Marxen, M. V., Hansen, A. H., Pedersen K. B., & Wandahl. S. (2026). Validating location-based carbon emissions forecasting. In F. Hamzeh, M. Poshdar, N. P. Garcia-Lopez, & V. Gan (Eds.), *Proceedings of the 34th Annual Conference of the International Group for Lean Construction* (IGLC34) (pp. 558–568). https://doi.org/10.24928/2026/0277

VALIDATING LOCATION-BASED CARBON EMISSIONS FORECASTING

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ABSTRACT

Following previous papers regarding quantifying and planning greenhouse gas (GHG) emissions using Location-Based Scheduling (LBS), this research seeks to validate the previously defined methodology. By implementing the defined methodology on a real-world construction project (an actual dataset), this paper assesses its accuracy and discusses the key factors in forecasting carbon emissions using LBS. This research identifies the need for accurate usage factors [U_{usage}] of the machinery (i.e. percentage of time machines are actively used) on site. In the literature (For Construction Pros, 2009), such usage factors were previously defined as ranging from 40% to 80%. However, that range has proven to be an oversimplification, and the usage factors depend heavily on the type of machinery and the nature of the related schedule activity. Using accurate on-site machinery usage factors, the LBS method for forecasting GHG emissions deviates by 9% from the actual emissions measured in the case project. This accuracy is significantly better than other methods, e.g., those using generic data such as BUILD data (BUILD, 2024), which deviate by 32% from the actual emissions measured for the project. In accordance with previous papers in the series on quantifying and planning GHG emissions using LBS, this paper focuses on the A5 phase of the LCA and excludes emissions from waste and transportation.

KEYWORDS

Location-based Management System (LBMS), Location-based Scheduling (LBS), Takt Planning (TP), environment, Greenhouse Gas (GHG) emissions, forecasting.

INTRODUCTION

Denmark's Climate Act includes the goal of a 30% reduction in total national GHG emissions, expressed in CO_2-equivalents (CO_2e) by 2030. One of the main contributors to total national GHG emissions is the construction industry, which accounts for approximately 15% of total national GHG emissions (5.600.000 tons CO_2e) (The Danish Energy Agency, 2023).

Even though the construction industry is highly resource-intensive and emissions need to be minimized across all phases, there has historically been a focus on operational-phase emissions of buildings.

Consequently, the Danish Ministry has recently (effective from 1st of June 2025) made it mandatory, under the Danish Building Regulations (BR18), to include A4+A5 emissions in

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Life Cycle Assessments (LCA) when documenting the CO2e of a large Danish building project (+1.000 m2). The A4+A5 phase of the LCA includes both the transport of building materials and construction-site activities (Kanafani, Magnes, Garnow, Lindhard, & Balouktsi, 2023).

Failing to comply with the BR18 requirements (threshold values for maximum emission) will entail denied occupation permit – it should be noted that in the time of writing it is not yet announced how an exceeding of the threshold values will be handled exactly, however a likely scenario is an economical penalty, as a continued denied occupation permit will render a building project unusable, which is not sustainable in any ways.

This new requirement necessitates forecasting A5 emissions to ensure that a building project can be initiated with certainty of obtaining an occupancy permit and avoiding economic penalties. However, the Danish Social and Housing Agency (2025) did not provide any estimation methodology. Anyone wanting to forecast the CO_2e of a construction project is referred to do so using BUILD data (average consumption rates based on excerpted projects) and the generic emissions factors provided by the Danish Social and Housing Agency (ibid.). However, as shown below, that method can be linked to a larger uncertainty (32%). The previously mentioned option and approximation by even more generic or experience values are the only existing carbon approximation or forecasting models.

Since A5 covers the on-site construction production, it is relevant to utilize Lean tools to minimize on-site construction waste by optimizing resource allocation and construction flows through planning decisions. Consequently, the LBS method proposed in previous research (Pedersen et al. 2024, Pedersen et al. 2025) is proposed as a potential alternative method for forecasting A5 emissions, as it is associated with lower uncertainty (5%). However, as discussed below, it is very sensitive to the accuracy of the usage factors $[U_{usage}]$ of all machinery used on-site, and sufficient data for such machinery usage factors does not yet exist.

Location-Based Scheduling (LBS) is a Lean scheduling tool (Huovila, P., & Koskela, L. 1998.; Seppänen, O., Modrich, R. & Ballard, G. 2015) that eliminates waste and optimizes workflow by planning and tracking work, activity-by-activity and location-by-location, providing the enhanced overview of resource alignment that Lean-based project management requires. Lean production principles have been proven to reduce waste and improve process performance in complex construction environments (Lapinski et al., 2006).

Building on Pedersen et al. (2025), who demonstrated theoretically how LBS could optimize construction-phase energy consumption, this paper provides a proof of concept and a preliminary assessment of the accuracy of LBS-based forecasting of A5 GHG emissions, as well as the factors that most influence it. The contribution comprises an empirical validation on an actual dataset and a practical analysis of the role of machinery usage factors.

While a full A4+A5 analysis would be desirable, constraints in time and data availability have forced the authors to delimit the scope of this study to the A5 phase. Transport (A4) and waste-related emissions, therefore, fall outside the scope of this study and are left for future research.

METHOD

To evaluate the accuracy of using LBS for forecasting CO_2e emissions, as described by Pedersen et al. (2024, 2025), the method is applied to an actual completed building construction project in which all carbon emissions were measured on-site during the construction execution phase. Likewise, the method of forecasting CO_2e based on BUILD data is applied to the project. This is done to investigate how LBS-based CO2e forecasting performs compared to using BUILD data for CO2e forecasting.

LBMS FOR FORECASTING CO2*e*

As defined in Pedersen et al. (2024, 2025) the total quantity of CO2e in phase A5 (excluding transportation and waste emissions) can be calculated as:

Total quantity of CO_2e in phase A5 (excluding transportation and waste emissions)

$$\boldsymbol{GWP = E_{electric} \cdot I_{electricity} + E_{fuel} \cdot I_{fuel}} \quad (1)$$

It is noted that both district heating and gas are excluded below; however, both sources can be added in eq.(1) in the same way as the electrical part.

Where:

All electric emission contributors

$$E_{electric} = \sum E_{electric_heating} + \sum E_{electric_drying} + \sum E_{electric_lighting} + \sum E_{electric_machinery} \quad (2)$$

$$E_{electric_heating} = N_{winter_days} \cdot A_{gf} \cdot C_{heating} \quad (3)$$
$$E_{electric_drying} = N_{drying_days} \cdot A_{gf} \cdot C_{drying} \quad (4)$$
$$E_{electric_lighting} = N_{days} \cdot A_{gf} \cdot C_{ligting} \quad (5)$$
$$E_{electric_machinery} = \sum(N_{hours} \cdot U_{usage} \cdot N_{machinery} \cdot C_{electric_machinery}) \quad (6)$$

$A_{gf} = Gross\ floor\ area$

$N_{winter_days} = total\ number\ of\ days\ requiring\ heating$
$N_{drying_days} = total\ number\ of\ days\ requiring\ drying$
$N_{days} = total\ number\ of\ days\ requring\ lighting$

$C_{heating} = base\ energy\ consumption\ per\ sqm.\ for\ heating\ per\ day$
$C_{drying} = base\ energy\ consumption\ per\ sqm.\ for\ drying\ per\ day$
$C_{ligthing} = base\ energy\ consumption\ per\ sqm.\ for\ lighting\ per\ day$

$I_{electricity} = emmision\ factor\ for\ electricity\ (source\ specific)$

Where:

All fuel emission contributors (machinery only)

$$E_{fuel} = \sum(N_{machinery} \cdot N_{hours} \cdot U_{usage}) \cdot ((C_{fuel\ machinery\ passive} \cdot U_{idling\ passive}) + (C_{fuel\ machinery\ active} \cdot U_{idling\ active})) \quad (7)$$

$N_{machinery} = number\ of\ machines$
$N_{hours} = total\ number\ of\ planned\ operational\ hours$
$U_{usage} = machine\ usages\ factor$

$C_{fuel\ machinery\ passive} = machine\ base\ fuel\ consumption$
$U_{idling\ passive} = machine\ idling\ factor$
$C_{fuel\ machinery\ active} = machine\ base\ fuel\ consumption$
$U_{idling\ active} = machine\ idling\ factor$

$I_{fuel} = emmision\ factor\ for\ electricity\ (type\ specific)$

Below results from using the method on an actual case is described.

CALCULATION (LBMS)

Project data

A_{gf}	576	m^2
N_{winter_days}	169	Days
N_{drying_days}	43	Days
N_{days}	299	Days

Electric

$C_{heating}$	0,3098	kWh/m²/d
C_{drying}	0,0853	kWh/m²/d
$C_{ligthing}$	0,0656	kWh/m²/d
$E_{electric_heating} = N_{winter_days} \cdot A_{gf} \cdot C_{heating}$	30.176,64	kWh
$E_{electric_drying} = N_{drying_days} \cdot A_{gf} \cdot C_{drying}$	2.112,99	kWh
$E_{electric_lighting} = N_{days} \cdot A_{gf} \cdot C_{ligting}$	3.102,05	kWh
$E_{electric} = \sum E_{electric_heating} + \sum E_{electric_drying} + \sum E_{electric_lighting}$	35.391,68	kWh

Fuel

Machine 1 (Excavator)

$N_{machinery}$	1	Pcs
N_{hours}	322,5	h
U_{usage}	12	%
$C_{fuel\ machinery\ passive}$	1,7	L/h
$U_{idling\ passive}$	30	%
$C_{fuel\ machinery\ active}$	8,0	L/h
$U_{idling\ active}$	70	%
$E_{fuel_machine1} = ((N_{machinery} \cdot N_{hours} \cdot U_{usage}) \cdot ((C_{fuel\ machinery\ passive} \cdot U_{idling\ passive}) + (C_{fuel\ machinery\ active} \cdot U_{idling\ active}))$	236,46	L

Machine 2 (Mobile crane)

$N_{machinery}$	1	Pcs
N_{hours}	150	h
U_{usage}	50	%
$C_{fuel\ machinery\ passive}$	8,6	L/h
$U_{idling\ passive}$	51	%
$C_{fuel\ machinery\ active}$	28	L/h
$U_{idling\ active}$	49	%
$E_{fuel_machine2} = ((N_{machinery} \cdot N_{hours} \cdot U_{usage}) \cdot ((C_{fuel\ machinery\ passive} \cdot U_{idling\ passive}) + (C_{fuel\ machinery\ active} \cdot U_{idling\ active}))$	1357,95	L

Machine 3 (Mini loader)

$N_{machinery}$	1	Pcs
N_{hours}	307,5	h
U_{usage}	5	%
$C_{fuel\ machinery\ passive}$	1,5	L/h
$U_{idling\ passive}$	25	%
$C_{fuel\ machinery\ active}$	2,2	L/h
$U_{idling\ active}$	75	%
$E_{fuel_machine3} = ((N_{machinery} \cdot N_{hours} \cdot U_{usage}) \cdot ((C_{fuel\ machinery\ passive} \cdot U_{idling\ passive}) + (C_{fuel\ machinery\ active} \cdot U_{idling\ active}))$	31,13	L

Machine 4 (Pile driver)

$N_{machinery}$	1	Pcs
N_{hours}	165	h
U_{usage}	4	%
$C_{fuel\ machinery\ passive}$	4,5	L/h
$U_{idling\ passive}$	53	%
$C_{fuel\ machinery\ active}$	25	L/h
$U_{idling\ active}$	47	%

$E_{fuel_machine4} = ((N_{machinery} \cdot N_{hours} \cdot U_{usage}) \cdot ((C_{fuel\ machinery\ passive} \cdot U_{idling\ passive}) + (C_{fuel\ machinery\ active} \cdot U_{idling\ active}))$	233,23	L
$E_{fuel} = E_{fuel_machine1} + E_{fuel_machine2} + E_{fuel_machine3} + E_{fuel_machine4}$	1.858,77	L
Emission factor		
$I_{electricity}$ (National value from Denmark 2025)	0,135	$kgCO_2e/kWh$
I_{fuel}	3,112	$kgCO_2e/L$
Forecasted CO2e emission		
$\boldsymbol{E_{electric} \cdot I_{electricity} + E_{fuel} \cdot I_{fuel}}$	10.562,37	$kgCO_2e$
Measured (on-site) CO2e emission:	9.674,44	$kgCo_2e$
Difference	*+887,92*	*$kgCo_2e$*
	(+9,18)	(%)

CASE AND RESULTS

The case project is a multi-story timber building. The building has a total calculated gross floor area of 577 m² and comprises five stories, with an average floor area of approximately 120 m² per story. The case project was selected because it comprised enhanced documentation, planning, and management of CO_2e emissions during the construction phase.

The project case is specifically used to validate the proposed method for forecasting CO_2e emissions during the construction phase. The method is based on a linkage between the project schedule, individual construction activities, and the associated resource consumption, including the use of machinery, fuels, and temporary energy consumption on the construction site. This activity-based approach enables more detailed, project-specific estimation of CO_2e emissions compared to traditional average-based methods, which often rely on standardized emission factors that lack a direct relationship to the actual construction process.

In the case study, access was available to key planning data, including the construction schedule used for execution, activity descriptions, and actual consumption data for relevant resources. This data foundation has enabled comparison of estimated CO_2e emissions with calculations based on actual consumption.

To test the method, the construction schedule and all associated data were entered into Tactplan, a location-based scheduling software, to assign CO_2e emissions to the relevant activities. The original construction schedule was not a location-based schedule; for this reason, optimization opportunities can be identified immediately, but it has been out of scope for this research. The schedule used for the estimate is shown in Figure 1; only activities that cause CO_2e emissions are included.

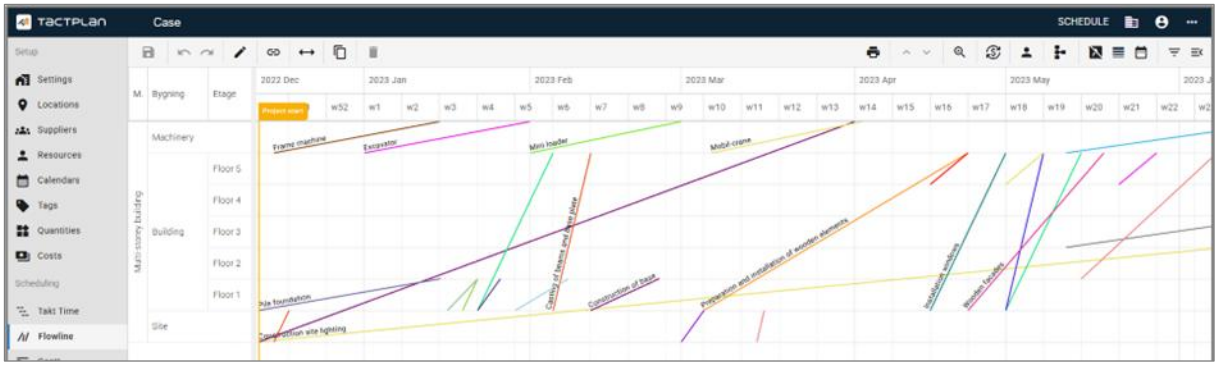

Figure 1: As-built location-based construction schedule with machinery resources linked to scheduled activities.

After loading the schedule activities with CO_2e emissions data, a PowerBI dashboard was used to calculate planned vs. actual CO_2e emissions as shown in Figure 2.

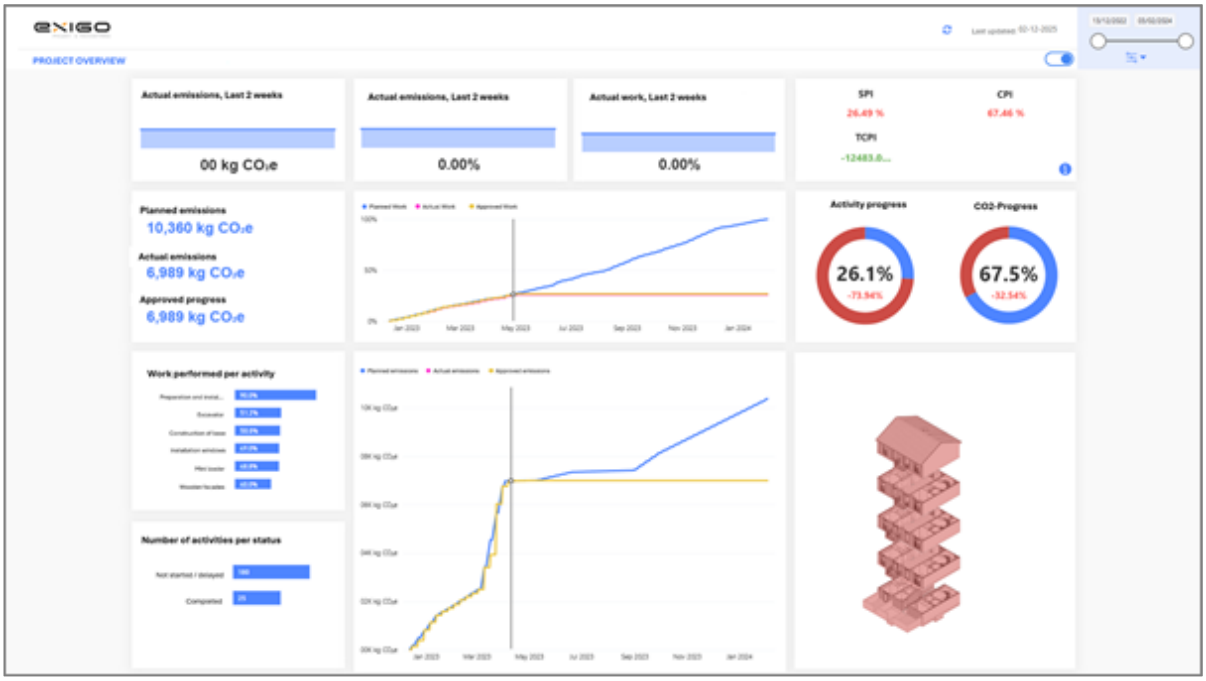

Figure 2: Tracking of CO2e emissions (simulation date may, 2025) (yellow line: actual emission, blue line: forecasted emission)

COMPARISON WITH BUILD DATA FOR FORECASTING CO2*e*

The Danish Building Regulation (30.01.2026) and the associated guide (Danish Social- and Housing Agency, 2025) provide only the threshold values of the maximum emissions allowed for phase A4+A5 (see Table 1). Consequently, no methodology for forecasting CO2e is provided. However, it does provide the emission factors for electricity and heating (Danish Building Regulations (BR18), Appendix 2, Tables for chapter 11 - Energy consumption, Table 8.1) and for fuel sources (ibid., Table 8.2). Consequently, one needs to identify expected electricity consumption (and/or other heating sources) and fuel consumption to forecast CO2e for the A5 phase. The Danish Social- and Housing Agency has been very explicit regarding the fact that the threshold values were determined based on a research project regarding resource consumption on the construction site (BUILD, 2024). Consequently, it is reasonable to assume that using the average on-site consumptions identified in that research project is legitimate when

forecasting against the threshold values. Accordingly, the electric consumption per sqm. gross floor of $38kWh/m^2$ and diesel consumption per sqm. gross floor of $2\ liter/m^2$ are used as approximation values (ibid.).

Total quantity of CO2e in phase A5 (excluding transportation and waste emissions) can be calculated with this approximate method according to (BUILD, 2024):

$$GWP = E_{electric} \cdot I_{electricity} + E_{fuel} \cdot I_{fuel} \quad (1)$$

Where:

All electric emission contributors

$$E_{electric} = E_{electric_consumption} \cdot A_{gf}$$

$$E_{electric_consumption} = electric\ consumptions\ per\ sqm.gross\ floor \quad (2)$$

$$A_{gf} = Gross\ floor\ area$$

$$I_{electricity} = \ emmision\ factor\ for\ electricity\ (source\ specific)$$

All fuel emission contributors

$$E_{fuel} = E_{fuel_consumption} \cdot A_{gf} \quad (3)$$

$$E_{fuel_consumption} = fuel\ consumptions\ per\ sqm.gross\ floor$$

$$I_{fuel} \ = \ emmision\ factor\ for\ electricity\ (type\ specific)$$

CALCULATION (BUILD)

Build data

$E_{electric_consumption}$	38	kWh/m^2
$E_{fuel_consumption}$	2	L/m^2
Forecasted CO2e emission		
$\boldsymbol{E_{electric} \cdot I_{electricity} + E_{fuel} \cdot I_{fuel}}$	6.543,79	kgCO$_2$e
Measured (on-site) CO2e emission:	9.674,44	kgCo$_2$e
Difference	3.130,65	*kgCo$_2$e*
	(-32,36)	(%)

DEVIATION

The objective goal is to lower the deviation (difference between forecasted and measured on-site) as it reflects accurate forecasts, and (assuming that the measurements are reliable and valid), thereby ensuring correct data for decision making. While zero deviation may be theoretically possible (e.g., machinery use varies from person to person), the goal is to get as close as possible. A sub-10% deviation is consequently much more acceptable than a 30+% deviation; however, there is still room for improvement by collecting further data on machinery usage factors, etc.

DISCUSSION

EMPIRICAL DISCUSSION

The total planned operational hours are easily extracted from the LBS schedule. However, if a machine is planned to be operational for a full working day, it rarely is not.

For this specific project, the usage factor (U_{usage}) for some machines was as low as 5%, meaning the specific machine was in use only 5% of the planned duration (including idle time). The usage factor, of course, depends heavily on the type of machine and task. A mobile crane, for instance, is much more likely to be utilized more intensively and continuously for craning

activities than a mini loader is for material handling activities or earthworks and ground preparation activities. It also depends heavily on the nature of the scheduled activity. Meaning that if a scheduled activity is scheduled to start Monday at 8 am and end Tuesday at 4 pm, because the grading and leveling, which requires a mini loader, is required to happen in that time window, the total activity duration is 2x8 = 16 working hours. On the other hand, if the same scheduled activity is scheduled to start Monday 10 am and stop 1 pm and restart Tuesday at 10 am and finish at 1 pm, because that is the exact hours needed for the mini loader crew to complete the level and grading task, the total activity duration is 3+3 = 6 hours.

The first way of scheduling is the easiest and often sufficiently accurate, whereas the second requires much more detailed coordination and results in a much larger task schedule and management effort. Consequently, many scheduled activities will, to some extent, reflect the time window during which the task needs to occur, rather than the actual hours required. In such cases, it becomes crucial to evaluate the machinery usage factor for a given activity, i.e., how many of the planned hours (activity duration) the machine is in use (including idling time).

If generic and imprecise usage factors (e.g. $U_{usage} = 60\%$ cf. Pedersen, et al. 2025; For Construction Pros, 2009) are utilized, the total forecasted fuel consumption will be much higher than the actual usage and thus corrupt the overall forecast accuracy.

Forecasted CO2e emission (using false U_{usage}):	**21.411,07 kgCo_2e**	
Measured (on-site) CO2e emission:	9.674,44 kgCo_2e	
Difference:	*+11.736,63 kgCo_2e*	*(+121,32%)*

Consequently, LBS CO2e forecasting can be both more and less accurate than an approximation based on BUILD data, and the outcome largely depends on the accuracy of the usage factor for specific machinery.

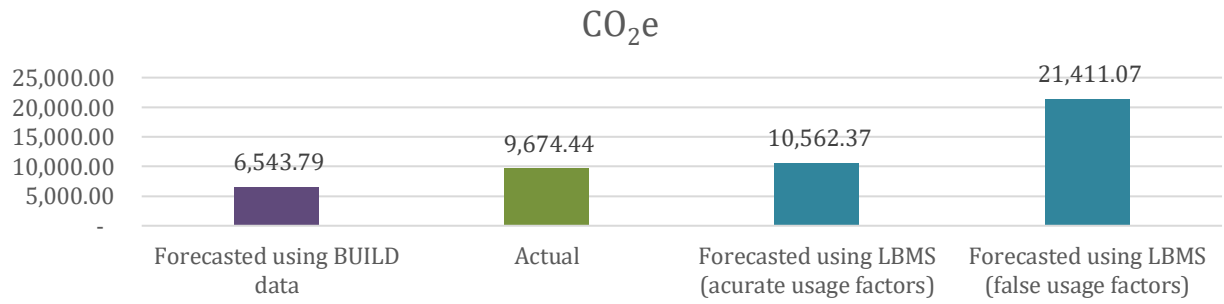

Figure 3: Overview of forecasted vs. actual CO_2e on the case project

The same conclusions apply to the machinery idling factors. However, a much more extensive dataset regarding machine idling has been available to the authors.

THEORETICAL DISCUSSION

Lean Construction seeks to eliminate waste and optimize workflow by making resource use and work sequences explicit throughout the project. Lean construction principles directly support sustainable development by minimizing unnecessary resource consumption and improving the predictability and flow of work on site (Huovila and Koskela, 1998). Location-Based Scheduling is a Lean scheduling tool (ibid.; Seppänen, O., Modrich, R. & Ballard, G. 2015) that eliminates waste and optimizes workflow by planning and tracking work, activity-by-activity and location-by-location, providing the enhanced overview of resource alignment that Lean-based project management requires. Consequently, if Lean processes and LBS are applied efficiently on a construction project execution, the waste and CO2e of the construction execution can be reduced (Lapinski, A.R., Horman, M.J., & Riley, D.R. 2006). Therefore, by

using LBS to forecast and track CO2e, sufficient project management decisions can be made to ensure that the CO2e threshold values aren't exceeded.

Systematically collecting and refining machinery usage factors align with the broader Lean principle of continuous improvement, whereby data gathered on-site is used iteratively to reduce waste and improve process performance (Chen, Y., Qiu, D., & Chen, X. 2024).

IMPACT DISCUSSION

This study suggests that integrating carbon forecasting into LBS can strengthen Lean scheduling by enabling project managers to make environmentally informed planning decisions. By linking activity-level resource use to emissions, LBS becomes not only a tool for workflow optimization but also a practical approach to managing CO_2e performance throughout the project.

Planners and contractors can further support this by consistently linking machinery to LBS activities and comparing planned versus actual use through existing sensor-based monitoring. When this usage-factor data is collected and reviewed regularly, just like schedule progress or resource utilization, it naturally becomes part of Lean continuous improvement, enabling teams to identify waste, refine workflow planning, and enhance the accuracy of future carbon and productivity forecasts.

Finally, the findings explicitly reinforce Lean concepts by demonstrating how making resource use visible reduces variability and exposes hidden waste such as idle time and inflated activity durations. In doing so, LBS-based carbon forecasting aligns with Lean thinking, supporting flow, transparency, and ongoing improvement in both production and environmental performance.

REQUIRED FUTURE DEVELOPMENT

For LBS to achieve sufficient accuracy in forecasting CO2e for building construction projects, sufficient data on machinery usage factors must be collected.

The contractor of the case project has collected extensive data on machinery idling. This has been done to investigate and minimize the idling time of all on-site machinery. The reason is that a machine in idle mode consumes fuel, which is both a direct cost and a source of emissions. Consequently, tracking and minimizing machine idle time is a tangible way to reduce both environmental impact and costs.

However, regarding the machinery usage factor (actual versus planned usage), the contractor on the case project had virtually no data available. Collecting and investigating actual machine usage time versus planned usage time does not reduce the project's cost or minimize its environmental impact.

In other words, the project scheduler is satisfied when the construction schedule deadlines are met, i.e., the on-site work is executed within the planned durations. And the person responsible for sustainability is satisfied when machinery is used as efficiently as possible on-site (with the lowest possible idle time). Consequently, there is no incentive to track and compare actual machinery usage against planned usage (activity duration).

Furthermore, the machinery usage factor, for which the industry currently lacks data, is project-specific (i.e., dependent on the nature of the scheduled activities) and virtually unimportant in any other context. Consequently, the effort required to collect data to calculate the machinery usage factor must be minimal to make it feasible.

Currently, the contractor on the case project is using LBS scheduling software, which can allocate resources to any location task. Until now, the contractor has used this feature only to schedule and forecast personnel (work gangs), as they have been the project's critical resources. It is assumed that the critical dependencies of machinery have been managed manually/separately from the schedule. Also, the contractor for the project currently collects

extensive data on machine usage time (including idling time) using IoTs and sensors. Consequently, if the contractor simply began assigning machinery resources to the construction schedule, a data link between the planned and actual machinery usage would be established, allowing the contractor to calculate the utilised machinery's usage factor.

As this data link is created and data collection increases, so does the ability to identify specific machine usage factors across different contexts, i.e., projects, schedules, machines, and activity types.

Table 1: Threshold values defined in the Danish National Building Regulations 2025

Year	Threshold values (A4+A5)	Low emissions class (A4+A5)
2025	1,5 $kgCO_2e/m^2/year$	1,1 $kgCO_2e/m^2/year$
2027	1,3 $kgCO_2e/m^2/year$	1,0 $kgCO_2e/m^2/year$
2029	1,1 $kgCO_2e/m^2/year$	0,9 $kgCO_2e/m^2/year$

Note that threshold values include A4 (transport) and waste and are therefore not directly comparable to the results presented in this paper.

CONCLUSIONS

The LBS method holds great potential for forecasting CO2e of a construction project execution phase (A5, excluding on-site waste), however, it is currently limited by a lack of data on machinery usage factors. This finding is in accordance with the Lean theory that machinery emissions as a central concern, and for emission targets to be embedded in early planning decisions (Tetik, M., Pikas, E., Koskela, L. and Vendel, K. 2025).

In order to collect sufficient data for estimating the machinery usage factors, contractors need to:

(a) Include all machinery as resources for relevant activities in an LBS construction schedule.

(b) Monitor the actual usage of machinery on-site (including idling time).

(c) Compare (a) against (b) to calculate machinery usage factors on a sufficiently large dataset.

Some contractors currently lack both step (a) and (b), some lack either (a) or (b) – as is the case with the contractor of the case project, who is currently missing step (a).

Currently, strong incentives exist to implement step (b), as it can directly minimise fuel consumption, thereby reducing both costs and environmental impact.

Regarding step (a), technology must be an enabler. It must be sufficiently easy to allocate machinery as resources in the LBS scheduling software, as no major incentive exists for implementing this step other than accurate forecasting of the A5 phase's CO2e.

Finally, the contractors need to experience the necessity for step (c), which will arrive when the need for accuracy in forecasting the CO_2e becomes sufficiently high, contractors must abandon forecasting using BUILD data. This will happen as the threshold values are lowered in the BR18 in the coming years (Danish Social- and Housing Agency, 2025).

From a practical standpoint, the method offers contractors a structured approach for integrating carbon considerations into everyday planning by linking machinery to schedule activities and comparing planned versus actual use. This creates a feasible pathway for embedding CO_2e tracking into routine project management without major changes to existing workflows. At the same time, the findings show that the approach can support emerging Lean-and-Green planning frameworks by enabling more accurate forecasting, improving resource alignment, and identifying operational waste, both in production flow and emissions. More broadly, the findings show how environmental performance metrics can be

operationalized within Lean planning systems, offering a foundation for expanding Lean Construction research toward integrated carbon-aware production control.

This research contributes to Lean Construction theory by demonstrating how the accuracy of machinery usage-factor data fundamentally affects the reliability of activity-based carbon forecasting within Location-Based Scheduling (LBS). By making resource behaviour explicit and measurable, the method strengthens core Lean principles such as flow reliability, waste reduction, and production transparency. In doing so, the study extends Lean theory into the environmental domain, showing that carbon forecasting can become a natural extension of Lean's focus on minimizing variability and non-value-adding work.

REFERENCES

BUILD. (2024). *Evaluering af den frivillige bæredygtighedsklasse*. Institut for Byggeri, By og Miljø. Aalborg University, BUILD.

Danish Social- and Housing Agency. (2025). *Guidance to the Danish Building Regulations (BR18) – A4 + A5 documentation*. Copenhagen: Social- og Boligstyrelsen.

For Construction Pros. (2009). *Utilization 101*. Retrieved May 15th, 2025, from https://www.forconstructionpros.com/rental/article/10116913/utilization-101

Huovila, P., & Koskela, L. (1998, August). *Contribution of the principles of Lean construction to meet the challenges of sustainable development*. In Proceedings IGLC (Vol. 98).

Kanafani, K., Magnes, J., Lindhard, S. M., & Balouktsi, M. (2023). *Carbon Emissions during the Building Construction Phase*: A Comprehensive Case Study of Construction Sites in Denmark. Sustainability, 15(14), Article 10992. https://doi.org/10.3390/su151410992

Lapinski, A.R., Horman, M.J., & Riley, D.R. (2006*). Lean Processes for Sustainable Project Delivery*. Journal of Construction Engineering and Management, 132(10), 1083–1091

Chen, Y., Qiu, D., & Chen, X. (2024*). Integrating Lean construction with sustainable construction: Drivers, dilemmas and countermeasures*. Sustainability, 16(21), Article 9387.

Pedersen, K.B., Stefankovics, G., Nachev, S.P. & Wandahl, S. (2024). *Quantifying and planning carbon emissions in construction with location-based scheduling.* Proceedings of the International Group for Lean Construction (IGLC33).

Pedersen, K. B., Marxen, M. V., Hansen, A. H., & Wandahl, S. (2025). *Method for Estimating and Planning Carbon Emissions.* Proceedings of the International Group for Lean Construction (IGLC33).

Seppänen, O. (Ed.), Koskela, L., & Murata, K. (2025). *Shaping the future of construction : Proceedings of the 33rd Annual Conference of the International Group for Lean Construction*. (Annual Conference of the International Group for Lean Construction, IGLC). International Group for Lean Construction (IGLC). https://iglc.net/Papers/Conference/35

Seppänen, O., Modrich, R. & Ballard, G.. (2015*). Integration of Last Planner System and Location-Based Management System*. In Seppänen, O., González, V. A., & Arroyo, P. (Eds.), 23rd Annual Conference of the International Group for Lean Const. (pp. 123–132).

Tetik, M., Pikas, E., Koskela, L. and Vendel, K. (2025). *Construction Site Emissions: Exploring Sustainable Practices*. In O. Seppänen, L. Koskela, & K. Murata (Eds.), Proceedings of the 33rd Annual Conference of the International Group for Lean Cons.(IGLC33) (pp. 1208–1218).

The Danish Building Regulation. (2026). *BR18 – Danish Building Regulations.* Copenhagen.

The Danish Energy Agency. (2023). *Denmark's Global Climate Impact – Global Report.* Retrieved January 30th, 2026from https://ens.dk/media/4871/download

Wahedi, H., Lind, K., & Haugbølle, K. (2024). *Evaluering af den frivillige bæredygtighedsklasse.* Institute for Byggeri, By og Miljø (BUILD), Aalborg Universitet. BUILD Rapport Bind 2024 Nr. 06.