Digitalizing Building's End-of-Life

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Abstract:

The end-of-life phase of buildings' life-cycles is still missing a structured approach that could align digitalization with research and practice in a single flow of topics of interest, within and beyond the phase. Performed processes are often not understood in a larger context. They are not related to each other, despite the growing interest in the architecture, engineering and construction industry, and regulatory bodies aiming to address sustainability. With this research, a framework that can contextualize existing digitalization approaches is provided. Therefore, an overview of tasks performed by three project partners is used to propose a framework. It is conceptualized with lanes describing the actors, processes, and assets, and further divided into two parallel lanes dealing with physical and digital assets; the framework is verified with business models, research papers, projects, and regulations. It encompasses existing processes and provides a structured, high-level overview. This research serves as a base for defining relevant factors for each step of the end-of-life phase, required to determine the influence matrix needed for clarification of existing and future business models concerning both physical and digital assets in the phase of interest. The provided structured overview will be used to determine obstacles and potentials in the end-of-life phase, and overreaching influence on domains like circular economy, building planning or ecological performance.

Keywords: *end-of-life; building; digitalization; framework; physical assets; digital assets; BIM*

1. Introduction

Waste reduction is one of the priorities of the European Union (EU) and a principle (as part of the waste hierarchy) of the waste framework directive (WFD), regulating the waste definition and the general handling of waste, as well as goals to reach (EU, 2008). It directly corresponds to four sustainable development goals defined by the United Nations (UN): goal 9 - Industry, Innovation, and Infrastructure, goal 11 - Sustainable Cities and Communities, goal 12 - Responsible Consumption and Production, and goal 13 - Climate Action, and indirectly affects several more (UN, 2022). Goals 9, 11, 12, and 13 have middle to strong interaction with each other, as shown by van Soest *et al.* (2019); similarly, Bleischwitz *et al.* (2018) focus on the goals 2, 6, 7, 11, and 12 including energy, water, food, land and material, and their interconnection to propose a resource nexus. UN goals emphasize the importance of waste reduction. Waste in the architecture, engineering and construction (AEC) industry makes up a third of all waste produced in the EU (construction and demolition waste (CDW) infrastructure). It is worth mentioning that there is a high degree of divergence within the individual member states.

Disposal of waste may lead to loss of material and energy (Antunes *et al.*, 2021) and needs to be reduced to a necessary minimum to improve sustainability. Resources such as energy, materials, and building elements, can be considered for further use after their primary use has been terminated. A high-level framework could encompass handling different resources due to similar trends to minimize waste. Economic gains are often in a gray zone due to process complexity (Pun *et al.*, 2006), and incentives could drive new, more sustainable approaches in the future and encourage them in practice. Essential questions about the reuse of building materials also encompass legislative and market barriers, lack of economic driving forces, and no information about used construction products (Nordby, 2019). From the national economic point of view, it makes sense to promote high-quality end-of-life (EoL) processes because of the increased employment and value added (EC, 2014; Meyer *et al.*, 2018).

The EoL phase of buildings' life-cycles is still underinvestigated. However, it has become a popular topic across the AEC industry lately. Research and industry aim to reduce the amount of CDW, having the largest share of the total waste across different sectors. Numerous studies deal with various aspects of digitalization of that phase (Cetin *et al.*, 2021), such as building geometry scanning using LIDAR, relations to BIM, new business models, or assessing building stocks. Activities leading to reuse, recycling, or disposing CDW have existed for a long time with lower digitalization levels and varying efficiency. The digitalization of a building's EoL tends to increase recycling and reuse at the expense of disposal, and in that way reduce the production of waste. However, various EoL activities are being digitalized at once, making it difficult to position the existing practices, research, and tools in the EoL ecosystem. Detailed analysis of the supply chain and projects is needed for achieving Integrated Design & Delivery Solutions, which is seen as the next step in the digitalization of the AEC industry (Owen *et al.*, 2009). A structured overview of the phase is missing, which could integrate traditional and novel practices, pinpoint the gaps, and provide a base for regulations and novel solutions. The main goal of this paper is to provide a structured framework for the EoL of buildings, which considers both digital and physical aspects of the phase. A suitable framework should serve to improve the CDW management in the long term.

2. Existing EoL Frameworks

The EoL phase of assets is the least sustainable phase (Charef *et al.*, 2021), and it is hard to grasp from the practice perspective as well as research. It often involves topics such as the creation of a BIM model or simply BIM, design for reuse, design for deconstruction and disassembly. These are common processes of a design phase, as well as the reuse of one or more building elements in the novel building, and high-quality waste management which already belongs to the next life of CDW (Akbarieh *et al.*, 2020; Akinade *et al.*, 2017; Charef and Lu, 2021). The EoL phase occurs for each unique product and may take place multiple times during the building's life-cycle (Figure 1), ending in a final EoL phase when the building is demolished. To reduce the CDW, existing tendencies direct the use of CDW produced during various EoLs towards new service, within the building construction and beyond (Figure 1 - b). Currently, the most popular practices still direct the CDW toward the deposition (Figure 1 - a). An essential factor that should decrease CDW disposal is the digitalization of buildings´ life cycles (Cetin *et al.*, 2021) and hence EoL phase.

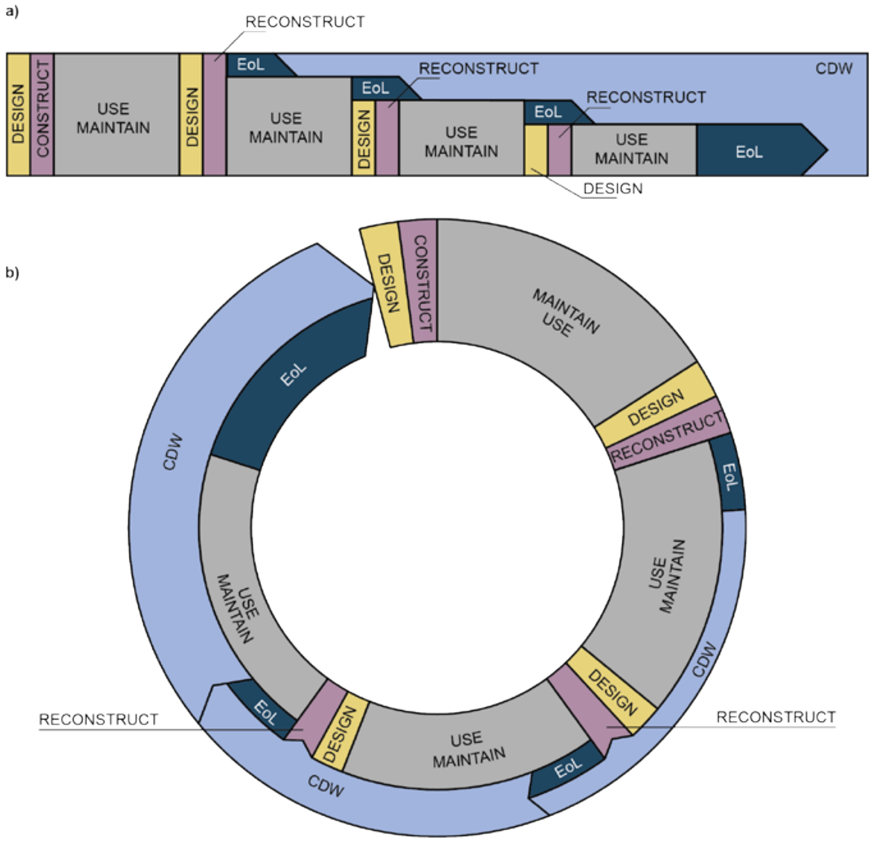

Figure 1 Schema of the EoL phase in a) linear and b) circular construction process (inspired by Bjork, 1999)

It is crucial to identify what the system limits of the EoL phase are to investigate it. Giorgi *et al.* (2018) present various approaches toward the life-cycle assessment, stating many uncertainties regarding its scope, as it occures in the future where large amounts of data are required for its achievement. Therefore, a unified, transparent data basis is crucial (EU, 2019). Based on Giorgi *et al.* (2018) EoL starts with the activity that produces waste and involves waste management. In EN 15978 (CEN, 2011) EoL is a “multi-output process that provides a source of materials, products and building elements that are to be discarded, recovered, recycled or reused”. This includes all the processes and the transport to the waste's final destination (EC, 2018).

Used metrics for the EoL phase are vague and may display the phase as less relevant in the whole life-cycle of a building. For instance, EN 15978 (CEN, 2011) proposes a cut-off approach, and thereby the benefits of a “new life” are not distributed to the EoL (Giorgi *et al.*, 2018). The basic framework for the EoL is EN 15643 (Austrian Standards, 2021), the relevant data in the form of EPDs ISO 14025 (ISO, 2006) in general, and EN 15978 (CEN, 2011) for buildings, and for building materials and products EN 15804 (CEN, 2019). It should be noted that the establishment of recycling, recovery and reuse does not necessarily lead to a reduction of environmental impacts, as shown by (Andersen, 2020; Demacsek, 2019).

Lopez Ruiz *et al.* (2020) propose a framework focusing on physical aspects of five life-cycle stages, but not aligning it to digitalization attempts. In their work, the EoL phase involves different types of deconstruction or demolition of buildings, is preceded by construction and building renovation, and followed by collection and distribution. Schutzenhofer *et al.* (2022) develop a framework for EoL based on the existing regulations in

Austria, and identify data requirements for CE calculations. Similarly, Yeheyis *et al.* (2013) developed a framework as a decision-help for reducing waste disposal, focused on the practices in Canada, based on environmental, social and economic indicators. BIM for various scenarios in EoL is investigated in Charef (2022). She identifies several models of how BIM can be used in the EoL phase, and emphasizes the need to consider the EoL at the project start. Akbarieh *et al.* (2020) provide a review of BIM supports for EoL, stating that a global framework is required for the uptake of more sustainable and circular buildings. Cetin *et al.* (2021) provide a Circular Digital Built environment framework and align it with multiple technologies. They align various digital solutions within the proposed framework, however the research scope is not focused solely on the EoL phase, which is not investigated in detail, nor the tasks within it.

As already identified in the literature, a global framework for the EoL phase is required. The novelty of our framework is on one side that we focus on the EoL phase and determine its limits. On the other side, we consider both digital and physical processes, as well as their alignment regarding the actors, processes and assets. A similar framework was not found in the literature. We find such framework to be necessary, for the future development of the EoL phase and further better understanding of existing practices and business models, intending to identify its enhancement potential.

3. Methodology

This paper aims to form a framework for positioning and evaluating the EoL phase in the AEC industry. The framework is conceptualized based on two research papers. Succar and Poirier (2020) propose a complex global framework for life-cycle information transformation and exchange. The framework aims to cover a great scope of possible scenarios in the AEC industry, with various scales, information flows, automation potential, etc. The scope of the herein presented research is solely the EoL phase of buildings. We concentrate on the deliverables or assets as described in Succar and Poirier (2020), which can be digital and physical, being interrelated in multiple ways. Sibenik *et al.* (2022) describe a 3A methodology for activity patterns that capture assets, activities and actors, with the aim to digitalize design workflows. These two approaches are combined to capture physical and digital assets, activities and actors within the EoL phase on a high level with less granularity. The captured processes are therefore not necessarily on the atomic level as described in Sibenik *et al.* (2022), and will remain named processes, as they may consist of multiple activities. The resulting lanes are produced via an introductory meeting with the consortium members of the project DiCYCLE. The consortium includes three companies dealing with different processes in the EoL phase who described their workflows and tasks in a nutshell. The meeting outcomes and consideration of the research papers mentioned above resulted in an initial framework structure.

After the framework setup, six lanes describing the EoL phase were generated (Figure 2). The verification of the framework model is applied to seven different business models (BMs) in the companies of the project partners, four research papers, seven regulations and four research projects. This verification is performed in order to (1) identify the activities currently performed in the EoL phase, (2) assess if the model is suitable to cover all the tasks and finally (3) fitting for understanding the roles of particular stakeholders and the assets of interest. The verification of business models is performed by sending a questionnaire to the corresponding experts familiar with these activities. The questionnaires were followed by three phone interviews. Scope and topics which the research covers is allocated in the proposed framework model. Afterwards, the results are mapped into the proposed process flows, considering actors and assets based on the inputs of project partners. Following the verification, possible improvements are concluded.

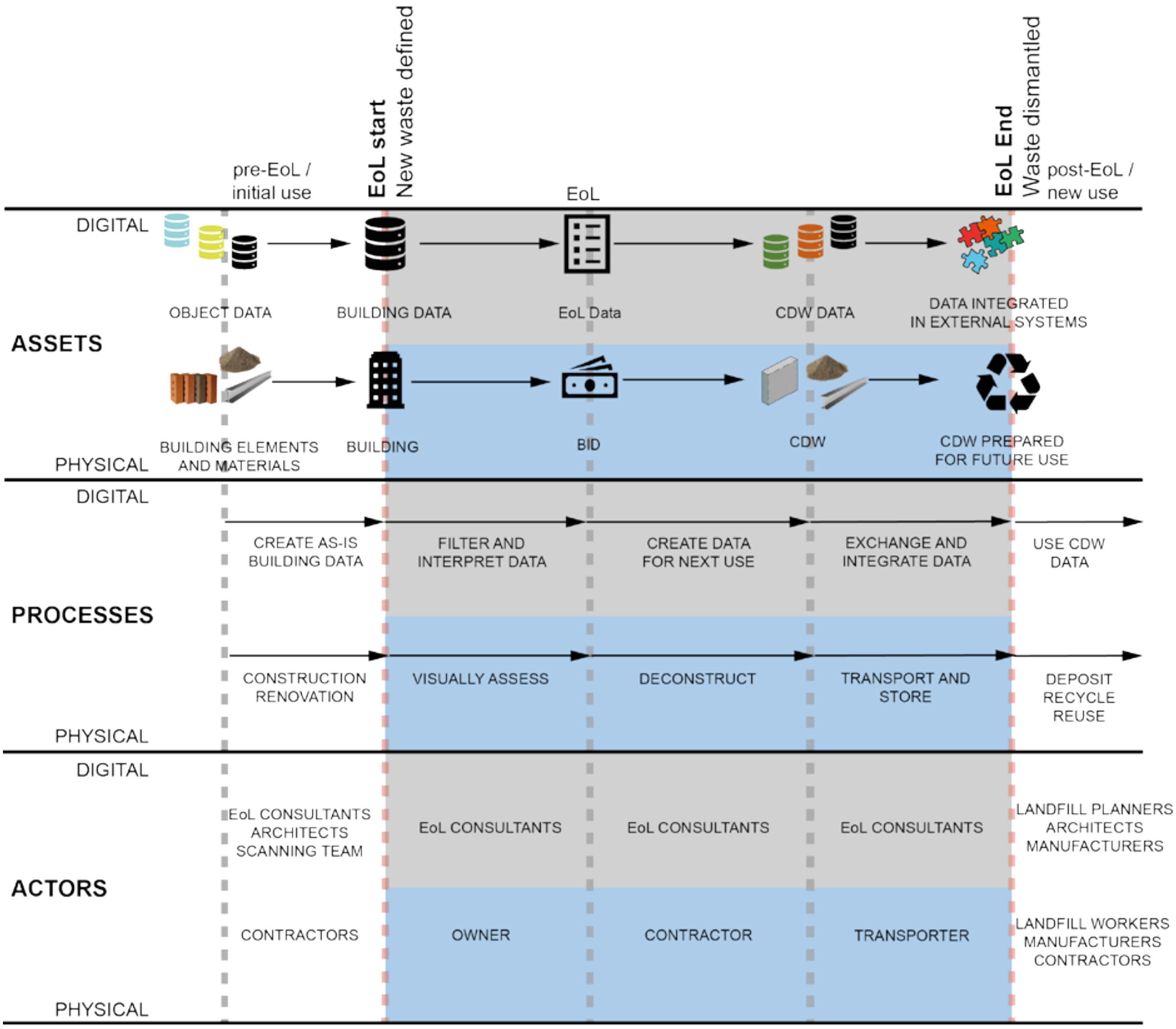

Figure 2 Framework for EoL phase

4. Results

The resulting framework is represented on Figure 2. It describes six lanes, including assets, processes and actors, each separated into digital and physical assets. There are several views on the EoL phase. This model aligns physical and digital assets, which means they occur at the same or close to the same moment. Therefore, an as-is BIM is a precondition for the digital support of the EoL phase, in the same way an existing building is a precondition for its deconstruction. A digital building model is used to create EoL data, which corresponds to the creation of bid for deconstruction. These two assets can be related if digital EoL data exists. The following digital asset is filtered CDW data for future use, or in the case of a physical asset, deconstructed CDW. The EoL phase lasts until the physical asset is transported from its existing position, whether on the site or to another construction site or deposition. Accordingly, digital assets are transferred to external system for further data use and management.

Processes dealing with digital and physical assets can take place simultaneously. Still, digital processes may be a precondition for a corresponding physical process, and such topics are described in Succar and Poirer (2020) in a wider scope. Herein the assets are related to each other as milestones, and provide a main organizational delimitators in the framework (vertical dashed lines). Regarding the digital process, preceding the EoL phase is the creation of BIM, which can be performed with numerous technologies, or be obtained from the continuous documentation of BIM from the preceding phases. As the EoL phase starts, the model needs to be filtered and interpreted to create EoL data. This data can be edited for next use, which is exchanged and integrated with other systems in the follow-up. As the data exits the system of the stakeholders responsible for EoL, it belongs to the next use. Parallelly, the physical processes take place. Related to the creation of as-is BIM are all the construction and renovation processes taking place in the building. Traditionally, buildings are visually assessed for deconstruction, thus the CDW next use is determined. Visual assessment is followed by deconstruction and the CDW must be transported and stored afterwards. As it reaches the next use, it does not anymore belong to the EoL phase.

The actors involved in the phase are not clearly defined. Pre-EoL tasks dealing with physical assets are performed by various stakeholders in the building process, mainly contractors. Creation of BIM can originate from architects in the initial building design phase, however, it could be later on generated by EoL consultants or scanning teams. The EoL consultants generally take over digitalization tasks of EoL. At the same time, various physical deconstruction processes involve investors, contractors, and transporters. The stakeholders responsible for the physical assets are affected by the EoL consultant's decisions. As the CDW leaves its primary use, after the EoL phase, various scenarios may take place. Therefore, various new stakeholders may be involved, like landfill planners, architects of new buildings, manufacturers, contractors of new buildings, etc.

5. Verification

Project partners (PP1, PP2 and PP3) activities and businesses represent the first verification step of the novel framework. The project partners were asked to review the proposed framework and provide feedback. All identified tasks performed by the project partners are aligned with the proposed framework in Figure 3. The practices of PP1 are straightforward and result from two business models (BMs). The main BM1 is buying metal waste, sorting it, storing and preparing for recycling to produce secondary raw material. This BM1 belongs to the new life of the material. BM2 is the practice when the PP1 is invited to assess, deconstruct and transport the material found in the building, which is followed by the main BM1. This practice belongs to the EoL phase. Regarding the data management processes, an internal database to record the flow of materials is used when it reaches the facility; building models are not a standard practice.

The PP2 displays a more complex practice involving two BMs. The BM1 of PP2 is mainly consulting regarding the EoL phase, which involves creating of as-is models, filtering and interpreting data for EoL, creating data sets for further use, and data exchange towards external systems. Their BM1 also engages with physical assets of the building, and involves visual inspection of the demolition site, deconstruction and transport and storage, generally on-site. BM2 represents accompanying new constructions with their expertise in using available CDW. Both BMs can be placed in the proposed framework.

The case of PP3 shows the most complex arrangement of the EoL tasks. They are organized as three BMs: BM1 involving visual assessment of physical assets and creating digital assets for next use, like the catalogues of building elements and products. BM2 is dealing with physical deconstruction of the building, transport and storage and arranging the further usage of stored CDW by combined use of digital and physical assets. BM3 involves reuse of data and physical assets in creating new products. Many factors influence CDW being considered and all three BMs, such as time, costs, available quantity and condition of CDW, regulation, idea for reuse, esthetics and functionality.

Literature used to verify the framework is placed within the framework and shown in Figure 3 as well. It involves seven BMs, four research papers, four research projects, and seven regulations.

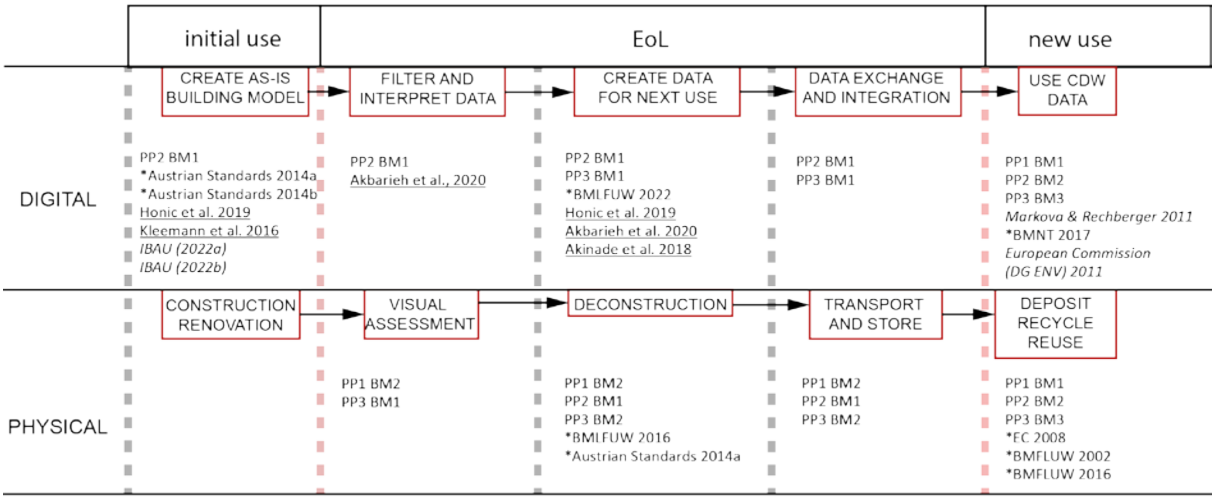

Figure 3 Results of framework verification with BMs: *regulations, research papers, and *projects*

6. Discussion & Conclusion

The examined work, including the practices, literature and projects can be placed in the proposed framework. This work provides a high-level framework to position the digitalization works for the EoL phase. The methodology to establish a framework results from two research papers: one describing a 3A pattern analysis (actor, activity, asset) and another describing the correlation of physical and digital assets. The framework is proposed based on the initial project meetings where the work of project partners was shortly presented. This framework will be used for future research within the project DiCYCLE - Reconsidering digital deconstruction, reuse and recycle processes using BIM and Blockchain.

The verification shows that it is possible to allocate the practices and research within the framework. Asset inputs and outcomes in the framework also correspond the aligned practices and research initiatives. The framework provides a structured EoL phase and will serve to identify gaps in that phase and the factors influencing particular steps in the phase. The need for a similar framework was already recognized in the literature (Akbarieh *et al.*, 2020). The main feature of herein proposed framework is the distinction of digital and physical assets during the EoL phase, which allows for aligning current digital and physical actors, processes and assets, resulting with more clear and exhaustive structure. Existing regulations such as Austrian Standards (2021) or ISO (2006) deliver numerous frameworks for particular topics. However, they mostly neglect some of the stakeholders in the EoL phase. A high-level inclusive framework has not been found. Relation between the framework and the existing research and literature can be visible on Figure 3. A more extensive literature review is required to precisely identify the gaps and the innovation potential on the market.

Limitation of the conducted study is primarily a limited number of verification cases, which have been taken from the existing cooperations and known projects. A more extensive verification is required in the future. The scope is focused on the Austrian EoL practices, and needs to be expanded to other countries. Also, the time factor in the EoL processes was not verified, which could affect the proposed framework.

The next step is to perform an extensive literature review in order to identify the gaps in the research of digitalization of EoL, and also to identify the factors for each particular step in the framework which influences the processes during the phase. The results will be used to enhance digitalization and provide tools for more efficient deconstruction. The project tends to facilitate use of Blockchain technology to support the novel improvements.

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