time and activity-level carbon intensity. The framework complements existing material-based carbon assessments and provides a basis for future empirical validation.

KEYWORDS

Lean Construction, Waste, Carbon footprint, Green Construction

INTRODUCTION

Lean Construction has been widely adopted to improve efficiency and reduce waste in construction projects by stabilizing production flow and improving workflow reliability (Ballard & Howell, 1998; Koskela, 2020). Increasing attention has also been directed toward reducing the environmental impacts of construction activities, particularly carbon emissions associated with material use and on-site operations (Denzler et al., 2018; Maraqa et al., 2022). Despite this shared emphasis on waste reduction, Lean Construction and carbon assessment are often examined through different analytical lenses.

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Research on construction-related carbon emissions has largely relied on material-based life cycle assessment approaches, emphasizing emissions from material production, transportation, and installation (ISO 14040; EN 15978). While these approaches provide robust quantification of physical construction waste, they offer limited insight into process-based inefficiencies during project execution. As a result, non-physical waste mechanisms such as waiting, downtime, and making-do are typically discussed in terms of productivity or schedule performance rather than their potential contribution to carbon-generating activities (Formoso et al., 2015; Saurin, 2017).

Recent studies suggest that inefficiencies in construction processes may indirectly influence carbon emissions by extending activity durations, increasing idle equipment use, and intensifying on-site resource use (Denzler et al., 2018; Pozzer et al., 2025). However, Lean-Green integration research often treats environmental benefits as secondary outcomes of improved efficiency, without explicitly clarifying how non-physical waste mechanisms relate to carbon emission pathways (Bajjou & Chafi, 2019; Bajjou & Chafi, 2021). This leaves an analytical gap between Lean Construction waste concepts and carbon-oriented assessment perspectives.

This study focuses on how non-physical waste in Lean Construction can be interpreted in relation to carbon emissions during project execution. It develops a framework that links non-physical waste mechanisms to carbon-relevant outcomes through a literature-driven synthesis. The framework complements existing material-based carbon assessments and contributes to a more integrated understanding of Lean Construction and environmental performance, with reference to the Indonesian construction context.

LEAN CONSTRUCTION WASTE AND CARBON EMISSIONS: A STRUCTURED REVIEW

NON-PHYSICAL WASTE IN LEAN CONSTRUCTION

Lean Construction conceptualizes waste not only as material loss but also as process inefficiencies that disrupt workflow and reduce production reliability (Formoso et al., 2015; Koskela, 2020). Non-physical waste mechanisms, such as waiting, downtime, and making-do, arise from variability, unmet constraints, and coordination failures during project execution (Ballard, 2000; Saurin, 2017). Empirical studies have shown that these forms of waste frequently occur on construction sites and significantly affect workflow continuity and task completion reliability (Igwe et al., 2022). Although these forms of waste do not immediately result in discarded materials, they extend activity durations, increase idle time, and destabilize work sequences.

Previous studies have predominantly examined non-physical waste in relation to productivity, schedule performance, and planning reliability. Waiting is commonly associated with unmet prerequisites, downtime reflects underutilized labor or equipment, and making-do occurs when activities proceed without satisfying required conditions (Saurin, 2021). Recent studies suggest that non-physical waste can indirectly contribute to environmental impacts through increased resource consumption, prolonged equipment usage, and workflow inefficiencies (Alazmi, 2021). While these mechanisms are central to Lean Construction theory and practice, their implications have largely been assessed from an operational perspective, with limited consideration of environmental consequences.

CARBON EMISSIONS DURING CONSTRUCTION PROJECT EXECUTION

Carbon emissions in construction projects are commonly assessed using life cycle assessment frameworks that emphasize material production, transportation, and construction activities (ISO 14040; EN 15978). These approaches provide robust evaluation of physical construction waste

and material-related emissions but tend to treat project execution as an aggregated process. Consequently, emissions associated with extended activity durations, idle equipment operation, or repeated construction processes are often implicit or overlooked (Denzler et al., 2018).

Several studies indicate that inefficiencies during project execution can increase carbon emissions by extending the duration and intensifying on-site carbon-generating activities, even when material quantities remain unchanged (Maraqa et al., 2022; Pozzer et al., 2025). However, existing Lean–Green integration research rarely distinguishes between physical waste and non-physical waste when interpreting environmental impacts (Bajjou & Chafi, 2019; Bajjou & Chafi, 2021).

This limitation highlights the need for an analytical perspective that explicitly links non-physical waste mechanisms in Lean Construction to carbon-related outcomes during project execution. Rather than extending material-based carbon accounting, such a perspective can complement existing approaches by clarifying how process inefficiencies translate into indirect emission pathways. These observations indicate the need for an analytical framework that explicitly relates non-physical waste mechanisms in Lean Construction to carbon-relevant outcomes during project execution.

METHODOLOGY

This study employs a structured, literature-driven approach to develop an analytical framework that relates non-physical waste in Lean Construction to carbon-related outcomes during construction project execution. The methodology is intentionally designed to synthesize existing knowledge rather than to perform empirical measurement or detailed carbon quantification. This approach allows the study to focus on clarifying conceptual and analytical linkages between process-based waste mechanisms and carbon-generating activities.

The methodological process consists of three main steps. First, relevant literature was identified from peer-reviewed journals and conference proceedings, primarily sourced from the Scopus database and the proceedings of the International Group for Lean Construction (IGLC), and further expanded using snowballing techniques. Studies were selected using the PRISMA methodology with defined inclusion and exclusion criteria, resulting in 70 relevant publications (Table 1 & Figure 1). These studies were further assessed based on their relevance to non-physical waste mechanisms, construction-phase activities, and carbon-related considerations, while those focusing exclusively on design-stage assessment or operational energy use were excluded to maintain consistency with the project execution focus.

Table 1: Summary of included and excluded records

Criteria	Inclusion	Exclusion
Publishing year	2001-2025	year $\leq$ 2001
Concepts / keyword	Combines lean and waste concepts, or the three concepts, LC, waste, and carbon	Studies only one of the concepts
Research domain	Focus on the lean construction concept	Other domains than construction

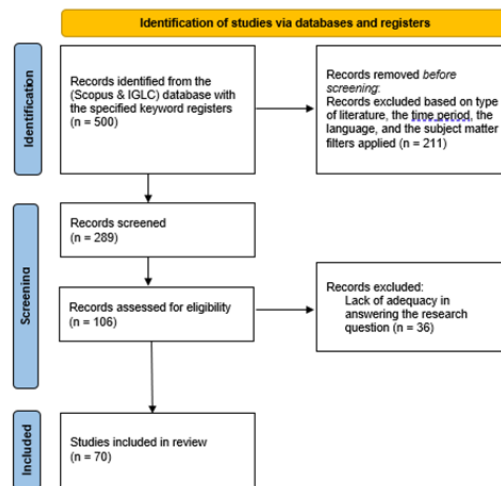


Figure 1: PRISMA Flow

Second, the selected studies were reviewed to identify non-physical waste mechanisms and related outcomes, categorized based on Lean Construction concepts such as waiting, downtime, and making-do, with outcomes including time inefficiencies, productivity losses, and extended resource use. Finally, these findings were synthesized into an analytical framework linking non-physical waste to carbon-related outcomes by emphasizing process duration and activity-level resource intensity, enabling a consistent interpretation of indirect carbon impacts during project execution.

RESULTS & DISCUSSION

TEMPORAL AND REGIONAL CHARACTERISTICS OF LEAN–GREEN CONSTRUCTION RESEARCH

Figure 2 shows a steady increase in publications on Lean Construction and environmental or carbon-related themes, indicating growing interest in integrating efficiency with sustainability. In this figure, the publications are classified based on keyword groupings, including Lean-related terms (Lean, Waste, DOWNTIME) and environmental-related terms (Green, Carbon). This trend is consistent with prior studies highlighting that lean practices contribute to improved environmental performance, particularly through waste reduction and lower carbon emissions (Francis & Thomas, 2020).

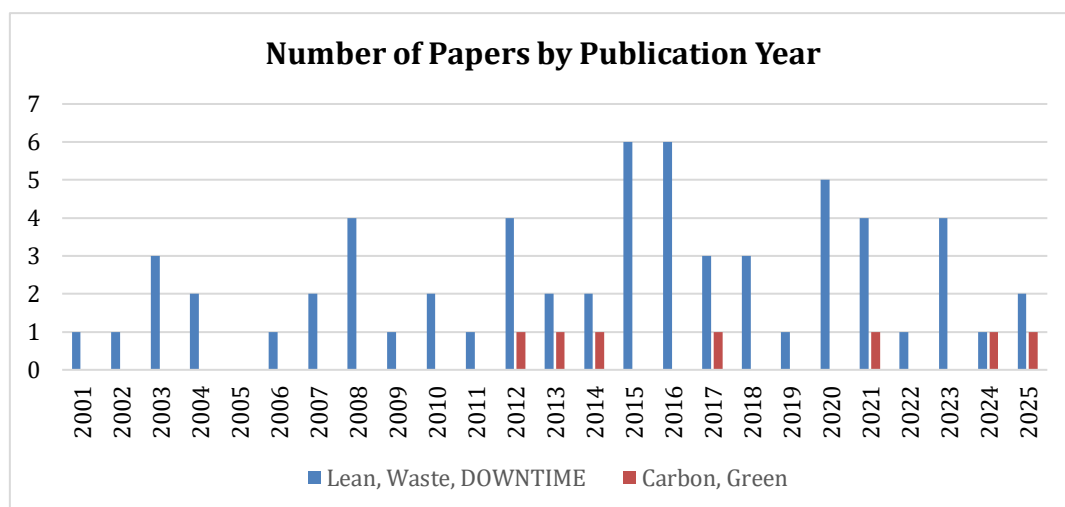


Figure 2: Distribution by publication year

In this study, green construction refers to efforts to minimize environmental impacts throughout the project lifecycle, while carbon mainly relates to greenhouse gas emissions such as CO₂ produced during construction activities. The integration of lean and green approaches is widely associated with improved resource efficiency and reduced carbon footprint (Sarhan & Pretlove, 2021).

In addition, Table 2 shows that many highly cited studies come from regions with well-developed construction research ecosystems. When considered together with Figure 2, this suggests that Lean–Green construction research is increasing over time but is still uneven across regions, with major contributions concentrated in certain areas. This indicates that theoretical and methodological developments are influenced by research capacity and local priorities, which is in line with previous studies stating that the lean–green relationship is still evolving and not yet fully conceptually established (Bhattacharya et al., 2019).

From a methodological perspective, the temporal growth and regional concentration of studies highlight the need to synthesize existing literature to clarify the relationship between Lean Construction and environmental performance. These trends indicate that the field is still evolving and that fragmented insights can be further consolidated into coherent analytical frameworks.

Table 2: Total number of citations by region

Region	Citation
North America	616
Europe (UK, Germany, Denmark, Swedish, Finland, Netherlands, Norway, Luxembourg, France)	664
South America (Brazil, Chile, Portugal)	310
Asia (Taiwan, South Korea, Indonesia, India, Lebanon, Singapore)	183
Oceania (Australia, New Zealand)	198
Africa (South Africa, Nigeria)	9

CONCEPTUAL RELATIONSHIPS BETWEEN LEAN WASTE AND GREEN WASTE

Table 3 presents the synthesized relationships between Lean Construction waste categories and green or environmental waste concepts as reported in the reviewed literature. The table indicates that several forms of non-physical waste particularly waiting, downtime, and making-do are conceptually aligned with environmental waste through their effects on resource utilization and process efficiency. This finding is consistent with studies showing that lean-related inefficiencies influence environmental performance beyond direct material waste (Heravi et al., 2020).

The synthesis shows that waiting and downtime are frequently associated with extended equipment operation, idle energy consumption, and prolonged site presence. These relationships suggest that non-physical waste contributes to environmental impact indirectly by increasing the duration and intensity of carbon-generating activities, even when material quantities remain unchanged. Empirical evidence confirms that idle time and equipment waiting significantly increase fuel use and CO₂ emissions in construction processes (Nguyen et al., 2026).

Table 3 also highlights that existing studies tend to describe these relationships qualitatively, often framing environmental impacts as secondary consequences of operational inefficiency. While the alignment between lean waste reduction and environmental improvement is generally acknowledged, the reviewed literature rarely articulates a clear conceptual framework that distinguishes between physical and non-physical waste in relation to environmental outcomes.

As a result, non-physical waste mechanisms are frequently subsumed under broader efficiency narratives without explicit linkage to environmental waste pathways.

Table 3: Relations between lean and green waste

Lean Waste (Downtime)	Description	Green Waste (Carbon-related impact)
Defects	Rework due to design errors, poor workmanship, or quality nonconformance increases labor hours and equipment operation time (Formoso et al., 2015; Denzer et al., 2018).	Additional embodied carbon from extra material production and increased equipment fuel use during rework activities (A1–A3, A5).
Over production	Producing components earlier or in excess of demand leads to unnecessary processing, handling, and storage (Bølviken & Koskela, 2016; Sarhan et al., 2019).	Embodied carbon locked in unused materials and emissions from storage, handling, and potential disposal (A1–A3, A5).
Waiting	Idle time of labor and equipment due to poor flow, material delays, or coordination issues is a major source of downtime (Kenley & Harfield, 2014; Saurin, 2017).	Prolonged site duration and idling equipment increase fuel consumption and electricity use (A5).
Non-utilized talent	Underutilization of worker knowledge and skills leads to inefficient task execution and repeated errors (Pasquire et al., 2015; Koskela, 2020).	Extended construction duration increases cumulative energy use and indirect carbon emissions (A5).
Transportation	Unnecessary movement of materials caused by poor site layout and fragmented logistics increases handling time (Perez et al., 2016; Cheng et al., 2017).	Increased fuel consumption and transport-related carbon emissions (A4).
Inventory	Excess onsite inventory leads to double handling, deterioration, and additional storage activities (Formoso et al., 2017; Popovic et al., 2019).	Embodied carbon in unused materials and emissions from additional handling and disposal (A1–A3, A5).
Motion	Excessive movement of workers and equipment due to poor layout and sequencing increases non-value-adding time (Aka et al., 2018; Saurin, 2021).	Additional equipment operation increases operational emissions (A5).
Excess processing	Performing unnecessary inspections, over-specification, or redundant activities adds time and energy without increasing value (Denzer et al., 2018; Arroyo & Gonzalez, 2020).	Extra energy use and material consumption increase embodied and operational emissions (A1–A3, A5).

From a results perspective, the relationships summarized in Table 3 demonstrate that non-physical waste occupies a distinct conceptual position within Lean–Green integration research. These waste mechanisms are neither purely operational nor purely environmental; instead, they act as intermediaries that translate process inefficiencies into increased environmental burdens. This finding provides a conceptual basis for further structuring the relationship between non-physical waste and carbon-related outcomes, which is developed through operationalization and measurement logic in the subsequent analysis.

OPERATIONALIZATION OF WASTE-RELATED OUTCOMES AND MEASUREMENT LOGIC

Table 4 summarizes waste-related outcomes and measurement approaches identified in the reviewed literature that are relevant for interpreting the environmental implications of non-physical waste in construction projects. Rather than directly measuring carbon emissions, most studies use time-based and process-related indicators such as delay duration, idle time, productivity loss, and extended equipment operation. These indicators act as a bridge linking non-physical waste to carbon-generating activities, as also highlighted in previous studies on lean–environmental performance relationships (Dieste et al., 2019; Heravi et al., 2020).

The results show that non-physical waste is commonly reflected through temporal inefficiencies. Waiting and downtime lead to additional idle time, while making-do is associated with process instability and rework. Although these impacts are not expressed directly in carbon units, they increase the duration and intensity of energy use, which in turn contributes to higher emissions. This supports prior findings that time inefficiencies in construction significantly influence fuel consumption and carbon output (Abbasian-Hosseini & Leming, 2016; Tabrizikahou & Nowotarski, 2021).

To support this interpretation, waste-related outcomes can be conceptually linked to carbon emissions using a simplified expression that emphasizes operational time and carbon intensity:

$$CF_{npw} = \sum (\Delta t_i \times CI_i)$$

where CF_{npw} represents the carbon impact of non-physical waste, Δt_i is the additional time caused by waste in activity i , and CI_i is the carbon intensity of that activity. This formulation is not intended for precise calculation but serves as an analytical proxy to explain how process inefficiencies translate into increased carbon-generating activities.

The operationalization presented in Table 4 shows that measurable links between non-physical waste and performance outcomes already exist in the literature, but they remain fragmented. By organizing these indicators around time, productivity, and resource intensity, this study provides a clearer structure for interpreting the carbon relevance of non-physical waste without requiring detailed emission data. This approach is consistent with studies advocating simplified models for integrating lean practices with environmental assessment (Bhattacharya et al., 2019; Tafazzoli et al., 2020).

In addition, the inclusion of institutional references such as PLN and KLHK, along with methods like Last Planner System (LPS), Building Information Modeling (BIM), Target Value Design (TVD), and Engineering, Procurement, and Construction (EPC), indicates that Lean–Green relationships are often discussed within regulated and complex project environments. The Indonesian context used in Table 4 therefore provides a relevant example of how non-physical waste operates in energy-intensive and policy-driven settings, offering insights that may also be applicable to similar construction environments in other countries.

Table 4: Waste-related outcome results and measurements

Lean Waste (Downtime)	Result	Measurable outcome	Metrics	Emission Factor
Defects	Scrap (Material production, recycling, disposal)	Energy used to recycle or dispose	m ² , m ³ , kg	Material EF (kgCO ₂ e/kg): Cement, steel, concrete (EPD Indonesia / ICE proxy); Waste treatment EF (kgCO ₂ e/kg) – KLHK
Over production	Storage (More space needed)	Energy used for heating/cooling/lighting space	kWh	Electricity EF PLN (kgCO ₂ e/kWh)
Waiting	Idle labor and equipment	Extended site duration and equipment idling	hour, kWh, L diesel	Electricity EF PLN; Diesel EF (kgCO ₂ e/L)
Non-utilized talent	Inefficient task execution, repeated errors	Extended working hours and indirect rework energy	hour, kWh	Electricity EF PLN; Diesel EF
Transportation	Extra trips, partial loads, return shipments	Fuel consumption and vehicle operation	km, trip, L fuel	Diesel EF (kgCO ₂ e/L); Electricity EF PLN (for EV/hoist)
		Electricity use for site logistics (hoists, tower cranes)	kWh	Electricity EF PLN
Inventory	Double handling, deterioration, disposal	Additional material handling and replacement	kg, kWh	Material EF (A1–A3); Electricity EF PLN
Motion	Extended shifts and equipment runtime	Additional equipment operation energy	hour, kWh, L diesel	Electricity EF PLN; Diesel EF
Excess processing	Redundant inspections, over-specification	Additional processing energy and material use	kWh, kg	Electricity EF PLN; Material EF

LIFE CYCLE BOUNDARY FOR INTERPRETING WASTE-RELATED CARBON OUTCOMES

Figure 3 illustrates the life cycle stages of a building (A1–A5), providing an interpretative boundary for understanding the carbon implications of non-physical waste during construction project execution. Within life cycle assessment (LCA) frameworks, these stages represent a standardized structure for evaluating environmental impacts across material production, transportation, and construction processes (ISO 14040, 2006; EN 15978, 2011). In this study, the life cycle representation is not employed for direct carbon quantification but rather to situate waste-related outcomes within an established conceptual boundary.

The waste-related outcomes and analytical expressions discussed in Section 4.3 are primarily associated with the construction execution phase, particularly within stages A4 (transport to site) and A5 (construction and installation). Non-physical waste mechanisms such as waiting, downtime, and making-do manifest as extended activity durations, repeated operations, and inefficient resource utilization. These process inefficiencies may indirectly influence carbon emissions through increased equipment operation time, additional

transportation activities, and prolonged on-site energy use, consistent with prior studies linking construction processes to emission intensities (Pomponi & Moncaster, 2017; Abanda et al., 2017).

It is important to note that physical construction waste remains the dominant contributor to carbon emissions in conventional LCA studies, particularly in stages related to material production (A1–A3). This study does not seek to replace or replicate material-based carbon accounting approaches. Instead, the life cycle boundary presented in Figure 3 is used to contextualize how non-physical waste-related outcomes expressed through time-based and process-oriented indicators may complement existing assessments by highlighting indirect emission pathways during construction.

By framing non-physical waste impacts within a defined life cycle boundary, this study aligns Lean Construction concepts with established carbon assessment perspectives. This boundary-based interpretation clarifies the scope of the proposed analytical framework in Section 4.2 & 4.3 and ensures that waste-related outcomes are consistently interpreted without extending the analysis beyond its intended conceptual and methodological limits.

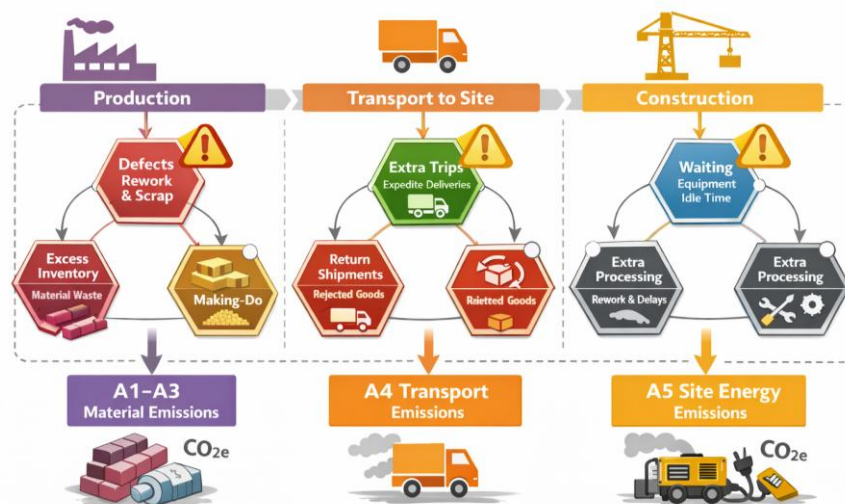


Figure 3: Life cycle stages of a building (A1–A5) to contextualize waste-related carbon outcomes in construction.

CONCLUSION

This study examined the relationship between non-physical waste in Lean Construction and carbon emissions during project execution through a structured synthesis of existing literature. By focusing on non-physical waste mechanisms such as waiting, downtime, and making-do the study addressed an underexplored aspect of Lean–Green integration that is often overlooked in conventional material-based carbon assessments.

The results demonstrate that non-physical waste contributes to carbon-relevant outcomes primarily through process-related inefficiencies that extend activity durations and increase the intensity of resource use. Rather than causing direct material loss, these waste mechanisms indirectly increase carbon emissions by prolonging equipment operation, energy consumption, and on-site construction activities. The generalized analytical expression proposed in this study provides a consistent proxy for interpreting how non-physical waste may translate into increased carbon-generating activity without relying on detailed material inventories or project-specific emission data.

By situating waste-related outcomes within a life cycle boundary, this study clarifies the scope and applicability of non-physical waste considerations in carbon-oriented analyses. The

proposed framework is intended to complement existing life cycle assessment and sustainability evaluation approaches by offering a structured perspective on process-driven emission pathways during construction project execution. This contribution supports a more integrated understanding of Lean Construction and environmental performance, while maintaining clear methodological boundaries.

Several limitations should be acknowledged. The framework is derived from literature synthesis and does not involve empirical validation or quantitative carbon calculation. Additionally, the analysis focuses on non-physical waste and does not address physical construction waste, which remains the dominant contributor to construction-phase carbon emissions. Future research may extend this work by empirically testing the proposed framework, integrating project-level data, or exploring the combined effects of physical and non-physical waste within comprehensive carbon assessment models.

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