IOP Conf. Series: Earth and Environmental Science 1122 (2022) 012061 doi:10.1088/1755-1315/1122/1/012061

Process-specific digital recording of construction site LCA-inventory to identify decarbonisation pathways

A Wagner[1]
S Ott[2]

Chair of Timber Structures and Building Construction, Technical University Munich

[1]anna.wagner@tum.de, [2]ott@tum.de

Abstract. In building life cycle assessment, construction site processes are currently hardly accounted for in detail. If considered, the emission values are determined by globally capturing effort values and by allocating them to individual work steps, equipment, or materials. To identify improvement potential to decarbonize construction activities, detailed process data must be captured for specific processes to determine the carbon dioxide emissions of single processes. The results can then be aggregated to larger process units e.g. to components or trades. To fully implement this approach, a recording of process-specific data at construction site is necessary. Therefore, the basic framework to record specific processes at construction site is developed in this article and LCA methodology to systematically link them to emissions is explained. Further, the method of computer vision for automated recording of construction site activities is being presented.

1. Introduction

To meet the climate protection goals of the Paris Climate Agreement, the European Union (EU) defined targets and measures. Within the scope of the *Green Deal*, which aims for a climate-neutral Europe by 2050, the EU's *Fit for 55* legislative package was implemented [1]. By means of this package, the reduction of net greenhouse gas emissions by 55 % in relation to the reference year 1990 should be reached until 2030. This means for the building sector in Germany, which accounts for 33 % (direct emissions from operation of residential and non-residential buildings) of the total national Green-House Gas emissions (GHG emissions) [2], that they have to be reduced by around 40 % until 2030, compared to the direct emissions in 2020 [3].

Not only building operations, but also construction sites can significantly consume energy and entail climate-damaging processes. In the city of Oslo for example, heavy-duty construction machinery causes over 20 % of total carbon dioxide (CO2) emissions [4]. However, due to missing data about processes at the construction site, and insufficient understanding of environmental impacts of the construction stage, effects are currently hardly considered in detail in life cycle assessments (LCA) [5,6]. To map emissions over a building's whole life cycle, it is necessary to take the environmental impacts of construction site activities into consideration [6,7].

Due to the reporting obligation on Environmental, Social and Governance (ESG) criteria, it will become more and more relevant for companies to identify and apply levers for reducing GHG emissions from construction site processes. To do so, it is necessary to create a robust data basis and a suitable method for evaluation.

2. Research state and gaps

2.1. The construction stage in life cycle assessment
According to DIN EN 15804:2020-03 [8] and DIN EN 15978:2012-10 [9], the construction stage in LCA is divided into the information modules A4 *Transport* and A5 *Construction*. Thus, the construction stage begins after the factory gate and ends with a building's use. However, to ensure comparability, prefabrication processes should be considered in life cycle assessment of the construction stage, even if they take place in the manufacturing stage [10].

At the beginning of every life cycle analysis in construction, it is important to define the objective and the scope of the analysis. This includes defining the product system, the associated process modules and the system boundaries [8,9].

According to DIN EN 15804:2020-03 [8], a process-LCA of the construction stage describes which process modules and associated elementary and product flows the information modules A4 and A5 generally contain. This includes:

- the energy flow as well as the flows of materials and products,
- the processing, disposal or recovery of waste produced in modules A4 and A5,
- and their influences and losses occurring within modules A4 and A5.

The information modules also include:

- the transport to the construction site,
- the energy and water consumption for the construction processes,
- the storage of the products and related energy consumption as well as preparation processes for products on the construction site and during transport,
- and the production of additional products at the construction site [8].

2.2. Share of environmental impacts of the construction stage in the building life cycle
With regard to the share of environmental impacts in the construction stage, different LCA-studies [10–13] show that the emissions from the construction stage account for a small share in contrast to those from the manufacturing stage. For example, according to [13], GHG emissions from electricity, fuel and water consumption and waste disposal for construction site processes account for 6.4% to 8.6% of the emissions from the manufacturing and construction stages. The transport of materials to the construction site accounts for 6.1 % to 8.4 % and sum up to 17 % in total for site operation [13]. According to Takano et al. (2014) [10], 6 to 10 % of total emissions from the manufacturing and construction stage are caused in the construction stage. Despite the relatively low share, there is a need to assess the emissions of the construction stage, because the related processes hold significant improvement potential for the construction industry [10].

2.3. Top-down approach to determine environmental impacts in the construction stage
The processes of the construction stage and their complexity are influenced by the individuality of the construction site and the respective boundary conditions [7]. Currently, most construction site activities are manually and hardly automatically recorded [14]. Further, the determination of the environmental impacts of construction site processes is not yet possible due to missing data [5]. As a result, emissions have so far been captured globally for the entire construction site or for large equipment like cranes (e.g. [13,15]). Only few recent examples (e.g. [16]) capture detailed data of individual construction processes and make even sub-process data traceable. The global tracking method, which we call *top-down* approach in this article, measures the consumption of e.g. diesel of the entire construction site and allocates e.g. the fuel spent for a specific material or process by volume, individual materials or activities. For example, [15] determined the water and electricity consumption globally across the entire construction site per m^2 of gross floor area (GFA). The consumption per m^3 concrete was then calculated by allocating the proportion of concrete per m^2 GFA. Due to such allocations, data about activities of individual machines can be generated and thus, emissions can often only be roughly allocated to construction sections, but not to individual building components.

To obtain consistent results for emissions during construction stage and to take into account the individuality of construction sites, processes and their environmental impacts must be determined and recorded in detail [7]. To apply and to validate the described approach in practice, the construction activities for the erection of two residential concrete buildings and two residential timber buildings are being analysed as part of a research project which started in March 2022. Since the focus of this project is to develop a method to calculate emissions during the construction stage, the shell of both, concrete, and timber buildings, is considered.

2.4. Bottom-up approach and Lean Construction

In the context of *Lean Production* or *Lean Construction*, analyses and improvements about disturbance-free, error-free and efficient construction activities can only be enabled at construction process level [5,17]. Furthermore, to simulate construction processes, detailed process steps to provide a complete picture of all construction activities of a building are required [18]. The process steps are divided into construction activities for different trades or to produce individual components. This structure enables the variation of effort values of individual parameters, for example of a construction machine. In such way, an optimisation can be achieved by reducing the associated effort. For the holistic consideration of emissions of jointing-processes and the auxiliary materials and equipment, processes have to be further divided to the sub-process level [19].

We call this detailed process analysis *bottom-up* approach. Through this approach, specific sub-processes are examined, measured, and analysed, and the processes with major emissions are detected. Examples of this very detailed approach are shown by [20,21].

2.5. Reasons and limits for a mixed approach and for a bottom-up approach

To calculate emission more precisely and to record the environmental impacts of particularly environmentally harmful processes, some publications use a mixture of *top-down* and *bottom-up* methods [10,12]. In such way, not all sub-processes can be captured in detail and variations of the overall processes or parameters cannot be retraced.

The overall objective is to carry out life cycle analyses for the sake of process improvement and emission reduction. To achieve this objective, the emissions must be precisely assigned to the belonging process by using the *bottom-up* approach. Such a procedure is also required within the framework of DIN EN 15804:2020-03 [8] and DIN EN 15978:2012-10 [9]. Concerning the calculation of effort values, the mixture of the two methods results in different levels of detail and accuracy. Strictly speaking, this violates data consistency and consequently ignores a constraint of life cycle analysis. However, the determination of the emissions of the production stage in information modules A1-3 and thus, the compliance with this requirement, is only possible to a limited extent due to the lack of detailed effort values. Hence, the two approaches are often combined. This consequently means that the consumption of certain factory-related processes is e.g. allocated from the global electricity consumption of the factory. Consequently, data consistency should be maintained as far as possible by collecting accurate data for applying the *bottom-up* approach.

Since this article is about the decarbonisation of processes at the construction site, the focus is on module A5 and on processes that result in GHG emissions. The procedure to determine GHG emissions from transport for module A4 equals the procedure to determine the emissions of module A2. Water consumption on the construction site is not considered in this article, as this does not result in direct GHG emissions.

3. Using computer vision to capture construction site information

To determine process-specific construction site emissions, on-site process information must be identified and captured. It is important to capture the data precisely for each component and trade because this provides the necessary transparency and the possibility to act in accordance with lean management and hence, to effectively reduce emissions within the respective disciplines.

To determine the emissions of the construction stage, the application of the *bottom-up* approach based on process-accurate data and component- and trade-specific emissions, requires new data-collection methods. Computer vision can be used to identify products and product systems and to link them with associated processes [22]. With computer vision, image data can be automatically evaluated and processed by identifying and classifying time-dependent pixel values (segmentation). Further computer vision methods are the identification of objects, tracing as well as three-dimensional reproductions [23,24].

Both in research and in practice, image data processing is used, e.g. to monitor and optimise construction site processes concerning progress and safety [25]. As current research shows, the use of image-data combined with object-detection and tracing seems to be an adequate way to identify construction components [26]. Nevertheless, the component-related identification of construction activities with computer vision still shows improvement potential, especially concerning occluded objects or difficult lighting situations [23].

However, to the authors' knowledge, the use of this method to collect relevant data for the determination of environmental impacts that occur during the construction stage has not yet been put into practice.

4. Determining process-specific on-site emissions

To determine process-specific emissions of the construction stage based on LCA, the identification and description of the associated process modules and system boundaries is required. To collect the necessary data, this article proposes computer vision, which can be used as a method to generate inventory data (see figure 1). By collecting data to determine effort values and linking them to impact indicators, emissions can then be calculated for the respective process module.

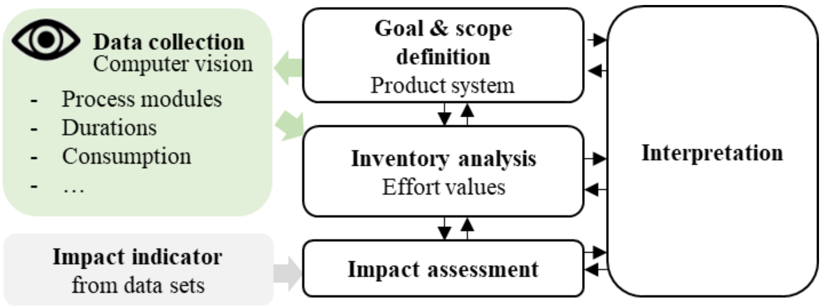

Figure 1. Using computer vision to capture data for life cycle assessment.

Thus, process modules associated with e.g. the crane work can be precisely defined. In such way the energy consumption of the crane can be assigned to these specific process modules. Thus, the lifting of an object (e.g. precast element) with the crane can be identified and the associated time span can be determined. In combination with the electrical power of the crane, an effort value for lifting this object can be determined.

To describe a building's production, a building can be described by a so-called *production model*, linking the building with the associated construction processes. The building itself can be described by a *product model*, which is linked to the *production model*. The elements of the *product model* directly influence the *process model*, in which information on the operations, sequences, sub-processes and resources are described [27].

In general, the information necessary to determine the effort values of individual processes and products (components) can be structured as shown in figure 2.

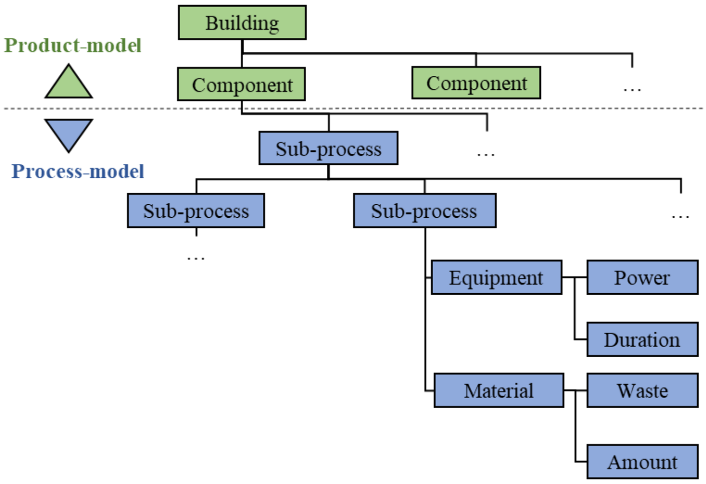

Figure 2. Construction stage products and processes according to [27].

Sub-processes are subdivided into interlinked, individual process-components at different levels of detail that represent a higher-level process [27]. In the end, the individual process modules depend on this description. As materials and equipment must be considered for a holistic accounting of the construction stage in LCA [7], the lowest hierarchy level shown in the figure divides the process modules into material and equipment. The life cycle inventory data for module A5 can be determined based on the information regarding the consumption and the use time of the equipment for a specific process module and the required material amounts for a specific sub-process (only material which has not been considered in information module A1-3, e.g. auxiliary and connectors).

By linking process-specific effort values of the associated equipment and materials to impact indicators, the emission-relevant input and output flows of the individual sub-processes can be quantified and aggregated to component-specific emissions (see figure 3).

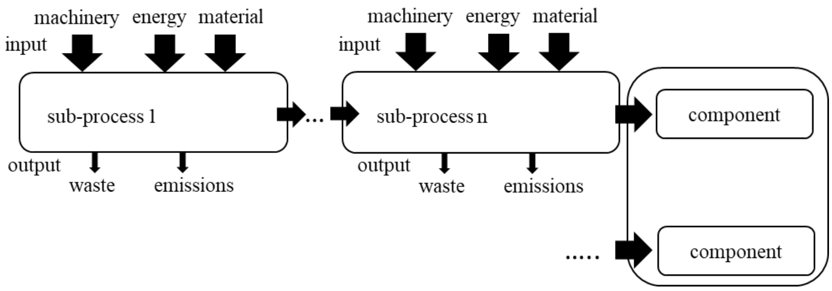

Figure 3. Scheme of sub-processes, inputs and outputs according to [11].

5. Using computer vision to generate effort values

To generate effort values to quantify the life cycle inventory of module A5, the applicability of computer vision based on continuously recorded video data is investigated. In the ongoing research project, a camera system attached to a crane on-site is used to continuously capture image data. To take a first step towards continuous and automated recording of the life cycle inventory data, relevant objects and processes for *bottom-up* modelling of the emissions are initially identified in this project, based on the image data and on a monitored electrical load profile.

First investigations with *OpenCV* (*Open Source Computer Vision Library*) for edge and corner detection, colour recognition and contour hierarchy have been conducted. These investigations show that relevant objects and effort values for bottom-up modelling of emissions can be identified based on the image data and a load profile measurement of the electricity consumption of the construction site.

This enables to recognise i.e. a precast element and to track the movement of the element from the truck to the mounting location. In such way, to quantify the life cycle inventory for module A5, construction site activities should be derived from automatically and continuously recorded film data from a construction site camera. For this purpose, semantic objects i.e. mostly construction machines, equipment and the objects involved in the process (e.g. formwork, concrete bucket), must be identified in the film material by segmentation and object recognition. Further, they must be tracked in relation to space and time. This is necessary to make the determination of the associated durations, energy-related data or material flows possible.

The difficulty here is to assign processes related to the process model to a component related to the product model. This is because in the context of the construction process of the individual construction site, non-linear manufacturing processes are difficult to assign to individual components. The reason for this is, that the simultaneous manufacturing processes of different components or the use of the same equipment for different components of the product model can lead to interruptions in the component-specific process chains. For example, sequential processes related to the construction of a concrete wall (see figure 4 and figure 5) can be localised and tracked in the image with edge-recognition.

To generate component-specific effort values, it is then necessary to establish a link between this process data and the associated object of the product model (here: reinforced concrete wall). Until now, such an assignment has not been necessary for the application of computer vision in construction (e.g. for progress control). With existing methods, the erection of a precast element can be captured, since the sub-processes (transport of the precast element with the crane) are not interrupted by sub-processes. In contrast, this is difficult for more complex construction site activities, such as the allocation of individual sub-processes of a reinforced concrete wall to the wall element itself. This is e.g. because one challenge is to assign the crane processes to this specific wall element, since the crane is usually used to erect different buildings or components during the production of the wall element.

Figure 4. Image sequence showing concreting of wall, transport processes and excavation on-site.

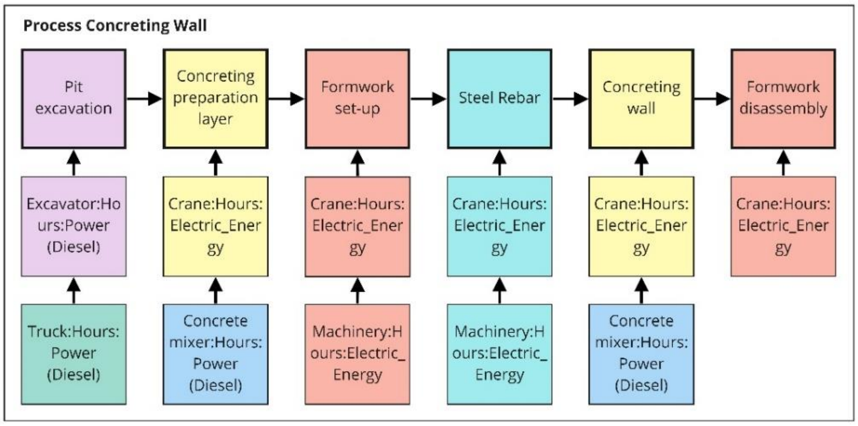

Figure 5. Main- and sub-processes for the construction of a wall.

Heat maps or movement paths of objects such as workers can be used to detect high activity in the image section and thus to locate the objects (see figure 6).

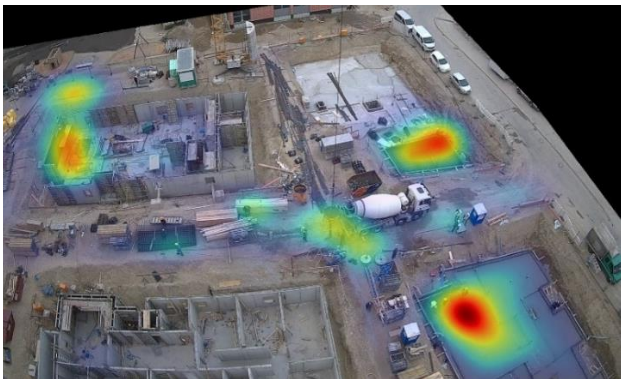

Figure 6. Heatmap to detect activities at construction site.

In combination with objects (e.g. concrete mixer), the construction progress of the concreting process of a wall can be tracked. Other processes such as the crane moving the concrete bucket can be recorded. However, due to limited image resolution, it appears difficult to record other sub-processes with sufficient accuracy such as the vibrating of the concrete. Hence, it can be assumed that further data is required to record and evaluate such sub-processes. E.g., such data could be generated by recording the load profile of the electric-power supply of the construction site. In addition to this continuously generated data, data from e.g. construction site records and BIM models, must be considered to calculate emissions based on process-accurate *bottom-up* data.

6. Discussion and conclusion

The theoretical considerations in this article show that the necessary effort data for a process-specific determination of emissions in the construction stage could be recorded using computer vision. The application of the method to determine emissions from individual construction activities and to assign them to construction elements are further research steps. Based on this application, it must be investigated whether complex processes can be automatically assigned to building components.

A process-accurate recording enables the application of the *bottom-up* approach. This makes a more precise determination of the emissions possible, than the application of the *top-down* approach and can enable the evaluation of results for specific trades or components.

By systematically observing and recording specific construction processes with consistent principles and documentation, it seems to be prospectively possible to create datasets which include the environmental impacts and the resource use of construction site activities. Such data sets can then be used to apply LCA for decision-making in early planning phases.

Acknowledgments

This project is supported by GWG München, Bundesverband der Deutschen Ziegelindustrie, Holzbau Deutschland Institut and it is funded by Deutsche Bundesstiftung Umwelt (DBU FKZ: 38075/01). We would like to thank Oculai GmbH for the support in digitising the construction site data.

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