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QUANTIFYING AND PLANNING CARBON EMISSIONS IN CONSTRUCTION WITH LOCATION-BASED SCHEDULING

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ABSTRACT

Many countries focus on limiting greenhouse gas (GHG) emissions, such as carbon dioxide, which also impacts the construction industry. The most forward-thinking countries have already enforced regulations on the maximum allowed emission from new buildings. Regarding building lifecycle stages after EN15978, the regulations primarily target product and usage stages, neglecting construction process emissions. This oversight is concerning as material innovations reduce product emissions, shifting the need for optimization to the construction stage.

This study quantifies construction emissions, optimizing GHG during construction using the Location-Based Management System (LBMS) method. It incorporates construction-related emissions and uses a Location-Based Schedule, calculating anticipated kilowatt-hours (kWh) usage per location with data from various sources. Tested on three cases—residential building, office renovation, and medical facility—the method shows varied results based on project size, complexity, and LBMS introduction time.

Findings indicate a potential 42% CO_2 reduction in the scenario with the longest construction time. The study identifies site emission rates surpassing the 2023 limit over 30 years, underscoring the importance of comparing planned and realized schedules. Given climate regulations until 2050, the research deems the quantification method crucial for accurately addressing construction site emissions.

KEYWORDS

Location-based Management System (LBMS), Takt Planning (TP), environment, greenhouse gas emissions (GHG), planning

INTRODUCTION

The Climate Act in Denmark, where the research is conducted, aligns with the Paris Agreement's aim to limit the rise in global temperature. Denmark targets a 50-54% emission reduction by 2025, 70% by 2030, and climate neutrality by 2050. However, the building industry, responsible for approximately 39% of global greenhouse gases (GHG) (UNEIEA, 2017), is often overseen in the green transition, which poses a challenge to achieving the

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ambitious targets. Historically, efforts to reduce GHG from buildings have mainly been focused on the use face, i.e., Operational Energy (OE), as it constitutes the majority of lifecycle energy use. However, in recent years, the emissions due to Embodied Energy (EE), i.e., the energy used for extraction of raw materials, processing into building materials, transportation, and on-site construction, have started to gain focus (Wandahl et al., 2021). Recognizing the slow pace of industry change, strategies and tools must be promptly discussed, tested, and implemented to meet targets concerning EE.

In 2011, the European Committee for Standardization (CEN) released a new standard for measuring the environmental sustainability of buildings. Figure 1 illustrates the diagram used for the LCA method in 'EN15978:2011 Sustainability of construction works' (CEN, 2011).

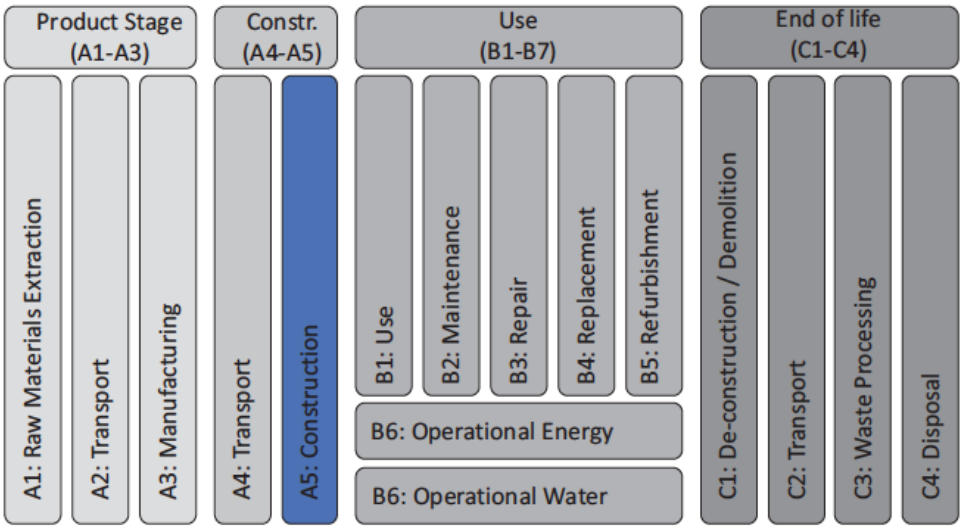

Figure 1: Life Cycle phases according to CEN (2011).

Today, many emissions arise from producing building materials (phases A1-A3), prompting a shift to more sustainable materials with lower life-cycle emissions. Architects and engineers will increasingly be responsible for proving the carbon footprint calculations, aided by tools like EC3 (CLF, 2023). Transportation emissions (phase A4) are challenging to quantify, but it is imperative to acknowledge their significance in the broader context of sustainable construction. Despite its complexities, efforts to address A4 emissions should not be sidelined. Meanwhile, energy consumption for heating, drying, lighting, and processing electricity on construction sites (phase A5) can more easily be monitored and quantified. Construction site-related emissions (phase A5) remain relatively undiscovered, studies on how scheduling can impact emissions are scarce (Lim et al., 2016), and suitable quantification tools are absent, leaving stakeholders in the dark.

This study explores how schedule changes impact energy consumption at construction sites (phase A5), caused by delays or schedule optimization using a Location-Based Management System (LBMS). Initially centered on A5 and leveraging LBMS for measurement, our research will prioritize A4 emissions in continuous sustainability assessments. This shift aims to provide a comprehensive understanding of construction-related emissions, thereby improving decision-making for sustainable practices.

Due to limited empirical data, this study relies on reports, some over five years old, using average values for analysis, making the methodology somewhat experimental.

METHOD

This paper presents a research work classified as an explorative case study (Yin, 2003). This research strategy was chosen because it enabled the present authors to investigate a phenomenon characterized by a lack of detailed preliminary research (Yin, 2003). The study's phenomenon comprises understanding how schedule changes positively or negatively affect construction site energy consumption.

As a starting point, a literature review is conducted to identify A5 energy consumption from actual cases. It is not easy to identify the necessary data, as many studies assume that the energy consumption in A5 is limited and, therefore, negligible (Hendrickson and Horvath, 2000; Lemay, 2011). In general, reported research on EE of construction is limited, and when said, it is often for the accumulated production stage only (A1 to A3) or occasionally as accumulated production and construction (A1 to A5). Very few case studies report designated A5 values, cf. Table. 1. This lack of data for A5 constitutes a critical knowledge gap in reducing lifecycle CO_2 emissions from buildings during the construction phase.

Table 1: Consumption of energy in A5 for different projects (values in kWh/m2)

Project	Heating of building (A5.1)	Drying (A5.2)	Process & lightning (A5.3)	Sum A5
DK1 – commercial (Sommer et al., 2013)	121.96	0.00	34.79	157
DK2 – commercial (Sommer et al., 2013)	12.86	67.50	24.74	105
DK3 – commercial (Sommer et al., 2013)	107.20	0.86	16.91	125
DK4 – residential (Sommer et al., 2013)	34.00	0.00	30.39	64
DK5 – commercial (Sommer et al., 2013)	154.22	17.33	25.85	197
TYR1 – residential (Bozdag & Secer, 2007)	na	na	na	148
TYR1 – residential (Bozdag & Secer, 2007)	na	na	na	159
TYR2 – residential (Bozdag & Secer, 2007)	na	na	na	143
Averages	86	17	27	130

As argued earlier, the focus of this study will be only on point phase A5. A5 can be split further into sub-groups, cf. equation 1, which are the most demanding energy sources during the construction phase - (A5.1) Heating, (A5.2) Drying, (A5.3) Lighting and Process (Sommer et al., 2013).

$$E_{construction} = E_{heating} + E_{drying} + (E_{lighting} + E_{process}) \quad (1)$$

Where:

$E_{construction}$ = Energy consumption in A5 in total [kWh/m2]

$E_{heating}$ = Energy consumption for heating of building [kWh/m2]

E_{drying} = Energy consumption for drying of building [kWh/m2]

$E_{lighting}$ = Energy consumption for lighting of the site [kWh/m2]

$E_{process}$ = Energy consumption for processes on the site [kWh/m2]

Table 1 includes five Danish cases, DK1 to DK5. For these cases, diesel-powered machines are not included, as the data is limited to machinery using on-site electricity, including lighting. Secondly, three Turkish case studies, TYR1 to TYR3, are included. In the Danish studies, the average energy consumption is 129.72 kWh/m2, while theoretical values from the early 90s suggest 150 kWh/m2 for the "Erection" phase (Bozdag & Secer, 2007), indicating a 15%

difference. Technological advancements may explain this gap, with site equipment improvements over the last 20 years. Notably, the Danish report excludes diesel-powered machinery, potentially contributing to lower numbers than the Turkish report. Despite variations, the Danish measurements align with literature expectations, justifying their use as a calculation base.

Although relevant, other aspects that impact the overall CO_2-Emission, such as changes to the project and materials, will be disregarded for this paper's focus.

As a result of exploratory work, the authors suggest 10 important parameters to estimate the base consumption factors called $C_{heating}$, C_{drying}, ($C_{lighting + process}$): The parameters are explained below:

1. **Construction period for the project.** How long does the project run for? It is relevant for calculating the number of workdays requiring lighting and construction process electricity. It is determined with the Start date of the first activity and the End date of the last activity and circled with purple below.
2. **Full construction period per location**. The start and End dates for activities within the location are used to determine operational days in the location. This is relevant to determining the days when lighting and construction process electricity will be required per location and marked with red below.
3. **Winter period definition**. Defining the Start and End date of a winter period. In this research, it is assumed to be from the 1st of October to the 31st of March.
4. **Number of winter periods**. Determining the number of winter periods during ongoing work, impacting heating energy consumption (highlighted in blue in Figure 2).

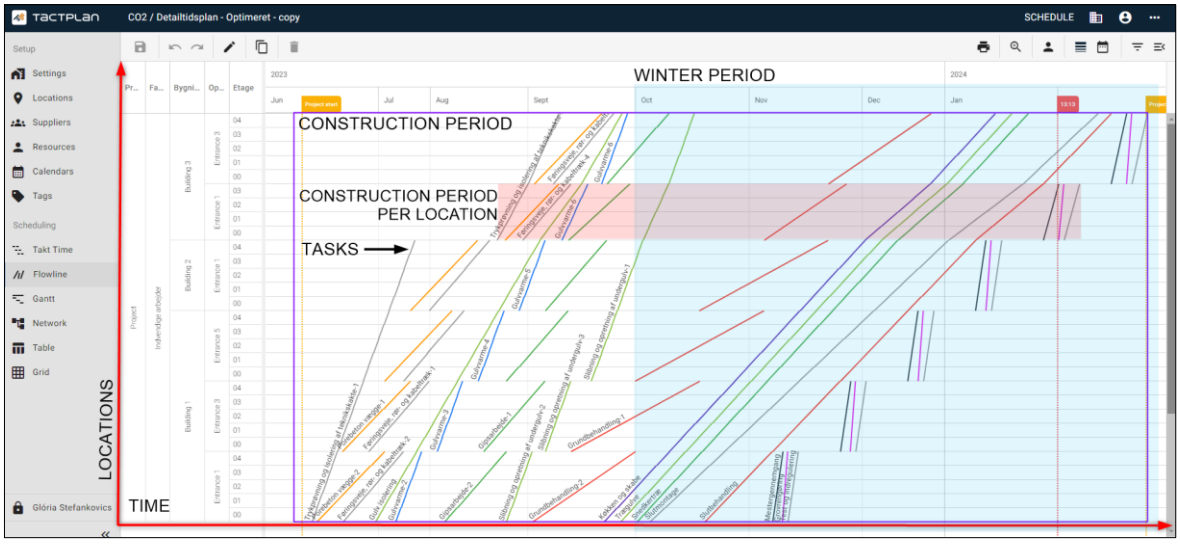

Figure 2: Location-based schedule illustrating full construction period, period per location, and winter period.

5. **Multiple construction periods within a location** – Investigating energy waste during idle periods in a location with starts and stops (marked in green in Figure 3) where no work is executed. The location must be segmented into multiple work periods to facilitate this calculation.

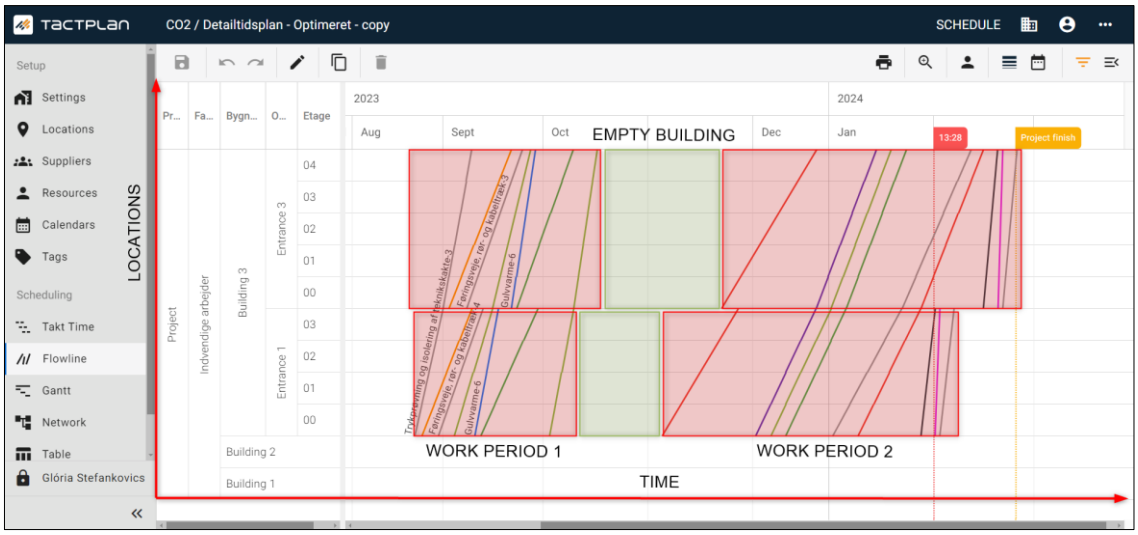

Figure 3: Possible break periods within a location during no work periods.

6. **Number of winter workdays (N_{wdays})**. Only the working days have been taken to calculate the energy consumption.
7. **Area per location (A)**. The size of each location. It is essential as the base values described earlier are measured in kWh/m2.
8. **Type of heating**. Identifying the heating method employed (e.g., district heating, calorifiers). This paper and the two referenced reports utilize district heating.
9. **Type of installation**. Determining if the electricity and heating for the construction site has one common installation or if each building has its own installation. This is important because if there is a period when there is an empty building, there needs to be a method to turn off the electricity and heating for that building without stopping it for the other parts of the project. It is understood that having such installation per floor might be very complicated to achieve, so this is limited to per building within a project.
10. **kgCO_2/kWh produced (I)**. Based on the production method for energy, this number varies depending on the country for which the calculations are made.

With the base consumption factors (Table 1) and the relevant parameters listed above, plus the use of Tactplan (Tactplan, 2024), a software designed to streamline location-based planning, which provides a seamless workflow, enabling efficient data collection for analysis, it is possible to calculate the consumption per location. The next section will present the results based on equations 2, 3, 4, and 5 below. Other software tools, such as Vico Schedule Planner, could also have been used. However, it is important that the scheduling tool show and utilize both task and location dependencies, which makes traditional CPM/Gantt-based tools unsuitable for this method and analysis.

$$E_{heating} = N_{wdays} * A * C_{heating} \quad (2)$$

$$E_{drying} = N_{wdays} * A * C_{drying} \quad (3)$$

$$(E_{lighting} + E_{process}) = Day * A * C_{lighting\ +process} \quad (4)$$

$$Q = \sum E * I \quad (5)$$

$E_{heating}$ = Energy consumption for heating of building [kWh]
E_{drying} = Energy consumption for drying of building [kWh]
$E_{lighting}$ = Energy consumption for lighting of the site [kWh]
$E_{process}$ = Energy consumption for processes on the site [kWh]
N_{wdays} = Number of winter days [days]
A =Area per location [m^2]
$C_{heating}$ = Base consumption for heating of building / day =86 kWh/m^2
C_{drying} = Base consumption for drying of building / day = 17 kWh/m^2
$C_{lighting\ +\ process}$ = Base consumption for lightning and process / day = 27 kWh/m^2
Day = Construction time [days]
Q = total quantity of CO_2 emissions [$kgCO_2$]
I = CO_2 intensity of the produced electricity [$kgCO_2$/kWh]

The total energy consumption for each scenario within every case study is determined by combining the kWh usage for lighting, process energy, and heating. Heating is calculated by summing up the square meters under construction, multiplied by the number of winter days in the building period, and multiplied by the heating consumption rate in kWh/m2. Similarly, the estimate for lighting and process energy involves multiplying the number of workdays in all work periods by the square meters of the areas under construction and the lightning + process electricity consumption rate in kWh. No additional drying equipment is planned, as temperature-sensitive internal works coincide with internal heating, resulting in an E_{drying} value of 0,2, which can then be disregarded.

CASE STUDIES AND RESULTS

This research examines three real-life cases, each described with preconditions, results, and conclusions. To maintain confidentiality, project names and details are undisclosed. The cases involve different building types, introduction periods for Location-Based Scheduling (LBS), and optimization tasks, aiming to mitigate single random good results and assess outcomes without bias towards single projects with the best results. Location-Based Scheduling is today widely adopted in construction (Lerche et al., 2019) and known for its ability to optimize the schedule (Kenley & Harfield, 2015; Seppänen et al., 2010).

CASE STUDY A – 9,000 M^2 NEW RESIDENTIAL

The task for this project from the management team was to create a Location-Based Schedule with given constraints for resources and start and end dates.

Preconditions

The project's management team adopted LBS exclusively for internal works, with energy consumption calculations covering the period from June 14, 2023, to February 23, 2024. The case study involves three buildings with varying entrances and five floors.

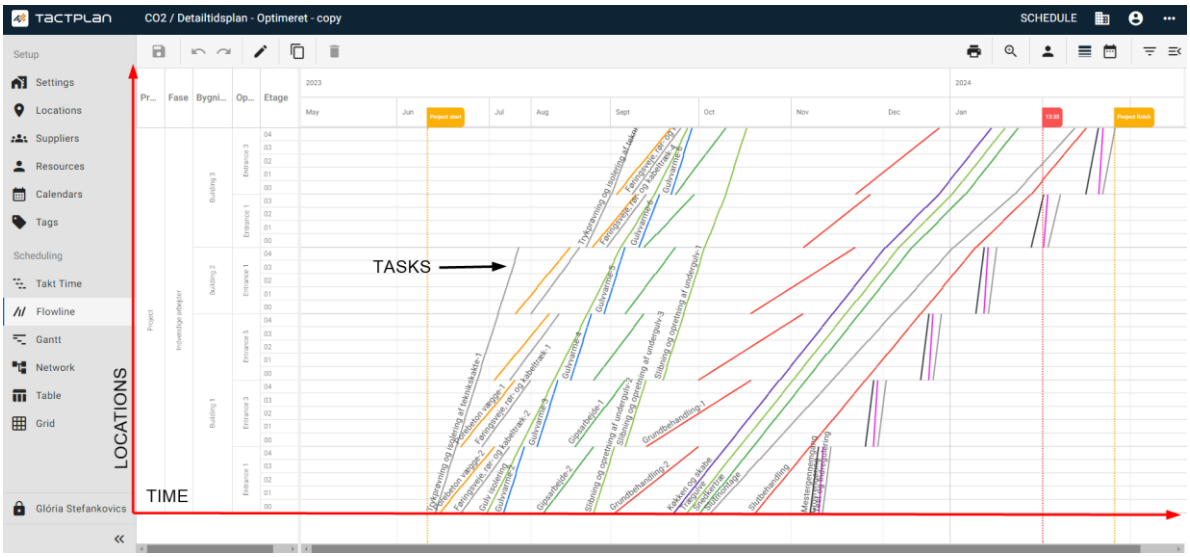

Figure 4: Schedule for Case Study A

- ***Scenario 1*** - Common heating and electricity installation for the entire construction site without the option to isolate empty buildings. Traditional practices involve continuous internal lighting and heating during the winter, serving as a benchmark for comparison.
- ***Scenario 2*** - Heating and electricity installation with the option to isolate empty buildings. Stricter emission control requires enhanced project management during construction, potentially prompting operational changes. This scenario explores optimizing heating and lighting schedules, proposing their shutdown during pauses of at least two weeks between two finish-to-start activities in the same building, as illustrated in Figure 3 (marked with green). Maintaining a minimum indoor temperature in colder climates is crucial for preventing materials from freezing or deteriorating, which could affect their quality and integrity. Completely turning off the heating could lead to issues, which could cause delays and additional costs to rectify. But continuously running heating systems during periods when no work is taking place can be costly in terms of energy consumption, so even though it is not the current practice, the point of the scenario is to see if the CO_2 emission savings justify further investigation into the feasibility of minimal or no heating strategies.
- ***Scenario 3*** - Shifting work to non-winter months. Results from previous cases highlight heating as a significant contributor to energy consumption. To determine potential energy savings, the project start is shifted to the first non-winter day (April 1, 2023) while maintaining other preconditions, resources, and durations, resulting in a project end date of December 5, 2024.

Case A - Conclusions

Table 2: Results for Case Study A.

Scenario 1			Scenario 2			Scenario 3		
Energy kWh	*CO_2 tons*	*CO_2 kg/m²*year for 30 years*	*Energy kWh*	*CO_2 tons*	*CO_2 kg/m²*year for 30 years*	*Energy kWh*	*CO_2 tons*	*CO_2 kg/m²*year for 30 years*
219,002	36	0.161	178,454	30	0.131	68,445	11	0.050

Transitioning from traditional site operations to a more sustainable process presents an opportunity to reduce emissions. In this case study, a potential improvement of 17% is demonstrated. For shorter projects lasting less than a year, minimizing internal work during winter can result in a 69% improvement in emissions without additional effort.

CASE STUDY B – 8,000 M2 OFFICE RENOVATION

Tasked with minimizing project extension in a delayed project, the management team aimed to address significant delay costs after initial milestones. Despite having a Location Based Schedule, commissioning works at the project's end overlapped, assuming contractors could share locations during that period. However, detailed analysis revealed finish-to-start relations among various activities, hindering simultaneous execution. The initially reserved time was insufficient, leading to a 3-month project extension and a potential one-year delay.

Preconditions

Due to tight deadlines, project complexity, and continuous work, a scenario like turning off heating in inactive locations is not feasible.

- ***Scenario 1*** **-** Lighting + process energy usage at all times and heating usage during winter periods – 12-month delay
- ***Scenario 2*** **-** Lighting + process energy usage at all times and heating usage during winter periods - Optimized 3-month delay.

Case B - Conclusions

Table 3: Results for Case Study B.

Scenario 1			Scenario 2		
Energy kWh	*CO_2 tons*	*CO_2 kg/m²*year for 30 years*	*Energy kWh*	*CO_2 tons*	*CO_2 kg/m²*year for 30 years*
1,544,112	256	1.187	1,323,216	220	1.017

The results highlight a potential correlation between project duration and energy consumption, a logical inference given the expectation of higher energy usage in longer projects. The transparency and detailed construction process provided by LBMS underscore its importance. As regulations evolve, the need for methods to quantify the energy implications of delays is anticipated.

CASE STUDY C – 50,000 M2 NEW MEDICAL FACILITY

The project's management team initiated LBMS from the project's inception. The available information includes start and end dates for the tender schedule and actual execution, allowing for an investigation into how time impacts energy consumption and emissions in the context of delays.

This case study compares actual project end dates with the industry average delay for medical buildings. A 2022 report by the Ministry of Health in Denmark indicates an average delay of 2.3 years for 16 medical facilities. Since structural works are typically on time while delays often occur during internal works, the 2.3-year delay is proportionally added to the planned duration of interior works.

Preconditions

Due to tight deadlines, project complexity, and continuous activity, creating a similar scenario to turn off heating in inactive locations is not feasible.

- ***Scenario 1*** - Tender Schedule: Lighting + construction process electricity usage at all times and Heating usage during winter periods.
- ***Scenario 2*** – Actual Schedule: Lighting + construction process electricity usage at all times and Heating usage during winter periods. Compared to the tender schedule, there is a delay of approximately 5 months.
- ***Scenario 3*** – Theoretical industry delay (+2.3 years): Lighting + process electricity usage at all times and Heating usage during winter periods.

Case C - Conclusions

Table 4: Results for case study C.

Scenario 1			**Scenario 2**			**Scenario 3**		
Energy kWh	*CO_2 tons*	*CO_2 kg/m²* year for 30 years*	*Energy kWh*	*CO_2 tons*	*CO_2 kg/m²* year for 30 years*	*Energy kWh*	*CO_2 tons*	*CO_2 kg/m²* year for 30 years*
6,552,733	1,088	0.725	8,336,426	1,384	0.923	11,839,282	1,965	1.310

As can be seen, there is a big difference between the actual (scenario 2) and the theoretical industry delay (scenario 3), amounting to 581 tons (42%) of extra CO_2 emissions. The amount has been converted to other equivalents in Table 5 to understand better what that means.

Table 5: Conversion to illustrate the amount of CO_2 emissions.

581 tons of CO_2	274 family homes' electricity for one year
	216,044 liters of diesel consumed
	2,396,992 km driven by an average gasoline-powered car
	70,674,377 smartphones charged

The results indicate that delays significantly impact energy consumption. Complex projects with a history of overrun risk face penalties for excess emissions, further adding to the already exceeded budgets due to delays.

CURRENT LIMITATIONS OF THE METHOD

The method relies on data from reports dating five or more years back, potentially underestimating efficiency gains in energy consumption due to technological advancements. However, the developed method allows quick parameter changes, automatically adjusting results with updated information.

The challenge lies in obtaining updated, reliable data, requiring cooperation from building owners, management teams, equipment vendors, and contractors willing to track and share relevant consumption numbers. Detailed research could be pursued with the involvement of interested parties sharing information.

Such factors are: 1) kWh used for electricity on site, 2) kWh used for heating on site, 3) kWh used for warm water, 4) kWh used for heating the temporary offices, 5) kWh used for heating the changing rooms for workers, and 5) Emissions from diesel-powered heavy machinery.

Another limitation is that the calculations are made with average values from different types of projects. A better approach would be if there were an extensive library of projects where the

most similar one could be chosen based on the parameters listed in Section 2. In that way, the correlation between historic projects and new estimates will be stronger. However, such reliable data currently doesn't exist.

DISCUSSION

Based on the results across the three case studies and examined scenarios, it is evident that the quantification method applies to various situations.

What is the ratio between the emissions from Production and Use compared to Construction process emissions?

Currently, material production (phases A1 to A3) and building operation (phases B1 to B7) contribute the most to emission production (Wandahl et al., 2021).

The construction phase (phase A5) accounts for approximately 10% of GHG emissions from buildings (Klimapartnerskab, 2020). Upcoming Danish regulations targeting 12 $kgCO_2$ per m^2 per year will decrease values for materials and occupancy, the most significant contributors. As these values decrease, the attention will shift to the construction phase as a substantial area for emissions reduction demands. Notably, the 12 $kgCO_2$ per m^2 per year regulations exclude the construction process but results from case study C demonstrates a potential reduction of over 1 $kgCO_2$ per m2 per year, constituting 8% of the threshold value solely from energy consumption. This 8% could increase by including transportation and diesel-powered machinery.

Additionally, the initial threshold of 12 $kgCO_2$ per m2 per year is just a starting point. As regulations become stricter, by 2050, there will be a growing need for a quantification method for emissions produced by construction sites, along with a requirement to document A5 and reduce A5 GHG.

Possibilities for future development

More recent data

Similar to Sommer et al. (2013), new research can validate if technological advancements have reduced overall energy consumption. Comparing calculations from study cases using this quantification method with actual metered consumption on construction sites can yield more accurate conclusions.

Resources – Manning linked to energy consumption

The simplest improvement entails considering heating consumption for temporary offices and worker changing rooms. By utilizing resource counts from a graph, one can determine the necessary work crews and their areas during different project phases. This calculation method, utilizing average numbers from Table 1, becomes applicable.

Resources - Diesel-powered machinery energy consumption

Addressing the limitations, the calculations did not consider energy use and GHG from diesel-powered construction equipment. However, by creating a catalogue of commonly used heavy machinery brands and examining their technical specifications for hourly consumption, it's feasible to multiply the number of resources by their consumption and convert it to CO_2 emissions. Fossil fuels are a significant source of CO_2 emissions, and the LBMS method facilitates efficient planning for heavy machinery use. The European Rental Association's "Equipment CO_2 Calculator" (ERA, 2024) is a potential source of inspiration.

Automated calculation method integrated into software

The calculations in this research are time-consuming, done in spreadsheets, and should be integrated directly into a scheduling tool, automating the process. With an LBMS engine, the software could extract start/end dates, identify winter periods, and apply base values for

heating/lighting, requiring only user input for area per location. Resources, including heating and diesel-powered machinery emission factors, should be part of any future construction schedule. Background calculations would enable rapid estimation updates with each schedule change, allowing users to evaluate the environmental impact of strategic moves in seconds.

CONCLUSIONS

Results from all study cases underscore that the primary correlation with CO_2 production is tied to duration and scale. Larger areas require more heating energy, and expansive projects often lead to longer construction periods, increasing winter periods and energy usage for heating. Given that heating is the primary energy consumer, building types prone to delays and cost overruns face a higher risk of surpassing CO_2 limits once regulations are in place.

The core reason for utilizing location-based planning methods such as Location-Based Scheduling or Takt planning (TP) in projects is to minimize the risk of time overruns, leveraging their superior overview and coordination capabilities. As also stated by (Ballard & Tommelein, 2021), when projects can be divided spatially, it is recommended to use a form of location-based planning method. Larger and more complex projects stand to gain significantly from LBMS, reducing risks in the planning phase and ensuring a healthier schedule.

LBMS enables pinpointing schedule problem areas by considering both time and location, a capability lacking in the Critical Path Method (CPM) due to its omission of task placement data. A CPM/Gantt-based schedule lacks the ability to show and optimize non-working zones which have been found critical for reducing CO_2 emissions. By highlighting location, LBMS facilitates analysis of electricity, lighting, drying, and other processes, allowing for consumption calculation based on area and time.

Another location-based method available is Takt planning (TP). This planning form is somewhat similar to LBMS apart from its rigidity, which stems from operating on fixed time intervals and relying heavily on completing preceding tasks within the allocated time frame. That is all to say, that bearing in mind the disadvantage of TP, the method could also be used to help quantify CO_2 emissions on site, as it also entails the necessary data (area and time).

In summary, optimizing schedules for time and resources doesn't necessarily equate to reduced CO_2 emissions. Sometimes, optimizing for time may inadvertently lead to increased energy consumption and emissions, particularly if activities are shifted to winter periods without prior heating plans. However, project management can make informed decisions by quantifying the impacts of schedule changes. They can evaluate the extra emissions and costs, compare them with the initial optimization, and choose between schedules aligned with milestones or delayed schedules.

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