

Lean Deconstruction Approach for Buildings Demolition Processes using BIM

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Abstract

Question: The static nature of existing building assets is not serving the continuous change in the functional requirements of their end-users. Therefore, buildings undergo renovation or reconstruction, which requires the total or partial demolition of the buildings in order to meet these new requirements. This results in more virgin materials pumped into the construction industry to substitute the wasted ones, leading to an increase in the construction and demolition wastes.

Purpose: This research investigates the interactions between Building Information Modelling and Lean Principles towards improving the deconstruction processes.

Research Method: Both initiatives, though they are applied independently, proved to have a profound impact on the construction industry. However, the synergies between them in deconstruction context is not yet fully explored. Therefore, this research analyzes the Lean-BIM interaction in deconstruction processes.

Findings: The proposed framework relies on the existing Lean-BIM interaction matrix to evaluate the compliance of each BIM Functionality with each perspective Lean Principle based on evidence from literature and current practice in demolition projects. Seventy-three unique interactions were found, all but nine were constructive interactions.

Limitations: The proposed research is limited to assess the building deconstructability processes.

Implications: The results can be translated into an assessment method to be validated in real world. This exploratory research can be a foundation for establishing stable markets for salvaged elements and encouraging a behavior change in the construction industry towards circular economy.

Value for authors: The authors aim to provide a methodology for improvement building deconstructability.

Keywords: Lean deconstruction, Building Information Modelling (BIM), Pull-Planning, Sustainability, Circular Economy.

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Introduction

Construction industry is characterized by having high consumption rates of raw materials (Horvath 2004), while also contributing to a large flow of materials exiting the supply chain. (Schultmann and Rentz 2001). This leads to a significant loss in energy and materials. Throughout the building lifecycle, the highest amount of Construction and Demolition (C&D) wastes are produced during its demolition phase (Schultmann and Sunke 2007). The rising rate of demolition projects is caused by several reasons. Buildings are designed to last longer, yet, the change in the users' functional needs are quite dynamic. This leads to a "use life cycle" of building materials that are quite shorter than their technical life cycle. Also, conceiving buildings as static, rigid structures with fixed connections hinders the possibility of adaptability and reuse of building elements (Durmisevic and Durmisevic 2006). However, the recent years have witnessed a thorough investigation of barriers for adopting deconstruction planning processes that promote a circular loop supply chain in construction.

Time constraints are considered one of the main barriers for adopting less invasive deconstruction processes. Demolition Contractors believe that deconstruction processes that focus on high material recovery is a time-consuming process with respect to mechanical demolition that saves a lot of time (Kuehlen et al. 2014). In addition, the initial deconstruction costs, including labor, are higher than the initial costs for traditional demolition methods (Greer 2004). Another complexity lies in the uncertainties related to the undocumented building conditions (Hübner et al. 2017). Most of the salvaged elements in a building are retrieved at the end of the building life cycle (Hosseini et al. 2014), at that time the building might lack a clear documentation of the modifications and changes applied to throughout the operation and maintenance phase. Accordingly, precise evaluation of the current status of building elements remains a challenge. Several research efforts have been made in the building demolishing including; environmental and economic modeling through stochastic simulations from recycled coarse aggregates from precast plants (Azúa et al. 2019), combining life cycle assessment and Building Information Modelling to account for carbon emission of building demolition waste (Wang et al. 2018), and forecasting demolition waste generation using chi-squared automatic interaction detection method (Cha et al. 2017). Ghisellini et al. (2018) conducted a review to evaluate the transition towards cleaner production in the construction and demolition sector of China.

Not only building conditions contribute to the uncertainties, but also the logistics related to selling the salvaged elements are a major source. These include: time, quantity and place of elements to be picked up and sent to the client for recovery or direct reuse (Schultmann and Sunke 2007). In case these items still have an undefined destination, it will require a storage location whether on or off-site, which requires more costs. On the other hand, the architectural engineering and construction (AEC) industry is witnessing two major developments that are gradually shifting it towards sustainability. Lean and sustainability have been analyzed in literature (Koskela et al. 2010, Emuze and Smallwood 2013, Vasconcelos et al. 2015, Sarhan et al. 2019). The first initiative relies on the implementation of conceptual approaches that target waste minimisation - Lean Construction - and the



second involves the making use of IT-based processes that support the integration of data and prevents its leakage - Building Information Modelling (BIM) (Sacks et al. 2010).

Although Lean and BIM have independent approaches that can be applied separately, the impact of their interaction on construction projects has proven to be advantageous when applied properly (Arayici et al. 2011; Dave et al. 2013; Sacks et al. 2009). However, the impact of Lean and BIM synergies on demolition projects is not yet fully explored. This research aims at exploring this diffusion from a deconstruction perspective.

First, each independent initiative is questioned for its applicability and previous uses in deconstruction projects. Afterwards a framework based on the Lean - BIM interaction Matrix developed by (Sacks et al. 2010) will be used to identify the potential synergies between them in the deconstruction and demolition phase. Finally, the interaction results will be discussed to evaluate the effect of the Lean - BIM integration towards establishing a sustainable behaviour in the construction industry by reducing the amounts of demolition materials exiting the supply chain.

Lean Construction

Ballard (2008) defined the “Lean project Delivery System” as a management system for projects. This system is defined by an aligned process of ends, means and constraints. “Ends” are represented by the End Customer’s needs and requirements. The process detects the “constraints” such as location, costs and time, and their effect on the “means” to be selected to finally achieve the “ends”. The system involves the engagement of “downstream” stakeholders in the early decision-making process. The optimization of the workflow of the whole process is given the priority over the optimization of a single activity productivity. There are also buffers in the process to account for variability. Additionally, Pull-Planning concepts are adopted in the system. The flow of information and materials are governed by the required needs that are “pulled” from downstream as opposed to the traditional “push” approach in conventional projects. Feedback loops are implemented on each level to provide immediate feedback and instantly apply the necessary adjustments. Abdelhamid (2004) argued the need of a production management theory in construction and TFV theory was reported by Koskela (1992). Several research efforts investigated the application of lean concept and principles (Howell et al. 2010, Abdelhamid 2004, Koskela 2004). Babalola et al. (2018) conducted a systematic review of published literature in Scopus, Science Direct and Google Scholar to identify and categorize the different lean practices implemented in the construction industry and the benefits derivable from them.

The application of Lean Concepts in deconstruction projects was rarely mentioned in Literature. However, there are insights of using some principles that directly conform with those adopted by Lean. Examples of which are: Pull planning principles and Just-in-time (JIT).Schultmann and Rentz (2002) implicitly referred to the efficiency of using Pull-planning principles in deconstruction projects. This was evident by proposing that the nearest manufacturing typology that best suits deconstruction processes is ‘Make to Order’ production. This means that the process relies on applying just-in-time concepts where the presence of inventory is minimal. In addition, ‘Make to Order’ means that the production line will capture the production signal only when a demand exists on a certain product.

To apply a “make-to-order” production approach in deconstruction projects, it is important to identify the strategic and the operational planning processes that best suits the nature of these projects. Unlike construction projects, selective dismantling activities are executed solely on the building site, that’s why deconstruction process resembles the production in an industrial facility where all resources exist inside it. Whereas in construction projects, items can be produced off-site and only the assembly takes place on-site. Thus, deconstruction requires a more informed planning to assign the resources on-site based on the required elements to be dismantled (Schultmann and Rentz 2002). Accordingly, by considering the deconstruction process as “Make-to-Order” production, the term selective dismantling can be updated. Not only the selection of elements to be dismantled is based on their high recovery potential (Schultmann and Rentz 2001), but also it requires the existence of a demand, on the salvage elements, by the end-customers. Therefore, to account for the end-customers’ needs in the planning of deconstruction projects, (Liu and Pun 2004) suggested a web-based platform for showcasing the expected salvaged materials, out of a building to be demolished, with their quantity take-off. Afterwards, the customer (e.g., the recycling facilities) interested in any of these materials specifies them on the website. The customer can then contact the owner for closing the deal.

Hence, this allows engaging the clients interested in buying the salvaged materials, a sufficient time before the actual demolition activities start. This will ensure that the these materials, once extracted, will be directed towards the new customer in a JIT manner. Otherwise, it will be sent to landfills. However, this material management system could have been more dynamic if it was linked to As-built BIM model of the building and its database for instant update to the execution schedule and for enhanced visualizations.

BIM in deconstruction projects

BIM is revolutionizing the Architecture, Engineering and Construction (AEC) industry. It is defined as the “digital representation of physical and functional characteristics of a facility” (NBIS 2015). It’s the process of producing and maintaining project related information throughout the different phases of building life cycle. The information does not only include geometric properties of the building elements, but also extends to include any customized information related to the building. There are various uses for BIM, this includes: 3D visualization, 4D scheduling, quantity take-off, etc. Although the use of BIM functionalities is an active field of research, benefiting from the advantages of BIM in the deconstruction stage remains limited (Krygiel and Nies 2008). Planning of the deconstruction projects is complex, due to the high level of uncertainty involved in the process (Hübner et al. 2017). For instance, the nature of the products to be dismantled have special characteristics, with a unique combination of parts of different technical life-cycles (Fletcher et al. 2000). These “meta-products” have different attributes and introduce several problems in the dismantling process. These problems are also due to the long-life time of the building, where it undergoes several renovation and modifications; a process that is normally accompanied by a lack of records of these modification at the time of building deconstruction. Thus, the presence of a platform that can capture the current state of the building to be demolished is necessary.

Moreover, the scheduling of such projects is considered to be resource-constrained. Due to the time, environmental, safety, space, and costs constraints, the project schedule needs



to consider the optimization of several parameters to ensure that the production flow is synchronized with the end-customer's needs. The planning of this detailed scheduling is also dependent on a data-rich environment with simulation capabilities that helps in choosing the optimum deconstruction scenario (Hübner et al. 2017). Therefore, there is a need for a common repository for integrating data from all sources (like on-site sensors, documents, drawings, etc). Building information models can provide this central hub needed for data integration (Tarandi 2011). It can also significantly support the decision-making process through visualization and accurate representation of current conditions (Volk et al. 2018). Thus, the uncertainties involved in the current practices can be reduced by using BIM tools and processes (Hübner et al. 2017).

RESEARCH METHODOLOGY

In this research, Lean - BIM interaction matrix is used to detect the potential synergies between Lean Principles and BIM Functionalities in deconstruction projects. This framework was first provided by (Sacks et al. 2010) to study the interactions of Lean and BIM in construction projects. After postulating the interactions, evidence was sought to support them. Evidence was either theoretically proposed in previous researches or has been retrieved from practice. The results showed a near complete synergy between BIM functionalities and Lean Principles in construction projects. Later on, this framework was extended to study the Lean - BIM interactions in other phases like the operation and maintenance (Oskouie et al. 2012). However, the analysis of synergies between BIM and Lean in deconstruction processes was merely mentioned. Most of the researches that explored the effect of Lean - BIM integration in reducing the amounts of Construction and demolition wastes (C&D) are focused on wastes generated during the construction phase only (Cheng et al. 2015). The framework is regarded suitable for exploratory research where the conformity between two processes need to be identified and explored. Especially when one is in the form of general principles and the other provides practical functionalities that can apply the core concepts of those principles (Sacks et al. 2010). First, Lean Principles and BIM functionalities included in the study are explained. The description involves how they are perceived by the authors in the deconstruction processes. Afterwards, the Lean - BIM interaction matrix is provided. Finally, an evaluation of the interaction results is discussed.

Lean Principles

Since there is no evidence yet for Lean “Deconstruction” principles, those mentioned in literature concerning “Lean Construction” are studied. The selection criteria for the principles was mainly based on regarding the production control approach in deconstruction process is based on pull-planning. Most of the Lean Principles provided by (Sacks et al. 2010) are used. However, some modifications and addition of more concepts are done to account for the variations between construction and deconstruction processes. Figure 1 illustrates the classification of lean principles into two main categories: strategic management and operational planning. As for the strategic management-related aspects, they have four sub-

categories: the decision making, transparency, value creation and developing partners. While the operational planning is divided into: inspection and flow of the process.

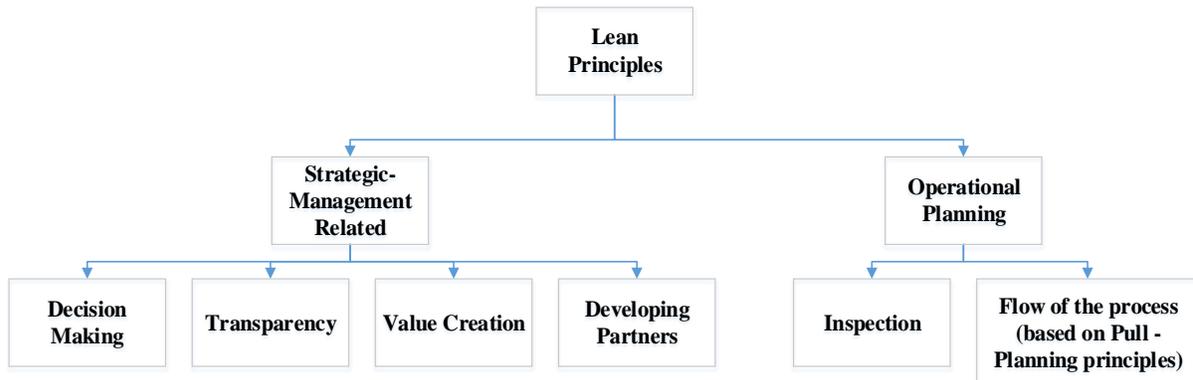


Figure 1:Classification of Lean Principles

The following list contains 16 main principles which are generically explained, and a detailed prescription of each principle is inferred in the “deconstruction” context.

1. Early Planning and Structuring the decision-making process

This is done through:

1. Planning the decision-making structure early in the process (Tsao and Hammons 2014).
2. The early involvement of the stakeholders in the process (Tsao and Hammons 2014).
3. Cultivate an extended network of partners (Sacks et al. 2010).

In Deconstruction Context:

Planning the Decision making early in the deconstruction process is related to making decisions on which Building Elements to be reused, repaired, refurbished, recycled, or sent to landfills while the early involvement of stakeholders can refer to engaging the demolition contractors and even the end-user (the client), who is willing to purchase the salvaged elements, early in the process. It is worth noting that networking is an extremely important aspect in establishing a reliable demand for salvaged elements in construction industry to cultivate an extended network of partners.

2. Consider all options

This principle promotes extending the number of options available to select from. The more options we have the probability to find a better solution increases (Sacks et al. 2010).

In Deconstruction Context:

An example from deconstruction practice can be the material recovery options. Through accurate analysis of the salvaged element quality and deconstructability, the available options for recovery are increased. Also, from a marketing perspective, if the platform for selling the salvaged elements has an exposure to a wider target audience, the chance that the items can be sold is increased.

3. Processes must be more transparent with decentralized decision making

This means that the state of the system can be seen by decision makers throughout the production system. This leads to making local decisions to support the system. Transparency implies decentralized decision making which, in return, allows people to coordinate through mutual adjustment (Tommelein 1998).

In Deconstruction Context:

Accessibility to the salvaged element conditions for all the involved stakeholders and their ability to evaluate these conditions, throughout the process, can support an informed decision-making process.

4. Careful selection of technology that reaps high value to the end-customer

Technology that adds value at any point in the process is essential (Sacks et al. 2005).

In Deconstruction Context:

An example of technology that provides value to the end-customer can be in the form of providing the end-user with visualization tools that enables the quality check of the salvaged elements without the need for being on-site. Also, photogrammetry can be used to document the facility electronically before deconstruction. The 4D modeling technique can be used as well to track the progress of deconstruction as well.

5. Ensure Comprehensive requirements capture

This principle addresses the value generation. Value generation needs comprehensive requirements capture (Sacks et al. 2005).

In Deconstruction Context:

In order to capture value when it comes to selling the salvage elements, a comprehensive set of Data is required. The data include element conditions, deconstructability, market conditions, pricing and costing, transportation, etc. Also, the following can be performed:

- Develop a platform or a database that include elements condition by 3D reconstruction to ensure the actual element condition and its potential pricing.
- Check a trend analysis for the market research.

6. Focus on Concept Selection

It means not to rush into the detailed design, without careful consideration and evaluation of the different conceptual options in the beginning of a project. If a wrong concept was adopted, the cost of change once reached the detailed design will significantly increase (Sacks et al. 2005).

In Deconstruction Context:

Rushing into demolition could hinder available recovery options for the building.

7. Ensure Requirements Flow-down

From the point of value generation, the next step is to ensure that the process flows smoothly till every single part of the product is designed and produced. This is done through Synchronization (Sacks et al. 2010).



In Deconstruction Context:

An example would be to ensure that every element in the building has been assessed for deconstructability. Also, during the execution process, the flow of processes is checked for being compatible with the baseline, where each salvage element is dismantled as planned.

8. Verify and Validate

The last principle related to value generation, this one promotes the validation of products against the planned specifications and customer requirements (Sacks et al. 2010).

In Deconstruction Context:

Ensure that all salvaged elements are dismantled within the planned sequence and that they meet the end-user requirements. The deconstruction can be performed in phases to have lesson learned from each completed phase to verify and validate the adopted methodology.

9. Go and see for yourself

This principle advocates the “personal inspection” compared to traditional reports and hearsay (Johnson et al. 2012). This concept stresses on the importance of site visits for visual inspection (Sacks et al. 2010). However, with modern remote sensing techniques, the update of the site progress can be visualized in the office. These technologies have the ability to stream real-time updates.

In Deconstruction Context:

Visual inspection is important for evaluating the current building conditions and the elements that have high recovery potential. It is also important for the end-customers interested in buying the salvaged elements to visually inspect their quality before purchasing them. It is worth noting that inspecting the process from the beginning would help in understanding what have been seen to improve the process.

10. Pull from Downstream

It means to plan backwards from a workstation or a customer need (down the supply chain). Requests from downstream “Pull” the resources, instead of the traditional “Push” approach. It has to be noted that that there is no production control system fully relying either on a pull system only or a push system only. However, depending on where the “push” from plans meets the “pull” from downstream identifies the behavior of the system.

To achieve this approach the following should be implemented:

1. Project planning is based on the end-customer needs (Sacks et al. 2005).
2. Minimize inventories of goods awaiting further processing or consumption by levelling the production (Sacks et al. 2005; Tommelein 1998).
3. Resource management based on production flow (Faloughi et al. 2015; Sacks et al. 2005). Examples of this kind of resource management include:
 - Resources delivery to the site should follow the order of the production strategy.
 - Releasing work, materials, or information from one specialist or trade to the next by pull rather than push.
 - Avoiding unnecessary transport of goods(Sacks et al. 2005)

In Deconstruction Context:

The “Pulling from downstream” approach is completely viable in Deconstruction processes. The reason relies on treating the deconstruction process as a Made-to-Order (MTO) process. It is the customer needs (demand) for salvaged materials that promotes the market for the reversed supply chain in construction. So, receiving a pull-signal from a customer need initiates the selling of the required salvaged element.

11. Reduce Variability

Both in the product and the production by:

- a) Creating a smooth workflow by removing variations in workloads(one-piece flow) (Tsao et al. 2014).
- b) Getting Quality right at the first time and reducing defects in products (Sacks et al. 2010).

In Deconstruction Context:

The production line in deconstruction projects refers to the dismantling of salvaged elements. Variations in the process can possibly come from the change in the final destination or the recovery strategy for a certain element (Resource Limburg 2017). On the other hand, an example of reducing variability in the product itself (the salvaged element) is to ensure the identification of the dismantling steps needed to retrieve this element before the actual start of the deconstruction activities. It should be noted that variabilities can be reduced by adopting Value Stream mapping.

12. Reduce cycle time

This is done by achieving the one-piece flow through minimizing the batch size and parallel processing. (Kalsaas et al. 2015; Sacks et al. 2010; Tsao et al. 2014).

In Deconstruction Context:

When scheduling the deconstruction process, we make sure that activities required for the dismantling a certain element is done consecutively. This is done by ensuring that each crew is entitled to dismantle an element at a time and then move to the other. (one element at a time).

13. Collaboration

Collaboration can be achieved by producing the plan in coordination with those who will do the work.

In Deconstruction Context:

When planning the deconstruction process, the personnel responsible for the actual dismantling activities should be involved in the formulation of the execution plan.

14. Flexibility

It means that the planning team must be open to revising the plan after learning and when new details emerge. (Tsao et al. 2014).

In Deconstruction Context:

Flexibility of the scheduling process is needed to adapt to changes in the salvaged elements to be sold. For example, a Client changes his opinion and decides to modify or cancel the purchase. In this case, the schedule should be flexible enough to allow this process and reschedule instantly.

15. Standardizing the Process

This is achieved by:

- Finding simplicity even within complex projects. (Kalsaas et al. 2015; Tsao and Hammons 2014).
- Structuring of the work to separate the standard activities from those relying on the change in information (Sacks et al. 2005).
- Using Visual Management (Sacks et al. 2010)

In Deconstruction Context:

An example of Simplicity can be found in trying to detect patterns between the different types of elements that have the same dismantling methods. Furthermore, another form of standardization is separating standard tasks from those susceptible to information change. This can be achieved through detecting the salvaged elements difficult to be dismantled and separating their activities from the elements that are dismantled easily.

16. Institute Continuous Improvement

By clearly documenting, updating and constantly reporting the status of all process flows to all involved stakeholders. This is done by what is called “Feedback Loops” (Tommelein 1998).

In Deconstruction Context:

Feedback loops should exist to update the dismantling activities on-site, constantly document them and report the status instantly to trace the productivity.

Table 1 lists Lean principles that would be used in Lean-BIM interaction Matrix, the key indicates the letter representing each principle in the matrix table.

BIM Functionalities

This section describes the functionalities that BIM technology provides and can be utilized in the deconstruction planning and execution. They are mostly derived from both literature and current practices involving deconstruction and demolition projects. However, some of the uses inferred in this context might still require testing and further exploration. Therefore, the proposed functionalities are considered the base foundation to build up on, with the possibility of adding, or omitting, functionalities in future work.

In several cases, the definition of a certain functionality in deconstruction context might differ from its traditional use in construction processes. For instance, “Detecting the Clashes” refers to finding modelling errors where elements from different disciplines happen to occupy the same space. However, in deconstruction projects, it refers to the “Dynamic” clashes that would occur during the removal of a desired element out of the building. This

research presents a total number of eight main functionalities that are decomposed into several sub-functionalities. These functionalities are then judged based on their conformity with Lean Principles to detect their potential usefulness.

Table 1: List of Lean Principles

ID	Lean Principle
	Early planning the decision-making process
A	Planning the decision-making structure early in the process
B	The early involvement of the stakeholders in the process
C	Cultivate an extended network of partners
D	Consider all options
E	Processes must be more transparent with decentralized decision making
F	Careful selection of technology that reaps high value to the end-customer
G	Ensure Comprehensive requirements capture
H	Focus on Concept Selection
I	Ensure Requirements Flow-down
J	Verify and Validate
K	Go and see for yourself
	Pull from Downstream
L	Project planning is based on the end-customer needs
M	Minimize inventories of goods awaiting further processing or consumption by levelling the production
N	Resource management based on production flow
	Reduce Variability
O	Creating a smooth workflow by removing variations in workloads (one-piece flow)
P	Getting Quality right at the first time and reducing defects in products
Q	Reduce cycle time
R	Collaboration
S	Flexibility
	Standardizing the Process
T	Finding simplicity even within complex projects
U	Structuring of the work to separate the standard activities from those relying on the change in information
V	Using Visual Management
W	Institute Continuous Improvement

1. Data Capturing

Digital Documentation from remote sensing data involves the digital documentation of buildings that lacks data on its As-built current conditions. There are several data capturing technologies that are currently used like laser scanning that produces a 3D point cloud, and photogrammetry. Current BIM tools can interpret the output of these technologies. This can improve the generation of As-built BIM models.

2. Modelling

The modelling functionality considers three aspects:

- *Rapid Generation of the model:* The daunting process of creating As-built BIM models is getting more intuitive and less time consuming. The reasons for that include:
 - The compatibility of BIM tools with point cloud data.
 - The ongoing advancements in the automatic extraction of BIM objects from this data.
 - The Modelers capability of working in parallel at the same time in one project
- *Visualization of form:* The 3D model navigation can allow project participants to visualize the model in a more convenient and intuitive way compared to the 2D technical drawings (Sacks et al. 2010).
- *Maintenance of Information and design model integrity:* BIM authoring tools detect discrepancies in the models and give warnings about them, like an unattached column to its upper floor, or a misplaced window ...etc. Besides, BIM tools detects clashes between different BIM objects which enhances the model integrity (Sacks et al. 2010).

3. Collaboration

- *Collaborative modelling environment:* The Collaborative environment is enabled by BIM authoring tools. It helps in providing a central file for communication and integration of model data from separate local files.
- *Improved Collaboration among stakeholders:* Following the latter point, Collaboration among stakeholders is more strategic. The BIM platform can act as a central hub for collaborative discussions and decision making. The BIM platform prevents data leakage and ensures the visualization of the actual actions to be executed on the project.
- *Interoperability:* Open standards provide data models for information exchange between different BIM platforms like Industry Foundation Classes (IFC). These data models facilitate the interoperability between various BIM software. Therefore, the interoperability between different BIM software packages eliminate the need for different stakeholders to obtain the same BIM application on which the model was originally produced. Despite the availability of IFC schemas for information exchange, they are still not equipped with parameters involved with deconstruction processes and waste analysis.

4. Object-based Programming

The architecture based on which BIM models were designed, resembles the object-oriented programming principles. This provides the ability to add new parameters to the existing BIM-object classes. This could be in the form of:

- *Manual input of Parameters:* The manual input of parameters and their values to a BIM authoring tools is possible. However, this process should be controlled as the manual entry of data is prone to human errors. This kind of data entry is suitable for limited amounts of parameters.

- *Connecting to External Libraries for Retrieving Data* (Akbarnezhad et al. 2014): This process can be more robust than manual entry of data. It is convenient when large datasets are needed to be imported from external libraries and attached to the BIM objects in the model.

5. Re-Use of model data for predictive analysis

BIM authoring tools provides the ability to export the model data to external plug-ins. These plug-ins can further process the data. Several authors provided BIM-based plug-ins for supporting the decision making over the optimum deconstruction scenario (Akbarnezhad et al. 2014; Akinade et al. 2017).

6. Rapid Evaluation and Simulation of Deconstruction alternatives

The existence of comprehensive data in the BIM model allows for further analysis. These analysis and evaluation processes include:

- *Deconstruction Processes Simulation 4D Scheduling*: This process is initially designed to simulate the construction activities sequencing and visualizing different scenarios. However, it can be extended to include the deconstruction processes, where the dismantling sequence of activities can be visualized (Ge et al. 2017).
- *Clash Detection Scenarios*: This BIM functionality is related to the detection of dynamic rather than static clashes (Autodesk University 2013). It is regarded as one of the most important functionalities that can serve the deconstruction activities. For instance, if a certain element is to be dismantled, the simulation of its dismantling path can detect the possible clashes when it is moved from its original place to outside of the building. Therefore, critical elements that needs to be dismantled are checked for different routes for getting them out of the building. This BIM functionality can precisely detect the clashes produced when the moving element faces a certain obstacle.
- *Quantification of recoverable materials*: This functionality automatically produces quantification schedules for the identified salvaged elements. The same goes with the quantification of the materials to be demolished.
- *Virtual Reality (VR) simulations*: VR is an emerging technology in the construction industry. Through the immersion in a virtual environment, the conception of simulated scenarios is possible. In deconstruction processes, the simulation of dismantling scenarios can be done using VR tools.

7. Automatic Generation of reports

Reports providing the results and data of different deconstruction scenarios can be automatically generated in the BIM models (Akinade et al. 2017). Various BIM software packages offer the generation of reports and documents with minimal user input or interference. Any change in the BIM model is propagated across all the types of reports and are instantly updated.

8. Online/Electronic based communication

The functionality considers three aspects:



- *Visualization of the process on-site:* Through the usage of rugged devices, workers can visualize the procedures needed within the BIM model to dismantle certain elements. This functionality can also be linked with augmented or virtual reality applications. Augmented reality applications are more convenient in on-site applications where the worker can visualize the succeeding tasks virtually, based on the existing actual conditions.
- *Update of on-site status:* This process is based on the updates retrieved from the site. They represent the status of the actual dismantling activities. BIM on-site tools can also be installed on rugged tabs. The feedback from the workers is synchronized directly with the BIM model. Therefore, the managers can visualize the real-time status of the production on-site.
- *Integration and update of BIM database from online applications:* In construction projects, BIM systems are integrated with supply chain partners which is considered a powerful mechanism for communicating the “Pull” production signals for materials delivery. In deconstruction projects, the process is reversed. BIM models can be synchronized with Web-shops that showcase the salvaged building components. Thus, the salvaged elements that are sold on-site are directly updated through the BIM model. The BIM objects in the model representing the sold elements are then scheduled for dismantling based on the agreed delivery dates. Therefore, the pull signals can be communicated online from the Web-shops or mobile stores to the BIM model.

Table 2 lists BIM functionalities that will be used in Lean-BIM interaction matrix. the key indicates the number representing each functionality in the matrix table.

Matrix Table

BIM Functionalities and Lean Principles are arranged in the matrix listed in Table 3. Each cell linking a certain BIM functionality with a Lean principle, if contains a number, indicates that there is a possible interaction between them. This number is described with its respective explanation for the interaction in Appendix I. Positive numbers indicate a positive interaction, while numbers in between brackets indicate a negative interaction. Additionally, the evidence based on which the interaction is inferred is also mentioned in Appendix I. There are four main types of evidence:

- **Type 1:** A previously identified evidence in construction context or in general. Proof of evidence of its applicability in deconstruction processes might be needed.
- **Type 2:** A source of evidence recorded in deconstruction context. It was retrieved from literature and its outcome is documented by the relevant authors.
- **Type 3:** Evidence captured from practice in actual deconstruction or demolition projects. The explanation is proved by an empirical evidence. In this research, the evidence is captured from Resource Limburg (2017) practices.
- **Type 4:** They are areas where no evidence has been detected yet. They are inferred from the informed reasoning of the authors as an expected projection of integrating processes from literature and practice. Therefore, their source of evidence is deemed “Not yet available”. Thus, more investigation is needed to prove the reliability of these suggestions.

Table 2: List of BIM Functionalities

ID	Process	BIM Functionality
1	<i>Data Capturing</i>	Digital Documentation from remote sensing data
2	<i>Modelling</i>	Rapid Generation of the model
3		Visualization of form
4		Maintenance of Information and design model integrity
5	<i>Collaboration</i>	Collaborative modelling environment
6		Improved Collaboration among stakeholders
7		Interoperability
8	<i>Object-based Programming</i>	Manual input of Parameters
9		Connecting to external libraries for retrieving data
10	<i>Reuse of model data for predictive analyses</i>	External Plug-ins
11	<i>Rapid Evaluation and Simulation of Deconstruction alternatives</i>	Deconstruction Processes Simulation 4D scheduling
12		Clash detection scenarios (from point cloud data)
13		Quantification of recoverable materials
14		VR Simulation
15	<i>Automatic Generation of reports</i>	Reports and Audits (Deconstruction Plan Development)
16	<i>Online/Electronic based communication</i>	Visualization of process on-site
17		Update of on-going activities
18		Integration and update of BIM data base from online applications

Table 3: Interaction Matrix of Lean Principles and BIM Functionalities

Lean Principle \ BIM Functionality	Early Planning the decision-making process			Consider all options	Transparency and decentralized decision making	Careful selection of technology that reaps high value to the end-customer	Ensure Comprehensive requirements capture	Focus on Concept Selection	Ensure Requirements Flow-down	Verify and Validate	Go and see for yourself	Pull from Downstream			Reduce Variability	Reduce cycle time	Collaboration	Flexibility	Standardizing the Process			Institute Continuous Improvement	Total no. of Lean Principles/sub-principles applied by each BIM Functionality		
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V		W	
Data Capturing	1	1	2		3	4	4	5		6	4				4	7	2		8		4	6	14		
Modelling	2	9	9					9								10							4		
	3			11	12			9	13	14	14				15		12		16		14		10		
	4					(17)	18		13	14	14				19				(20)		21	22	9		
Collaboration	5						23		13	14			23	23	23		23, 24	23	24	24		25	26	12	
	6		12	29	12	12		27	28									30				31		8	
	7			29, 34				(32)									35, (32)							4	
Object-based programming	8						(32), (36)			(36)									37, 38		37			4	
	9						38			39									37, 38		37			4	
Re-Use of model data for predictive analyses	10	41	41		41		39,40	41		33		40			42	42	42	41	39	(43)	42		39	15	
Rapid Evaluation and Simulation of Deconstruction alternatives	11	44	44		45	45	46	45	(48)	45	46	44	47	50	49	50	67	50, (51)	44	52	67	53	45	44	22
	12				45	45	46			46	44					67	54	54		54		45	44	11	
	13									55					55		56		55	56					5
	14				11		57				57											57			4
Automatic Generation of reports	15														58		(59), 60		58					3	
Online/Electronic based communication	16					(61)				62		63	64	64	65	66	65			67		67		10	
	17					(61)				62	68									69			69	5	
	18	70		70		71			73			71		72	72		73				71	4		10	



It should be noted that the research provides a foundation for a more complex framework which can be practically utilized. The interactions are meant for exploratory studies, hence, they are susceptible to further enhancements and verifications or contradictions in the future. The interactions of “type 3” evidence were postulated from the close review of one of the initiatives adopted in the Dutch Construction Industry. The aim of this initiative is to increase the adoption of circular economy practices in demolition projects. This is done through the establishment of a new market demand for salvaged elements. This initiative is supported by local organizations that take over the building to be demolished, then work on selecting the elements with high reuse potential and try to secure a second destination for them.

The typical process workflow involves the digital documentation of the building to be demolished. The produced building model is then used to evaluate the current building conditions. Afterwards, the data interpreted about the condition of each element is stored in a relational database along with several information about the element (e.g.; dimensions, type, panoramic view of it, etc.). The database is then published on an online Web-Shop for selling the salvaged elements.

DISCUSSION OF RESULTS

Analysis of the interaction results requires in-depth understanding to validate its applicability. However, the preliminary results are expected to give insights on how to structure a framework for deconstruction projects. There were 154 interactions, of which 73 were unique. 64 of the 73 unique interactions indicated a positive impact while the remaining nine interactions indicated a negative impact or a contradiction to the lean principle investigated. Thus, there is an 88% compliance between Lean Principles and BIM Functionalities in deconstruction projects. To start with, the Lean principles with highest concentration of interactions were: “Verify and Validate”, “Reduce Cycle Time” and “Standardizing the process through finding simplicity even within complex projects”. The first is a core Lean principle that ensures the continuous verification and validation of the project throughout the production process. Through applying this principle, it is possible to control the deconstruction process and ensure that the dismantled salvaged elements meet the end-customers’ requirements. Also, the elements’ conditions are verified for their recovery potential.

Second, since “reduce cycle time” is among the top Lean Principles with the highest interactions with BIM Functionalities, this means that BIM-based processes effectively reduce the overall cycle times of different activities in deconstruction projects. This proves that the time exhausted early in the process to capture the building details and data paying back. The informed decisions, along with visualization and simulation of different processes, ensures that less time is spent on the actual dismantling activities. Similarly, “Simplicity” is also achieved in the execution of dismantling activities through the thorough planning of deconstruction projects using BIM processes, despite some complexity in the integration of discrete data sources within the BIM model and other discrepancies in detecting patterns between different BIM objects. Furthermore, BIM functionalities that appeared to have the highest number of interactions with Lean Principles were “Deconstruction Processes Simulation 4D scheduling”, “Re-use of model data for predictive analysis”, and “The digital documentation from remote sensing data”.

This output makes sense to a great extent. Starting in chronological order, data capturing through digital documentation is regarded as a unique process when it comes to deconstruction projects. It is the start milestone based on which the rest of the data layers are accumulated. Secondly, the wide range of analysis provided by external plug-ins serve a large span of Lean principles. It also adds an edge to the BIM model by adding intelligent layers of integrated data. Finally, the 4D scheduling and deconstruction process simulation had the highest number of interactions. Besides being the significant reason for adopting BIM processes in traditional construction projects, the simulation capabilities of BIM can be extended and used in deconstruction process.

On the other hand, the principles that appeared to be served the least or were even negatively represented were “Cultivate an extended network of partners” and “Remove Variations in workloads to create a smooth flow”. Having less interactions does not necessarily mean that they are neglected, as long as one functionality implements a Lean Principle effectively. For instance, BIM collaboration platforms provide a stable hub for integration the efforts of different stakeholders involved in the planning of the deconstruction project. In addition, synchronization of BIM data with online portals for selling salvage elements helps in creating connections with the end-customers and promotes the establishment of long-term relationships. The BIM functionality with fewer interactions was the “automatic generation of reports”. It also has negative impact on the “Cycle time”. Reasons for that were mentioned in the explanation table, where the easiness of generation of reports yields an undesired amount of data. This could cause more wasted time on determining and tracing the latest working version of data. Finally, the dominance of positive interactions over negative ones does not necessitate that the implementation of Lean Principles through BIM functionalities in deconstruction projects is a straightforward process. The large number of interactions that only have evidence in construction projects confirms the need to validate their applicability in real world deconstruction projects.

Conclusion and Future Research

The synergies of BIM and Lean in deconstruction projects were examined. The alignment of BIM technologies within Lean Concepts required, first, determining the production system that best suits the nature of deconstruction projects. Accordingly, these types of projects were assumed to resemble the manufacturing industry by regarding the abandoned building a factory producing recovered elements. This requires the presence of the needed resources on-site. Then, BIM functionalities were examined for conformity with each Lean Principle in deconstruction projects. Using Lean - BIM interaction matrix, high degree of accordance was found. However, interactions were only studied from a 2D perspective; meaning that each functionality is examined against each Lean principle. Therefore, it is regarded as an integration of isolated parts. These parts are the separate cells of interaction. The Lean-BIM interaction should be seen as a complex process where the interaction occurring between two elements might intensify or attenuate the effect of other neighbouring interactions. Perhaps the use of system dynamics approaches can help in understanding the non-linear behaviour of the interdependent system binding Lean and BIM in the deconstruction processes. This research can set up a foundation for building up a generic framework covering different aspects of the deconstruction process. The

framework can be designed based on a “Pull” management system applying Lean Principles at its core and structured on the end-customers’ needs. BIM technologies can be the engine linking different processes together and providing a collaboration platform with smooth flow of information.

The process can extend from data capturing of undocumented building conditions, moving towards the rigorous analysis of building information through the migration of information from the as-built BIM model to external applications. Afterwards, the refined data can be used to assess the building deconstructability, and hence, the elements with high recovery potential can be determined. These elements can be showcased on online resource store for attracting interested customers. The BIM platform can handle the flow of information from the online store and feed this data to the execution schedule. Accordingly, the development of this process flow is considered the next research step based on the outcomes inferred from this study.

Future research can investigate the identified 16 lean principles to understand them in the context of the TFV (Transformation-Flow-Value generation) theory of production. This can be done by analysing building deconstructability with respect to the three interdependent angles to production including transformation oriented (T), materials oriented (F), and customer oriented (V). Further, the H&S potential benefits and advantages that could be achieved by adopting lean principles and BIM functionalities can be analyzed in future research. Also, the internal dependency of lean principles and BIM functionalities can be further analysed. It is worth noting that analysis of the interaction matrix relied on number of interactions rather than impact. Future research can qualitatively examine the identified interaction between lean principles and BIM functionalities to test the strength of empirical evidence as well as conceptual arguments or hypothesis.

Appendix I

Table I: Interaction Matrix: Explanations of Cell Contents

No.	Explanation	Reference	Evidence
1	Scanning processes provide accurate visualization of on-site conditions, thus the decisions on the building deconstruction can be planned sufficient time before actual demolition take place.	(Ge et al. 2017; Resource Limburg 2017)	2,3
2	Organized meetings with the persons who can do the work, early in the process, is enhanced by visualizing the site-data in the office.	(Eastman et al. 2011)	1
3	Decision makers can digitally visualize the on-site existing conditions. Thus, the visual exploration of the building is a transparent process compared to written reports.	(Resource Limburg 2017)	3
4	Digital documentation adds value to the end-product through visualization of accurate building conditions. It also captures comprehensive requirements like measuring accurate distances and detecting defects in building elements through thorough inspection.	(Böhler and Marbs 2004)	2
5	Scanned buildings help in discussing different preliminary alternatives by navigating through the model.	(Resource Limburg 2017)	3
6	Validating the dismantling processes can be achieved by comparing the condition of the salvaged elements with respect to their initial condition that were digitally documented before deconstruction.	Not yet available	4
7	Digital scans reduce the time of activities needed and the errors made to create an As-built BIM model from scratch. Point cloud data can be imported as reference models in BIM authoring tools for an accurate drafting process.	(Autodesk Revit 2017)	1
8	Available applications for viewing point cloud/photogrammetry data enables focusing on the important details and deleting or hiding the unrequired data (e.g.: the noise point sets).	(Autodesk Recap 2018)	1

No.	Explanation	Reference	Evidence
9	Having the As-built BIM model ready for analysis early in the project, provides a sufficient amount of time for discussing the conceptual plans of different deconstruction strategies thus early informed decisions by key participants can be made.	(Eastman et al. 2011)	1
10	The generation of As-built BIM models in a short amount of time helps in investing more time on the planning of deconstruction project activities	Not yet available	4
11	The Visualization of a complete As-built BIM model enables the discussion of different scenarios and options available. The compatibility with virtual reality also enhances the visual experience.	(Eastman et al. 2011)	1
12	BIM Collaborative Platforms acts as a central hub for different parties in the project. This guarantees that changes in the model or different options proposed are identifiable to all stakeholders. Thus, the workflow of processes is formulated in a collaborative environment.	(Eastman et al. 2011)	1
13	Changes in BIM models are instantly synchronized in all views and related documents. This allows the smooth flow of requirements.	(Eastman et al. 2011)	1
14	BIM models can help in the quick assessment of the deconstructability of a certain building element by the visual detection of BIM objects hindering the extraction of a certain element. Also clash detection along with other intelligent modelling tools ensure the model integrity and its proper simulation to the real-world building elements	Not yet available	4
15	The visualization of 3D As-built BIM models along with the different navigation and view filters improves the quality of the end-product. This would eliminate the misinterpretations of building parts from different views of 2D cad drawings.	(Eastman et al. 2011)	1
16	Building Systems are complex. Interpreting functional and structural relationships between building elements from drawings alone is onerous. BIM simplifies the complexity in creating a mental model for the building analysis.	(Eastman et al. 2011)	1
(17)	BIM processes still have a margin of data loss. Difficulties exist in implicitly detecting several relationships between BIM objects.	(Ali and Mohamed 2017)	1
18	The maintenance of the BIM model and its integrity ensures that the comprehensive requirements are met and maintained in an efficient way.	(Eastman et al. 2011)	1
19	The maintenance of the BIM model helps in reducing the discrepancies between the BIM objects and what the elements they represent in real-world. Thus, the defects that might arise during the modelling process are being instantly detected for the sake of model integrity.	(Eastman et al. 2011)	1
(20)	Part of the modelling time is normally consumed in fixing the coordination errors on the central file resulting from working on separate local files. Perhaps the use of machine learning algorithms that can be trained on common coordination errors can eventually solve them.	Not yet available	4
21	BIM authoring tools support the visual detection of the modelling issues. This ensures solving the related warnings in a smooth and efficient way	(Eastman et al. 2011)	1
22	Solving the modelling issues when they arise helps in identifying the common errors to avoid them in the future work.	Not yet available	4
23	BIM Collaboration tools reduces the time needed to create the As-built BIM model through parallel processing and working in smaller batches of the project simultaneously. This ensures the work conformity with the comprehensive project requirements. The workload on each local file can also be modified based on the performance and to assure a smooth production flow.	(Autodesk Revit 2018)	1
24	Dividing the work in a BIM project into several work-sets improves the continuous feedback on the project output. Work sets can be monitored and revised while in progress. Also, the flexibility in modifying the scope of the drafting responsibilities improves the productivity and helps in overcoming several modelling issues.	(Autodesk Revit 2017; Hamad 2017)	1
25	The work executed in local files can regularly be updated and visualized on the Central file for tracking the overall progress.	(Hamad 2017)	1
26	"Feedback loops" are provided in the collaborative modelling process. Through the visualization of updates on the central file and giving "feedback" on the work performed for further improvement.	(Autodesk Revit 2018)	1
27	Collaboration ensures the compliance of the project outcomes with the different requirements.	(Gu et al. 2008)	1
28	Collaboration among stakeholders ensures the discussion of different concepts before settling on the most convenient one	(Gu et al. 2008)	1
29	The strategic collaboration through BIM Cloud services enables the remote connection of the main project stakeholders. Also, various forms of data exchange standards like (IFC) helps in exporting the models to any other entity.	(Autodesk Revit 2018; Succar 2009)	1
30	Collaboration is strengthened among different stakeholders due to the presence of a reliable platform that supports the different BIM processes	(Ma et al. 2018)	1
31	BIM platform visualizes the As-built model and make it accessible for all the project stakeholders to communicate and comment on the model itself	(Autodesk Revit 2017)	1
(32)	Current open standards for information exchange do not comprise all the data already included in the BIM model. Data loss is inevitable during this process. Additionally, the manual input of new parameters that has no definition in the exchange schema leads to the loss of this data during information exchange.	(Fischer and Calvin 2002)	1

No.	Explanation	Reference	Evidence
33	Interoperability in BIM-based applications allows data migration to external application for validation and/or analysis	(Pazlar and Turk 2008)	1
34	BIM authoring tools facilitates the data exchange through interoperability. If each partner has a BIM authoring tool different than the one in which the model was created, the use of open standards for information exchange like (IFC) can solve these issues.	(Nizam and Zhang 2017)	1
35	Open standards for data exchange allow the direct migration of models regardless the authoring tool used by different organizations	(Eastman et al. 2011)	1
(36)	Manual data entry render difficulties in verification and validation of the output, due to the high probability of having errors.	(Alanjari et al. 2015)	1
37	BIM authoring tools allows adding additional parameters. This facilitates the integration of data related to the deconstruction phase of the project with the existing parameters of the As-built BIM model. These parameters can be either added manually or from linked from external databases. This provides flexibility in selecting the suitable option based on the complexity of the data and its available form.	(Akbarnezhad et al. 2014)	2
38	Adding different types of parameters facilitates the capturing of comprehensive data and integrating them with the model. For instance, deconstruction related parameters can add information about nearest recycling facilities available for each type of building elements, the carbon footprint resulting from transportation, etc.	(Akbarnezhad et al. 2014; Pauwels et al. 2016)	2,1
39	BIM model data (independent of its source) can be exported to external applications for further analysis. Also, data processing can be done using developed imbedded plug-ins. This can also help in verifying the reliability of imported data from additional parameters.	(Akbarnezhad et al. 2014)	2
40	BIM tools enables the development of plug-ins that can evaluate the recovery potential of building elements. This ensues the early assessment of these elements, thus, the quality of the end-product is leveraged. This evaluation and prediction analysis can be executed for different deconstruction scenarios.	(Akbarnezhad et al. 2014)	2
41	Assessing the deconstructability of building elements using BIM model data facilitates the early planning of deconstruction processes. This also allows the project stakeholders to participate in the decision-making processes and agree on the deconstruction strategy (concepts) to follow in the project.	(Eastman et al. 2011; Ignatova et al. 2018)	1
42	Exporting BIM model data to deconstruction assessment tools identifies the elements with high re-use potential a sufficient time before actual demolition activities starts. This process helps in prioritizing these elements during execution and separating them from those with no recovery potential, thus reducing the time needed on-site to evaluate the building elements.	(Akbarnezhad et al. 2014)	2
(43)	Extensive use of detailed parameters could hinder the achievement of reliable results in the predictive analysis and obstruct the proper extraction of information from the BIM model	(Alanjari et al. 2015)	1
44	BIM simulation tools visualizes different deconstruction scenarios and helps the different stakeholders in deciding the optimum strategy.	(Ge et al. 2017)	2
45	4D scheduling helps in visualizing the progress of deconstruction sequencing. This helps in detecting conflicts in location, time and resources. It also provides insights on the safety procedures needed and keeps track of the production flow to ensure its efficiency.	(Eastman et al. 2011; Ge et al. 2017)	1,2
46	Using BIM collaboration tools ensure the visual simulation of the dismantling activities that results in error free elements dismantling on-site.	(Eastman et al. 2011)	1
47	The benefits of BIM collaboration platforms can be employed in selecting the optimum deconstruction strategy by visually comparing several alternatives.	Not yet available	4
(48)	Simulating different conceptual scenarios early in the project still requires a mature developed As-built BIM model with enough data added to support the analysis.	Not yet available	4
49	BIM environment allows the simulation of different resource assignments for different execution scenarios. Once the optimum deconstruction strategy is chosen, actual resources on-site can be tracked and compared against the planned strategy.	(Eastman et al. 2011; Ge et al. 2017)	1,2
50	BIM 4D simulation tools can provide virtual first runs to ensure the levelling of the production, the optimization of cycle times and reduction in productivity variations	(Ge et al. 2017)	2
(51)	The use of 4D scheduling in the evaluation of different deconstruction alternatives early in the planning process is expected to increase the number of alternatives provided. This can delay the selection of the most appropriate strategy until the last moment.	(Khemlani 2009)	1
52	During the planning of the deconstruction process, once a change is done concerning the salvaged elements to be extracted, the As-built BIM model is instantly updated along with all the related quantities, costs and labour needed.	(Ge et al. 2017)	2
53	Using BIM collaboration platforms, the different scenarios for the selective dismantling of elements can be separated from the traditional demolition activities of the rest of the building.	Not yet available	4
54	Dynamic clash detection process needs to be programmed each time a new BIM object is studied. However, for the dismantling of complex and valuable assets in a building, the time spent on accurate simulation processes is reimbursed by the smooth execution on site.	(Autodesk University 2013)	2

No.	Explanation	Reference	Evidence
55	Automated Quantity take-off provides accurate quantification of the recoverable materials and elements by eliminating the human error. Thus, variability in quantities outcome is reduced. The process is also adaptable to instant changes and modifications.	(Akinade et al. 2017; Eastman et al. 2011)	2,1
56	No matter how complex the project is, the quantification of the recovered elements is automatically created once the As-built BIM model is completed. The time saved is significant compared to the manual calculations.	(Akinade et al. 2017)	2
57	In deconstruction, VR applications can bring a whole new level in the visualization of the dismantling of salvaged elements.	Not yet available	4
58	No matter how many changes happen to the BIM model, the changes are instantly applied to all views and the relevant documents to be issued.	(Eastman et al. 2011)	1
(59)	Abuse of the ease of issuance of 2D drawings, documents and reports can lead to more versions of the drawings more than required. This unnecessarily increases the unrequired paperwork and may waste time and effort to trace the versions produced.	(Sacks et al. 2010)	1
60	The quick and robust generation of detailed information about the recovery potential and dismantling requirements of each element enables the control of the batch size.	Not yet available	4
(61)	The online communication through BIM applications for synchronizing on site-processes with the Model data is not yet fully adopted in the construction industry.	(Manning and Messner 2008)	1
62	Visualization of processes on site as well as the progress updates all through a BIM platform verifies and validates the process information.	(Dehlin and Olofsson 2008)	1
63	Processes visualization enables the production teams on-site (teams responsible for the dismantling of elements) to prioritize their subsequent work to ensure the smooth flow of work with respect to the required salvaged elements. Thus, implementing a pull-flow.	(Sacks et al. 2009)	1
64	The Online visualization of the process during execution on-site can help in the reduction of "work-in-process" inventories. and production batch sizes. Therefore, resources (mainly labour in dismantling processes) can be managed based on the "one-piece-flow" of salvaged elements.	(Sacks et al. 2009)	1
65	Visualization of the BIM processes on site enables the consecutive execution of the activities (deconstruction activities) one after the other in a one-piece flow manner. This reduces the delay between activities and shortens the cycle time for any disassembly group of elements.	(Sacks et al. 2009)	1
66	Available BIM applications installed on-rugged devices allows the visualisation of each activity sequence on-site. This process may be used in the disassembly of building elements to reduce errors and preserve the quality of elements during the dismantling process.	(Svaleur et al. 2017)	1
67	Visualization of dismantling sequence can be regarded as a reference for on-site workers and ensures that the processes are standardized.	(Schall et al. 2009)	1
68	Managers can 'see' a near real-time progress of on-going activities on site through updates on the BIM model. This could be an alternative for on-site inspection.	(Sacks et al. 2009)	1
69	On-site BIM applications provides real time status reporting. This can be an accurate and feasible tool for measuring the on-site productivity. Performance measurement is then standardized, and all the updates are instantly recorded and integrated into the central BIM model.	(Sacks et al. 2010)	1
70	An example for external applications can be the Web-shops for showcasing the potential salvaged elements. Based on the demand, early decisions can be taken on the destiny of these elements. This process facilitates the execution of the deconstruction processes based on the end-customer needs (the buyers of the salvaged elements). It also helps in creating deals and long-term relationships among different stakeholders involved in the recovery and re-use of building elements as a convenient start towards the adoption of circular economy in the construction industry.	(Resource Limburg 2017)	3
71	Where BIM database is connected to online resource stores, they provide a powerful mechanism for getting pull production signals and delivery of salvaged elements and materials (to the buyers). The actual deconstruction processes can then be executed with minimum inventories. since the final destination and time of delivery will be known earlier. This maintains a transparent process of closed loop supply chain. Additionally, the dismantling of the rest of elements with unknown second destination can be postponed till a demand arises for them. Thus, standardized activities can be separated from the ones with uncertainty.	Not yet available	4
72	Direct delivery of information (about the salvaged elements requested by customers) eliminates the waiting time (time needed to know which salvaged elements to be dismantled). Therefore, a smooth flow of information is established.	(Khemlani 2009)	1
73	Synchronizing BIM database with the updates on the sold salvaged elements on the Web shop improves the cycle time (time needed for elements to be dismantled and delivered). For instance, sold salvage elements are given a priority to be dismantled and be ready on their transfer date.	Not yet available	4

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