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ARTICLE (PEER REVIEWED)

The Impact of Construction Labour Productivity on the Renovation Wave

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Abstract

The European Green Deal's Renovation Wave aims to renovate 35 million energy-inefficient buildings to reduce carbon dioxide (CO_2) emissions by at least 55% by 2030. Historically, efforts to reduce CO_2 emissions focused on Operational Energy (OE) of the finished buildings. However, in recent years the Embodied Energy (EE) of the building's construction process has gained attention because of its essential role in construction renovations projects. In this context, construction efficiency, and more precisely, workers' efficiency, is a vital catalyst to achieve the European Union (EU) targets. To identify the impact of Construction Labour Productivity (CLP) on the renovation wave an exploratory case study was adopted as research strategy. Data from four domestic housing renovation projects were gathered. Three specific research goals are outlined.

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The first is to demonstrate the effect of the adoption of Lean tools and methods to increase CLP. The second is to quantify the correlation between improved productivity and the EE emissions saved during the construction phase. The third goal is to estimate the effect the higher productivity has on OE emissions. The results show that the adoption of several Lean tools and methods has a potential to improve CLP to 45%. This rate of improvement for the 35 million housing units to be renovated could save 6.9 million tonnes CO_2e from EE and 386 million tonnes CO_2e from OE. This novelty link between process improvements and reduced energy consumption and emissions can support politicians and infrastructural developers in decision-making for a more sustainable construction industry.

Keywords

Construction Labour Productivity (CLP); Embodied Energy (EE); Lean Construction; Renovation Wave; Carbon Dioxide (CO_2) Emissions

Introduction

The energy consumption for establishing, maintaining, and operating buildings accounts for approximately 39% of the world's total carbon dioxide (CO_2) emissions (UNEIEA, 2017). To achieve a full green transition in construction, all phases of the building lifecycle should be examined for possible Greenhouse Gas (GHG) reductions. Historically, efforts to reduce GHG from buildings have mainly been focusing on 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, the processing into building materials, and on-site construction, have gained attention. This also includes end-of-life phases with the circular aspect of reuse and recycling. This is because EE and embodied GHG emissions (EEG) due to building construction and civil engineering account for 20% of the entire energy consumption and GHG emissions in the world (Yokoo and Yokoyama, 2016).

As a reply to these challenges, the European Union (EU) leaders have agreed on a European green deal that must reduce CO_2 emission by at least 55% in 2030 and build the foundations for a carbon-neutral Europe by 2050 (EU, 2020). This deal includes a renovation wave with an objective of renovating 35 million existing energy-inefficient buildings by 2030. This effort is essential to reduce emissions as 85-95% of current buildings in the EU are expected to be still standing in 2050.

The embodied GHG emissions due to construction industries are approximately 5 to 10% of the entire energy consumption in developed countries and 10 to 30% in developing countries (Yokoo and Yokoyama, 2016). However, the construction process itself has attained little interest in the green transition agenda. Furthermore, construction generates billions of tonnes of construction and demolition waste yearly (EEA, 2020). Besides, resource efficiency is poor, research studies (Wandahl, Neve and Lerche, 2021) report that only about 33% of the operating time is destined on value-adding tasks; consequently, construction processes generally waste two-third of their time on non-value-adding activities. All these non-value-adding operations require energy and thus emit unnecessary CO_2. Consequently, today's tacit acceptance of time and cost overruns in construction is effectively the same as the industry's acceptance of unnecessarily large CO_2 emissions. In this context, construction efficiency and more precisely Construction Labour Productivity (CLP) is a vital catalyst in order to realize the ambitious targets of the European renovation wave.

The necessity to reduce CO_2 emissions together with the broad problem addressed regarding the lack of previous studies focusing their effort on the efficiency of workers during the construction process for reducing the Embodied Energy (EE), allowed the authors of this research to identify the knowledge gap in previous work and to state the Research Question (RQ) of this work, which is:

RQ: How could the improvement of Construction Labour Productivity (CLP) impact the reduction of both Embodied Energy (EE) and Operational Energy (OE) on renovation projects?

To address this question, the authors conducted an exploratory case study in four domestic housing renovation projects to quantify the impact of the implementation of Lean tools and methods on CLP. Then, to quantify the correlation between improved productivity and the possible EE and OE savings, the authors adopted several assumptions and values of energy consumption from the existing literature. As the goal of this paper is to understand the impact of the improvement of construction workers' efficiency on the renovation wave, the scope of this research work is limited to the construction phase, and it does not consider other phases during the case studies. That is why the values of EE collected from the literature only considered the aforementioned phase.

Literature Review

RENOVATION PROJECTS

Renovation projects distinguish themselves from other project types by having several unique characteristics. Renovation has not been given great attention in past research, however recent works by Kemmer (2018), Neve, et al. (2020), and Tzortzopoulos, Kagioglou and Koskela (2020) have shed light on renovation and point out that the main challenges are: (1) existing building structure with several unknown characteristics; (2) an often not optimal construction site layout for logistics and material handling; (3) highly specialized tasks and trades, e.g. removing asbestos, etc.; and (4) dealing with occupied buildings and tenants on site. Tenants in proximity to ongoing construction work require a high level of protection (e.g., dust, noise) and make the management of the craftsmen-tenant relationship an additional challenge in renovation. These characteristics of renovation projects furnish a challenging environment to manage.

Kemmer (2018) reviewed the literature and points out that the traditional project management approach is insufficient in renovation and argues that Lean management is superior. Ballard (2000) argues that the traditional approach has a too-narrow focus on transformations, whereas Lean expands to cover both transformations, flow, and value. According to the Lean philosophy, the actions performed along the flow can be classified as value-adding work (VAW) and non-value-adding work (NVAW) (Womack and Jones, 2003). In this way, the concept of waste is directly associated with the use of resources that do not add value to the final product. This means that there are two kinds of approaches to improving processes. One is to improve the efficiency of both VAW and NVAW, and the other is to eliminate waste by removing non-value-adding activities. This second approach focuses on process improvement and usually results in more dramatic performance improvements (Ohno, 1988).

Kemmer, et al. (2016) demonstrated that significant productivity improvement could, among other methods, be obtained by integrating the Last Planner System (LPS) and renovation production systems. They found that regarding the benefits of utilizing the LPS, there is a potential, especially regarding reducing the disruptions on-site and regarding compressing lead time. Improvements in project communication and coordination were also noted as a result of the LPS adoption. Overall, less waste and better flow are the outcomes of implementing Lean in renovation projects (e.g., Kemmer, et al., 2016; Neve, et al. (2020). Performance due to the implementation of Lean tools, practices, techniques, and methods can be assessed on a range of different Key Performance Indicators (KPIs). Acknowledging the diverse and complex issues related to renovation, this paper continues with a focus on CLP obtained from the WS technique as a KPI.

CONSTRUCTION LABOUR PRODUCTIVITY (CLP) AND WORK SAMPLING (WS)

CLP is usually defined as the gross product output per person employed or person-hour worked. Despite being a partial factor productivity measure, labour productivity has been widely accepted as a performance measure in the construction industry. The emphasis on labour derives from several reasons: labour is the most important factor and most easily quantifiable (Lemma, Borcherding and Tucker, 1986); it is the only factor that has conscious control over its contribution to output (Lowe, 1987); its significance for the total project cost (Buchan, Grant and Fleming, 2003; Kazaz, Manisali, and Ulubeyli, 2008); it has a direct impact on the profitability and competitiveness of construction companies (Hamza, et al., 2019); among other reasons.

Regarding this understanding of productivity, the most common CLP metrics are unit rate (ratio of labour cost to units of output); labour productivity (ratio of work hours to units of output), and productivity factor (ratio of scheduled or planned to actual work hours) (Gouett, et al. 2011). Hence, understanding how time is used during the input-to-output conversion process is also vital to modelling CLP; work-study methods are commonly used for this goal (Tsehayae and Fayek, 2016). The Work Sampling (WS) method is a statistical technique based on random observations to investigate how efficiently a workforce uses its work time, and it is the most widely used work-study method (Josephson and Björkman, 2013).

WS, originally developed by L.H.C. Tippett in 1935, consists of a series of instantaneous, randomly spaced observations of the activities being carried out by the group of workers (or possibly the machines) under study. WS is a fact-finding tool based on the laws of probability (Fields, 1969). The WS technique can estimate the proportions of the total time spent on a task in terms of various components (Barnes, 1968). WS involves taking a small portion or sample of occurrences in the overall activity. A process is observed at intervals so that each activity has an equal chance of being observed.

WS establishes the percentage of work time spent on selected work categories. Previous studies have shown that the definition of work categories and the subsequent task classifications can significantly affect the different proportions and, hence, their relationships with CLP (Thomas, 1991). In this research study, the Lean work categories of Value-Adding Work (VAW) and Non-Value Adding Work (NVAW) are adopted. Keeping in mind this assumption, the Direct Work (DW) category represents the proportion of work time spent on VAW.

EMBODIED ENERGY (EE) AND OPERATIONAL ENERGY (OE)

Embodied Energy (EE) of buildings is commonly measured using Life-Cycle Assessment (LCA). In 2011 the European Committee for Standardization (CEN) released a new standard for measuring the environmental sustainability of buildings. Figure 1 represents the predominant diagram used for the LCA method in 'EN15978:2011 Sustainability of construction works'.

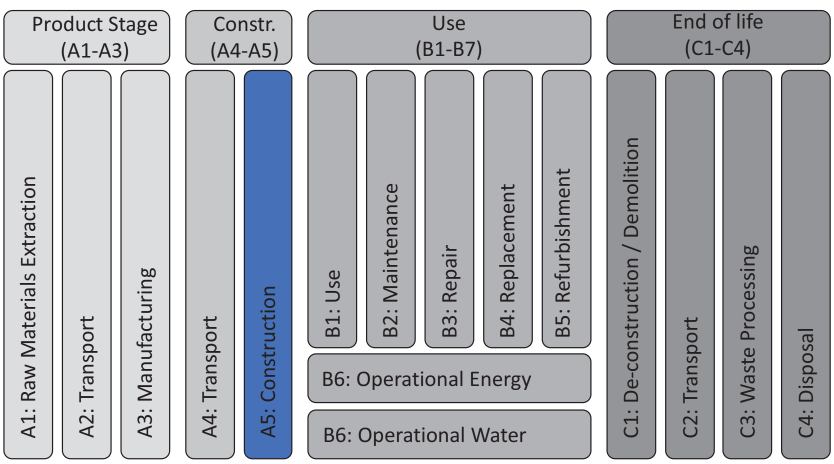

Figure 1. EN15978 System Boundaries.

The EE of buildings refers to the energy used for all other lifecycle phases than the use phase (phase from B1 to B7 in Figure 1); however, in this paper, the EE analysis focused on the construction phase (only phase A5 in Figure 1). The construction phase, A5, includes all processes carried out on-site from start to end of construction works, as well as the production, transportation, and management of site and construction waste (Moncaster and Symons, 2013).

Among widely used methods for embodied energy calculation are process-based, Input-Output (IO) based, statistical, and hybrid methods, each of which differs in system boundary coverage as well as the types and sources of data (Dixit and Singh, 2018). Most research on LCA phase A5 focuses on actual activities and adopts the IO method.

Reports on research that link Embodied Energy (EE) to the schedule are scarce (Lim, Gwak and Kim, 2016). However, it is not easy to obtain the necessary data, thus many studies assume that the energy consumption in A5 is limited and, therefore, negligible or underestimate its impacts (Hendrickson and Horvath, 2000; Lemay, 2011). In general, reported research on EE of construction is limited, and when reported, 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 the effort to reduce lifecycle CO_2 emissions from buildings during the construction phase.

Table 1. Case studies with dedicated values for A5

	Project type	Project size [m²]	Project duration [months]	Energy use in A5 [kWh/m²]	Reference
DK1	Commercial	33,500	33	157	(Sommer et al., 2013)
DK2	Commercial	6,200	14	105	(Sommer et al., 2013)
DK3	Commercial	10,000	11	125	(Sommer et al., 2013)
DK4	Residential	9,000	30	64	(Sommer et al., 2013)
DK5	Commercial	9,000	14	197	(Sommer et al., 2013)
TY1	Residential	410	12**	148	(Bozdag and Secer, 2007)
TY2	Residential	450	15**	159	(Bozdag and Secer, 2007)
TY3	Residential	100	12**	143	(Bozdag and Secer, 2007)
NO1	Residential	9,207	24	33	(Melvaer, Hertwich and Houlihan Wiberg, 2012)
SE1	Residential	3,982	12	94	(Larsson et al., 2016)
SE2	Residential	8,173	24	117	(Liljenström et al., 2015)
SE3	Residential	198	12**	146	(Fröberg, Larsson and Mendez, 2018)
SP1	Residential	17,724	24**	72*	(Rodríguez Serrano and Porras Álvarez, 2016)
SP2	Residential	25,932	30**	125*	(Rodríguez Serrano and Porras Álvarez, 2016)

*MJ converted to kWh. **not reported, thus assumed by authors.

Research Methodology

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 given *phenomenon* characterized by a lack of detailed preliminary research (Yin, 2003). The study's *phenomenon* comprises the understanding of how

Table 2. Research design description

Research Goal (RG)	Source of evidence/ technique/tool/task conducted	Purpose
RG 1: To demonstrate the effect of implementing Lean construction tools, practices, techniques, and methods in renovation projects to increase construction productivity	Direct observation (Construction site visits)	It allows the authors to identify the main construction activities conducted on sites for each construction process
	Work Sampling (WS)	It allows the determination of how workers use their time, mainly to determine the time spent on Direct Work (DW)
	Informal interviews with site engineers and workers	It allows to identify the Lean tools adopted in each construction project
	Document analysis	Provides additional information about the adoption of Lean tools
	Lean Implementation Degree (LID) Index	To identify the number of Lean tools implemented on construction projects
	Linear regression analysis	To determine the effect of the work sampling size (R)
RG 2: To investigate and quantify the correlation between improved productivity and the buildings' lifetime energy performance	Literature review of case studies that calculated EE phase A5 in LCA	To associate the DW obtained from RG1 to the possible Embodied Energy (EE) savings
	EE reduction analysis during the A5 stage	To identify the possible EE reduction during the construction phase in the EU Renovation wave
	Uncertain analysis of the EE	To estimate the possible EE reduction considering some uncertainties
RG 3: To investigate and estimate the potential indirect effect a more productive renovation process has on reducing Operational Energy emissions.	OE reduction analysis during the A5 stage	To identify the possible OE reduction during the construction phase in the EU Renovation wave
	Operation Energy (OE) saving analysis	To estimate the possible indirect OE savings regarding DW measures

an efficient construction labour production could influence both Embodied Energy and Operational Energy reductions in renovation projects.

For understanding this *phenomenon,* three research goals were proposed: (1) to demonstrate the effect of implementing Lean construction tools and methods in renovation projects to increase construction productivity; (2) to investigate and quantify the correlation between improved productivity and the buildings' lifetime energy performance; and (3) to investigate and estimate the potential indirect effect a more productive renovation process has on reducing operational energy emissions.

There are several ways to obtain data about a given unit of analysis: observing the *phenomenon,* asking questions to the stakeholders, and examining written documentary elements. Each of these procedures corresponds to a category of research source of evidence: direct observation, interview, and document analysis (Yin, 2003). All those sources of evidence were adopted along with other tools for achieving the research goals. The three research goals are outlined and summarized in Table 2, together with main research methods, tools, techniques, source of evidence, and tasks conducted. Further description is presented in the following subsections.

METHODS FOR RESEARCH GOAL 1 (RG1)

To pursue the first goal of this research study, data from four construction projects were gathered. Data collection aimed to identify the main characteristics of the four construction projects and to understand how the work time is being used by workers. For that, two variables were collected of each case during construction site visits. The first variable consists of Direct Work (DW) collected from the work sampling application. The second consists of the Lean Implementation Degree (LID) collected from the quality evaluation of the case studies.

CASE STUDIES

The four cases were all domestic housing renovation projects located in Denmark. All the cases comprise a similar building structure consisting of multiple similar housing units in 1, 2, or 3 story buildings. Case 1 was conducted in a very close collaboration with the contractor company through an action-based approach. In this case, Lean Construction tools, practices and methods were implemented to the daily site management, and the effect of the implementation was monitored closely for two years. The main characteristics of the four cases are summarized in Table 3.

Table 3. Characterization of the four cases

	Case 1	Case 2	Case 3	Case 4
Contract type	General	Turnkey	General	Turnkey
Project duration	5 years	4 years	4 years	3 years
Housing units	291	297	601	470
m2	22,800	23,700	46,500	41,000
Stories	Basement to 2	Basement to 2	Basement to 3	Ground to 1
Originally built	1950s	1960s	1950s	1970s

The cases were all planned to go through deep renovation, including interior, installations, and building envelope. The main construction processes studied during the cases were: demolition of all non-structural elements; establish new elevators, removal and installation of new façade elements; build new masonry walls, install electric, heating and ventilation elements, install new steel profiles for internal walls, renovate bathroom tiles, sink and toilets, plaster and paint, and install floors and new kitchens.

WORK SAMPLING

For time study, the Work Sampling (WS) technique was applied, which in this research consists of the following seven steps:

1. Establish the construction processes of the study.
2. Clarify the categories of the activities to be measured: in these empirical studies, the activities can be direct work (DW), indirect work (IW), and waste work (WW).
3. Develop data collection forms for sampling: as the focus of this investigation is on CLP, the worksheet adopted for the work sampling had a detailed breakdown of seven sub-categories. Thus, the main categories of the activities in the worksheet were: producing as part of the DW category; talking and preparing as part of the IW category; transport, walking, waiting and gone as part of the WW category.
4. Select the confidence interval and the accuracy desired.
5. Calculate the number of observations needed. The formula that describes the relations between the number of observations needed and the desired accuracy is presented in Equation 1.
   $$n = p \cdot (1-p) \cdot (\sigma)^2 \qquad (1)$$
   Where:
   n = the total number of observations, named as number of data points
   p = expected percent of time required by most important category of the study
   σ = standard deviation percentage
6. Collect the data.
7. Summarize the results: it focused on identifying the time spent on DW, IW and WW.

LEAN IMPLEMENTATION DEGREE (LID) ANALYSIS

Lean methods cover a broad aspect of different tools and different implementation degrees. Especially the implementation of Lean tools has been widely discussed in literature (e.g., Cerveró-Romero, et al., 2013; Kalsaas, Skaar and Thorstensen, 2009), and it is concluded that different Lean tools are implemented differently from case to case, and often implementation does not match the theoretical description of the tool (Neve, Lerche and Wandahl, 2021; Wandahl, 2014). A typical reported situation, which was valid for this case, is that the Last Planner System is only partially implemented (Ahiakwo, et al., 2013; Lindhard and Wandahl, 2013; Porwal, Fernández-Solís and Rybkowski, 2010; Viana, et al., 2010). This raises the question of to which degree the implementation of Lean methods influences productivity, named in this research works as Lean Implementation Degree (LID).

A taxonomy was developed to classify the LID in each case (Table 4). The taxonomy is based on several main categories (first column in Table 4) and their subcategories (second column in Table 4) based on a literature review of previous studies related to Lean implementation and by discussions with peers and industry consultants with expertise in Lean (Table 4). Wandahl's (2014) industry survey of the use of Lean in the Danish construction industry provided the foundation for the six main categories presented in Table 4's first row. The subcategories of A, B and C were defined according to discussions with academic peers and industry consultants. The remaining subcategories were primarily based on the following literature and supplemented with input from discussions: Subcategory D comes from Johansen and Kragh-Schmidt (1999), Subcategory E is from Lindhard and Wandahl (2013) and Subcategory F is from Kenley and Seppänen (2009).

In this research, to classify the four cases according to their LID the Likert Scale of five points was adopted for measuring their level of adoption of the Lean tools, techniques, and methods. Hence, the Likert Scale assumes the following possible classification: 0 for total absence (of e.g., knowledge or training) to 5 for full implementation (of e.g., JIT or 5S).

Table 4. Lean implementation degree evaluation form

Lean Implementation Degree (LID)	Lean tools/ practices/methods
A: Training provided by company	1a - General Lean
	2a - Just-in-time
	3a - Last Planner System
	4a - Location Based Planning
B: General knowledge meaning	1b - General Lean
	2b - Just-in-time
	3b - Last Planner System
	4b - Location Based Planning
C: Holistic use of BIM	1c – JIT-Kanban
	2c - JIT- Small batches
	3c – Degree of a Lean/Kaizen culture
D: Just-in-Time (JIT)	1c - JIT-Kanban
	2c - JIT-Small batches
	3d – JIT-SMED
	4d - JIT-TPM
	5d – JIT-Production Layout
	6d – JIT-SCM (Material Delivery)
	7d – JIT-TQM-TQC
	8d – JIT-Kaizen
	9d – JIT-5S
	10d – JIT-A3
E: Last Planner System (LPS)	1e – Weekly meetings with foremen
	2e – Weekly workplan formalized into a plan
	3e – Process planning/Pull Planning/Takt time
	4e – PPC measured on a weekly basis
	5e – Causes for non-compliance based on PPC
	6e – Lookahead Plan is formalized
	7e – Workable backlog
	8e – Learning Process/5x Why

Table 4. continued

Lean Implementation Degree (LID)	Lean tools/ practices/methods
F: Location Based Scheduling (LBS)	1f – Overall sequencing/ Master plan
	2f – Progress tracking
	3f – Forecasting
	4f – Control Action
	5f – Lookahead planning phase
	6f – Process planning/Pull planning/Takt time

The LID for each case was evaluated by the authors and industry consultants because it was assessed that the project team in each case did not have the necessary knowledge to do this. This evaluation was conducted through the information and observations obtained during the job site visits and by conversations with the whole project team. Calculating the LID average was done by weighing averages from the main 6 categories equally. This was done to avoid that the implementation of e.g., JIT becomes more important than e.g., Location Based Scheduling (LBS) due to its lower number of subcategories.

DIRECT WORK (DW) AND LEAN IMPLEMENTATION DEGREE (LID) ANALYSIS

The analysis of DW and LID data was done using linear regression analyses. The regression model was evaluated using a t-Test determining the model's coefficients 95% intervals, analysis of regression coefficients to determine the effect size (R), and predictive capabilities (R2) to investigate the predictive capabilities, and finally an ANOVA analysis to determine the statistical confidence level (p-Value). The R was compared to Cohen (1988) and Cohen's (1992) work categorizing effect sizes. The p-Value will be used as a foundation to determine how statistically valid the identified relationship is. No lower limit for neither the R-value nor p-Value was adopted since the research was explorative and set out to explore a potential relationship on a small data sample.

METHODS FOR RESEARCH GOAL 2 (RG2)

To pursue the second goal of this research study, which consists of investigating and quantifying the correlation between improved productivity and the buildings' lifetime energy performance, the authors conducted three main activities: (1) associating the DW obtained from RG1 with the possible EE savings in phase A5, (2) identifying the possible EE reduction during the construction phase in the EU Renovation wave, and (3) estimating the possible EE reduction considering some uncertainties.

EMBODIED ENERGY (EE) IN PHASE A5

The present authors conducted a small review to identify a number of cases that could provide insight on EE emissions in phase A5 in order to link with the DW obtained in the four cases studied in this research work. This review was primarily presented in the literature review section (Table 1). A summary of the values from the studies identified is presented in Table 5.

The EE of A5 contains significant variations as energy use varies from 33 to 197 kWh/m2, which is a difference of factor six. For that, in this research the average values of this sample were adopted, those being: μ= 120.4 kWh/m2 and a standard deviation σ=43.7 kWh/m2.

Table 5. Summary of EE in phase A5 obtained from the literature review

Number of Projects	Min. Energy use in A5 [kWh/m²]	Max. Energy use in A5 [kWh/m²]	Mean [kWh/m²]	Standard deviation [kWh/m²]
14	33	197	120.4	43.7

The causal connection between DW and EE has a logical connection. As DW is improved, the efficiency and productivity of the project are increased. This can impact the project by either achieving the expected result and deadline with fewer resources, or the expected result can be achieved faster with the same resources. Based on this review, the potential EE emission saving in phase A5 was linked with DW and quantified. In this way, the CO_2 equivalents (CO_2e) saving potential due to improved construction site productivity can be calculated with Equation 2 proposed by the present authors:

$$EE = U \cdot a \cdot \mu \cdot i \tag{2}$$

Where:
EE = million tonnes CO_2e saved [CO2]
U = number of housing units to be renovated [no of units]
a = the average unit size in EU [m2/unit]
μ = the mean of potential savings of phase A5 obtained from RG1 [kWh/m2]
i= GHG emission intensity of electricity generation [CO_2e/kWh]

EE REDUCTION CONSIDERING SOME UNCERTAINTIES

The previous EE estimation is uncertain mainly due to three assumptions: (1) it is uncertain how many of the renovation projects in Europe can be expected to optimize productivity by implementing Lean construction principles, (2) there are significant uncertainties in the effect improved VAW and DW have on reduced execution times; and (3) the future GHG emission intensity of electricity generation is uncertain. These uncertainties should be taken into consideration as suggested in equation 3.

$$EE_u = EE \cdot imp_u \cdot e_u \cdot i_u \tag{3}$$

Where:
EE_u = million tonnes CO_2e saved including estimation uncertainties [CO_2]
EE = million tonnes CO_2e saved [CO_2]
imp_u = Lean implementation uncertainty [%]
e_u = execution time uncertainty [%]
i_u = GHG emission intensity of electricity generation uncertainty [%]

METHODS FOR RESEARCH GOAL 3 (RG3)

To pursue the last goal of this research study, the authors calculated the Operation Energy (OE) emission of each case regarding the Direct Work (DW) measures of each study.

For that, the identified productivity improvement in RG1 was indirectly linked to a potential OE saving occurring as more housing units can be renovated for the same cost. This allows to identify the additional units that can be renovated. To achieve that, the authors proposed the equation 4. However, several assumptions were required to estimate the OE carbon saving on the macroeconomic scale. Most significant was the GHG emission intensity of electricity generation, and the difference in energy framework between the current average housing standard and future nZEB standard.

$$\Delta U = U \cdot imp_u \cdot e_u \cdot \Delta p \tag{4}$$

Where:
ΔU = additional units that can be renovated [no of units]
U = number of housing units to be renovated [no of units]
imp_u = Lean implementation uncertainty [%]
e_u = execution time uncertainty [%]
Δp = improved productivity [%]

Finally, these additional energy renovated housing units, ΔU, will have a superior energy performance compared to before renovation, thus the OE will be reduced. To estimate the CO_2 saved for these additional renovated units, the present authors proposed equation 5.

$$OE = \Delta U \cdot \Delta OE \cdot y \cdot a \cdot I \tag{5}$$

Where:
OE = million tonnes CO_2e saved [CO_2]
ΔU = additional units that can be renovated [no of units]
ΔOE = operational energy saving [$kWh/m^2/year$]
y = expected lifetime of a renovated building [year]
a = the average unit size in EU [$m^2/unit$]
i= GHG emission intensity of electricity generation [CO_2e/kWh]

Findings

The findings section presents the results according to the three main goals of this study.

FINDINGS FOR RG1 - LEAN IMPLEMENTATION TO IMPROVE CONSTRUCTION EFFICIENCY

The Work Sampling results of the four case studies are outlined in Table 6. The first row lists the four cases, the second row presents the measured DW levels found from the WS application, and the fourth row gives the total number of data points from the WS study. The Table shows that DW levels are lowest in case 1 and increase steadily going towards case 4. Table 6 shows the LID being lowest in case 1, increasing steadily going towards case 4.

Table 6. DW levels from the four studies

	Case 1	Case 2	Case 3	Case 4
DW	26.0%	33.0%	36.0%	40.7%
LID	0.35	0.46	0.86	1.99
n	29,884	3,927	13,682	861

Figure 2 plots the DW levels and LID from the four cases together using two different y-axes, with the left being in percent reflecting the DW level and the right going from 0-5 reflecting the LID. Figure 2 reveals a seemingly positive linear relationship between the two variables. Regression analysis was conducted to assess the correlation. LID was the independent (predictor) variable, and DW was the dependent (response) variable in the regression analysis.

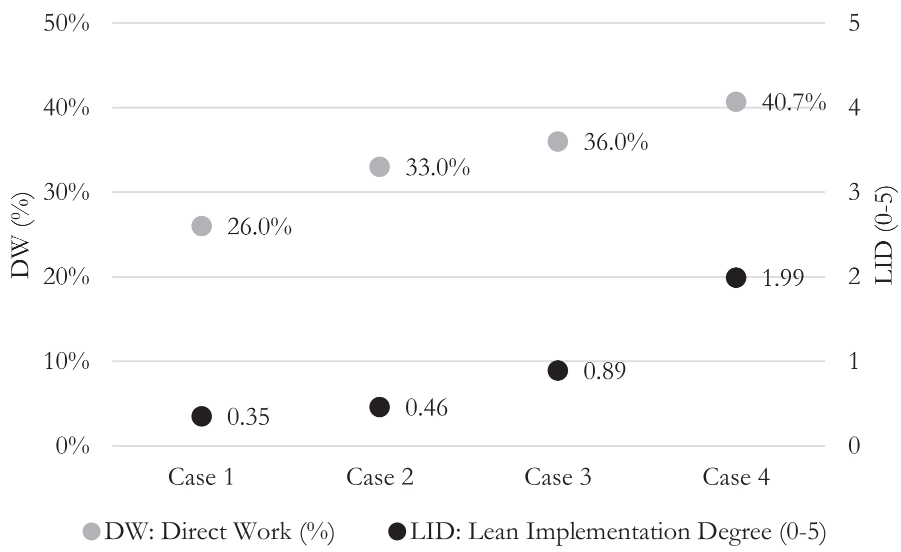

Figure 2. Connected DW and LID values for the four cases.

Table 7 presents the result of the linear regression with the final model, the number of data points (N), t-Test outlining the 95% confidence intervals for the predictor coefficient (a) and constant coefficient (b), Effect Size (correlation coefficient (R)) predictive capabilities (R2) and the ANOVA analyses giving the statistical significance level.

Table 7. Result of linear regression analysis

Model Y=ax+b	N	a	b	R	R^2	ANOVA p-value
y=7.21x+27.27	4	[-4.84;19.26]	[13.68;40.87]	.876	.768	.124

x=LID, b=constant and y=predicted DW level

The regression analysis showed an effect size (R) of .876, which far exceeds .5, which often is the lower limit for large effect size. The predictive capabilities (R2) match well with the coefficient's confidence intervals. This shows that the Lean Implementation Degree had a large effect on DW and thus CLP.

The statistical significance level at 87.6% (p=.124) reflects that in 1 out of 8 cases, the DW changes are not explained by LID. This is lower than the 95% (p=.05) statistical confidence level, usually regarded as the lower limit where the risk of a false result is 1 out of 20. This shows that the result is relevant and has an apparent effect, but the regression model included some uncertainty. Besides, regression analysis with a low sample size (N=4) should often be interpreted with limitations. This was an explicit limitation in this research and should be kept in mind when interpreting the overall conclusion.

To further test Lean's ability to improve construction productivity, case 1 was closely examined. The case was observed three times in total to collect DW data. A baseline when only limited Lean methods were implemented was collected 6 months after construction started. It was essential to observe typical construction conditions, and not during start up and learning. A second observation was done after 15 months when some Lean methods were initially implemented. The Last Planner System (Ballard 2000) was partially implemented on the site. It was solely the project and site managers who implemented and trained superintendents and subcontractors. It was later observed that the LPS method was gradually de-implemented, and at year 2, only a weekly meeting was left, and the case did no longer work with the seven flows, look-ahead planning, or PPC. However, short daily huddles on the site and weekly whiteboard meetings to identify critical tasks and solve emerging and critical production issues were also implemented. The weekly whiteboard meetings continued through construction. When the site management removed attention from these daily meetings, superintendents and craftsmen soon began to not conduct daily huddles any longer.

An additional 9 months later, the third and final observation was carried out. At that time, Location-Based Scheduling (LBS) (Kenley and Seppänen, 2009) and a visible site manager concept were implemented in addition to the above. LBS soon became the dominant scheduling and production update tool and continued to be so until the project was completed. It also changed the weekly meeting, where the process manager was now in charge and navigated through next week's tasks and locations. In addition, the process manager weekly updated the plan with a 12-week look ahead.

Work Sampling was applied during all three construction site visits to gather data to determine how craftsmen used their working hours. The collected WS results are shown in Table 8.

Table 8. WS data collected on case 1

		Direct Work	Indirect Work			Waste Work		
		Producing	Talking	Preparing	Transport	Walking	Waiting	Gone
Baseline (based on n=29,884 observations)								
$\bar{p}$	(%)	26.0%	20.9%	15.7%	7.7%	6.3%	6.7%	16.6%
15 months (based on n=4,507 observations)								
$\bar{p}$	(%)	34.0%	11.0%	20.2%	9.1%	10.5%	3.6%	11.7%
24 months (based on n=1,891 observations)								
$\bar{p}$	(%)	35.1%	10.5%	15.5%	12.4%	11.8%	3.7%	11.0%

A significant increase in productive time was observed from the baseline (limited Lean implementation) to 24 months later (several Lean tools implemented). That the workforce now spent more time on value-adding activities did effectively also mean that the productivity was increased respectively. DW was improved by 35% from 26.0% to 35.1%, cf. Table 5. This is a significant improvement. Improved was, in particular, the Talking category, which more than halved, showing that planning and coordination improved, leaving fewer issues to be clarified. The credit for this was mainly the implementation of LPS and LBS in combination. Waiting and Gone categories had also been reduced. Waiting time was reduced by 45% as an effect of improved flow. The logistics were an increasing issue during the project. As work progressed, the construction site layout became less and less effective. The distances from worksite to material storage, equipment containers, cars, site offices, and service pavilions increased. Only smaller adjustments were possible due to the layout of existing buildings and the infrastructure of the neighbourhood. Overall, movement (Walking and Transporting categories) increased 73% from the baseline to time 24 months.

The number of observations was fewer from the first round of construction site visits to the last round of visits for several reasons. Firstly, the baseline observation was highly detailed, with observations every 2 minutes from morning to work ends in the later afternoon for 5 days in a row, including observing 5 different trades each of 3-5 workers. The reason was that the observation was part of a large research project set out to understand the renovation as a production system (Neve and Wandahl, 2018; Neve, et al., 2020). The large amount of data in the baseline sample was not needed to obtain a statistically valid sample. Further, as WS's data collection is very resource-demanding, it was decided to collect fewer data points for the two following samples. Visually, the approval of a smaller sample size can be based on a stabilization curve, where one can track the fluctuation in the average DW value as the number of observations grows, cf. Figure 4. Theoretically, several studies have concluded that at least 510 data points must be collected in a WS sample to obtain a 95% confidence level (Gouett, et al. 2011; Hwang et al. 2018; Thompson, 1987). To validate the third and final observation, the stabilization curve with a 95% confidence level is illustrated in Figure 3.

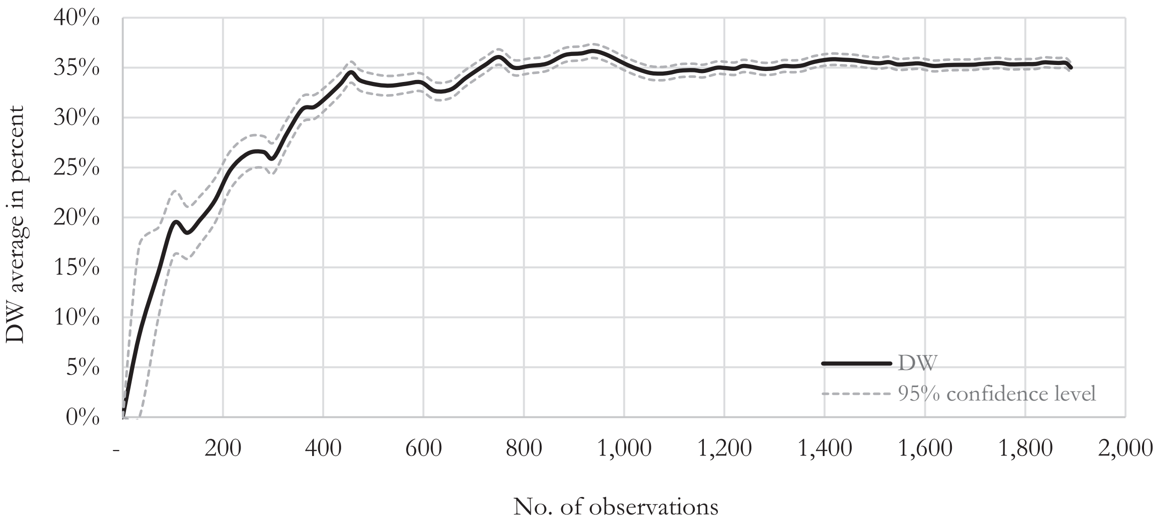

Figure 3. Stabilization curve for DW values of the renovation case.

It can be concluded that the amount of data was enough to make a valid conclusion of a productivity increase of 35% due to the implementation of Lean methods. Besides, on concluding the four case studies, it was clear that there is a relationship between Lean implementation and performance increase.

Research findings showed that it is possible to significantly improve construction efficiency by implementing Lean construction tools. The case studies showed that DW could be enhanced by 35%, and potentially even more. If a LID of 2.5 out of 5 is achieved, a DW of 45%, cf. Table 7 is achieved. This is significantly higher than typical renovation DW values reported. For further analysis in this research. Therefore, an improvement of DW from 31% to 45% is applied, which equals a relative improvement of 45%. In the case that efficiency improvement results in shorter execution times, it is not the improvement of VAW times (the 45% relative improvement) that is relevant, instead, it is the reduction of NVAW. The reduction is from 69% to 55%, which is a 20.3% relative reduction. Thus, improving DW by 45% will at a maximum result in a 20.3% shorter execution time.

FINDINGS FOR RG2 - CONVERTING DIRECT WORK TO EMBODIED ENERGY EMISSIONS SAVINGS

The findings of RG1 showed that shorter construction execution time is feasible. Shorter project execution times result in a shorter time where the contractor needs to have a production facility, i.e., a construction site. Any production facility requires energy to be run. On a construction site, this is typically: (1) energy to run machines and equipment; (2) energy for lighting, heating, and de-humidifying; and (3) energy to site offices. If the execution period is shortened, the energy consumption decreases.

As outlined in the introduction section, there is an international ambition to reduce GHG emissions due to energy use in the lifecycle of buildings. Energy use therefore needs to be converted into GHG emissions which often is expressed in CO_2e. The conversion of kWh to CO_2e for a specific case depends largely on the local energy mix, i.e., the mix of various fossil fuels and renewable sources in the energy production. Currently, the GHG emission intensity, i,e., of electricity generation is in Europe average of i=275 g CO_2e/kWh (EEA, 2021). However, this is expected to decrease over time to less than 100 g CO_2e/kWh in the year 2030 due to increased penetration of renewable energy production.

The results obtained from the four-case studied conducted to achieve the first research goal of this work indicated that improving DW by 45% will lead a reduction of a maximum 20.3% of execution time. Having this in mind, Table 9 illustrates the impact a 20.3% reduction of execution time would have on the EE in phase A5 for each of the cases identified previously in the literature.

Table 9. Possible reduction of EE in A5

	Size [m²]	Duration [months]	EE in A5 [kWh/month]	Saved EE in phase A5 if the duration is 80% [kWh/m²]
DK1	33,500	33	159,379	31.4
DK2	6,200	14	46,500	21.0
DK3	10,000	11	113,636	25.0
DK4	9,000	30	19,200	12.8
DK5	92,000	14	126,643	39.4
TY1	410	12**	5,057	29.6
TY2	450	15**	5,963	31.8
TY3	100	12**	1,192	28.6
NO1	9,207	24	12,660	6.6
SE1	3,982	12	31,192	18.8
SE2	8,173	24	39,843	23.4
SE3	198	12**	2,409	29.2
SP1	17,724	24**	53,172*	14.4
SP2	25,932	30**	135,063*	25.0

*MJ converted to kWh. **not reported, thus assumed by authors.

The saving potential in Table 9 has a large variation, from 6.6 to 39.4 kWh/m², which is almost a factor of six. The sample has a mean value of μ= 24.1 kWh/m² and a standard deviation σ=8.7 kWh/m². Outliers are defined as data points that are more than one standard deviation away from the mean, and these are removed from the sample. The mean of the new Lean sample is a potential EE saving in phase A5 of μ= 26.4 kWh/m², and this value is used in the further analysis.

The identified saving potential of EE in phase A5 (26.4 kWh/ m²) was converted to CO_2e, resulting in a saving potential of 7.3 kg CO_2e/ m². For an average renovation of a multi-dwelling residential building of 5,000 m2, the total saving potential is 36.3 tonnes CO_2e. This is roughly is equivalent to a 135 persons' airplane one-way flight from Frankfurt to Madrid and is therefore not immediately a significant impact.

However, a significant impact arises as a consequence of the scale as the EU has the ambition to renovate 35 million building units. An average housing unit in the EU has a size of 96.4 m2 (Eurostat, 2021) thus, the total built residential area to be renovated during the next 10 years in the EU is approximately 3.4 billion square meters. The CO_2e saving potential due to improved construction site productivity would be 24.6 million tonnes CO_2e. This value was obtained from equation 2:

$$EE = U \cdot a \cdot \mu \cdot i = 24.6 \text{ million tonnes } CO_2e \tag{2}$$

Where:
$U = 35{,}000{,}000$ [no of units]
$a = 96.4$ [m2/unit]
$\mu = 26.4$ [kWh/m2]
$i = 275$ [g CO_2e/kWh]

This emission is 0.1% of the world's annual emission, or in other words, almost equivalent to the national annual CO_2 emission of Denmark. For a better estimation, the following three assumptions were adopted: (1) the number of renovation projects in Europe that can be optimized by implementing Lean tools and methods is at least 50% of the total renovation projects ($imp_u = 50\%$); (2) it was considered that at least 75% of the construction process time is reduced by improving VAW and DW ($e_u = 75\%$); (3) the future GHG emission intensity of electricity generation is reduced at least 75% ($i_u = 75\%$). These uncertainties were considered for calculating EE_u in equation 3:

$$EE_u = EE \cdot imp_u \cdot e_u \cdot i_u = 6.9 \text{ million tonnes} \tag{3}$$

Where:
$EE = 24.6$ million tonnes CO_2e [CO_2]
$imp_u = 50$ [%]
$e_u = 75$ [%]
$i_u = 75$ [%]

Hence, the potential CO_2e saving due to reduced EE in phase A5 as a result of improved construction efficiency for the EU renovation wave is estimated to 6.9 million tonnes of CO_2.

FINDINGS FOR RG3 - CONVERTING DIRECT WORK TO OPERATIONAL ENERGY EMISSION SAVINGS

The EU renovation wave target is 35 million housing units. From an environmental perspective, the benefit is that these housing units will have a lower energy consumption after renovation, thus also a lower rate of GHG emissions. The more housing units society can afford to renovate, the better is for the environment with regards to mitigating global warming. Improving construction productivity is a valuable catalyst in this effort. Improved productivity is equal to producing the same output faster or with less resources. Using fewer resources will save costs and realize the target at a lower price. Thus, theoretically, society can renovate more housing units at the same cost.

Considering that DW and productivity improvement result in a 20.3% decrease in resource consumption, a significantly higher number than the targeted 35 million housing units in the renovation wave can be achieved. In fact, 2.67 million (ΔU) more units can be renovated in the EU at the same costs, cf. equation 4.

$$\Delta U = U \cdot imp_u \cdot e_u \cdot \Delta p = 2.67 \text{ million housing units} \tag{4}$$

Where:
U = 35 million [no of units]
imp_u = 50 [%]
e_u = 75 [%]
Δp = 20.3 [%]

These additional energy renovated housing units, ΔU, will have a superior energy performance compared to before renovation, thus the OE will be reduced. An EU average housing unit uses 200 kWh/m²/year (Enerdata, 2021), whereas an nZEB building uses around 50 kWh/m²/year (Groezinger, et al., 2014). The saved CO_2 is calculated in equation 5 for an expected 50 years life span.

$$OE = \Delta U \cdot \Delta OE \cdot y \cdot a \cdot i = 386 \text{ million tonnes } CO_2e \tag{5}$$

Where:
ΔU = 2.67 million [no of units]
ΔOE = (200-50) [kWh/m²/year]
y = 50 [year]
a = 96.4 [m²/unit]
i= 0.200 [kg CO_2e/kWh]

The indirect potential OE saving of upscaling construction productivity on the European housing renovation market is during the next 50 years 386 million tonnes of CO_2e. However, this is a potential but indirect benefit of improving construction productivity. The potential OE savings by renovating more housing units are significantly larger than the EE saving of efficient and productive construction processes. However, the assumption is that the resource gains obtained by higher productivity are reapplied to renovate more housing units.

Conclusion

Renovating energy-inefficient houses plays a vital role in the effort of reducing the CO_2 emissions and achieve a more sustainable built environment. Among the EU leaders, a renovation wave has been agreed that should ensure that 35 million housing units should be renovated by 2030. In this research, the objective was to investigate how and how much an efficient and highly productive construction process can act as a catalyst for reaching even higher CO_2 savings in the renovation wave effort.

The present research aimed to demonstrate that it is possible to improve construction labour productivity by implementing Lean tools and methods on renovation projects and that this will reduce both the EE during construction and ensure future OE savings. For that, the authors conducted an exploratory case study in four domestic housing renovation projects. In order to achieve the main goal of this project, three research goals were proposed: (1) to demonstrate the effect of implementing Lean tools and methods in renovation projects to increase construction productivity; (2) to investigate and quantify the correlation between improved productivity and the buildings' lifetime energy performance; and (3) to investigate and estimate the potential indirect effect a more productive renovation process has on reducing operational energy emissions.

In research goal 1, the results showed that a causal correlation between Lean implementation degree and construction labour productivity exists. A potential construction labour productivity improvement of 45% is demonstrated by the adoption of several Lean tools, practices, techniques, and methods. Research goals 2 and 3 investigate and quantify the emission savings in both EE and OE this improved productivity can create. The potential EE emission saving in the construction phase is estimated to 7.3 kg CO_2e/m². On a project level, the EE emission savings can be considered relatively low compared to the overall emission from a construction project. However, if sustainability of scale is considered, and EE emission savings was achieved on all the 35 million housing units to be renovated in the EU renovation wave, the result would be an overall 24.6 million tonnes CO_2 saving. The potential OE emission saving is only assessed on the macroeconomic scale of the EU renovation wave. The potential long-term OE emission saving is estimated to 386 million tonnes CO_2e.

A number of limitations should be considered when interpreting the emission-saving results, as a high degree of uncertainty applies to this research. The EE emission saving calculated only considered the construction phase of the buildings, named as phase A5 by the European Committee for Standardization (CEN). Few LCA studies report EE for phase A5. Thus, the data foundation for the EE-saving conclusion is weak. The EE emission saving in LCA for phase A5 is based on only the 14 case studies identified in the literature. More research should be established in this field. Also, the shown OE emission saving potential includes a large assumption. It is assumed that resources saved due to higher productivity is reinvested to conduct additional renovation projects, with additional OE savings as a consequence.

Nonetheless, the findings are highly relevant to both academia and industry. The link between process improvements and reduced energy consumption and emissions is a focal point worldwide and can support politicians and infrastructural developers in decision-making for a more sustainable built environment.

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