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Camilo Mercado Siles **BIM-based Framework for Deconstructability Assessment of Steel Structures**

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Camilo Mercado Siles

BIM-based Framework for Deconstructability Assessment of Steel Structures

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Camilo Enrique Mercado Siles

BIM-based Framework for Deconstructability Assessment of Steel Structures

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Para mi Mita Lola

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STATEMENT OF INTEGRITY

I hereby declare having conducted this academic work with integrity. I confirm that I have not used plagiarism or any form of undue use of information or falsification of results along the process leading to its elaboration.

I further declare that I have fully acknowledged the Code of Ethical Conduct of the University of Minho.

Camilo E. M. G.

RESUMO

Desenvolvimento de uma Metodologia Baseada em BIM para Avaliação da Desconstrutibilidade de Estruturas de Aço

Edificações em desuso, e que sofrem de degradação ou abandono são vistas pela Economia Circular como possíveis bancos de materiais. A desmontagem ou a desconstrução dessas instalações permite recuperar os materiais, que podem posteriormente ser reintroduzidos no ambiente construído, seja por meio de reciclagem ou da reutilização na construção de novos edifícios. A desconstrução representa uma oportunidade de aliviar parte do ônus que a extração de matérias-primas para a construção e os resíduos gerados pela demolição representam para o meio ambiente. O setor de Arquitetura, Engenharia e Construção (AEC) deve evoluir no sentido de se tornar uma indústria mais limpa e competitiva e fazer a transição para um modelo circular.

A conceção e o dimensionamento de edificações com foco na desconstrução (*Design for Deconstruction - DfD*) é uma das abordagens alinhadas com a Economia Circular que permite a recuperação de materiais quando um ativo construído chega ao fim da sua vida útil. Os princípios do *DfD* também podem ser úteis na análise do potencial de desconstrutibilidade das estruturas existentes e no planeamento da desativação da instalação, independentemente de terem sido inicialmente projetados sob o *DfD* ou não. Em linha com o *DfD*, a metodologia *Materials Passports* (passaporte dos materiais) define as diretrizes que permitem coletar e gerenciar as informações necessárias na execução de abordagens de design circular.

No contexto atual, onde a adoção da Circularidade no setor AEC se tornou um objetivo estratégico para a Europa, o *Building Information Modeling (BIM*) surge como um facilitador para a adoção de abordagens disruptivas, onde se incluem o *DfD* e o *Materials Passports*, e um facilitador na transição da indústria de AEC para um modelo circular. A presente pesquisa concentra-se em explorar o modo como os recursos de BIM podem apoiar a tomada de decisão, a avaliação e o planeamento da desconstrução de estruturas de aço no momento em que estas atingem o final da sua vida útil, e como a informação necessária pode ser transferida para um projeto subsequente, reutilizando o aço recuperado na construção de novas instalações, sob os princípios do *DfD* e o suporte do *Materials Passports*. É proposto um fluxo de trabalho baseado em BIM para a avaliação da desconstrutibilidade, tirando proveito das funcionalidades de uma ferramenta BIM comummente utilizada no projeto dessas estruturas. Além disso, é definido um conjunto de indicadores para medir a desconstrutibilidade da estrutura analisada e é desenvolvido um aplicativo para auxiliar na avaliação e planeamento da desconstrutibilidade com base nos parâmetros dos objetos BIM. A aplicabilidade do fluxo de trabalho proposto e do aplicativo é demonstrada através de um estudo de caso.

Palavras-chave: BIM, Economia Circular, Desconstrução, Materials Passports, Reutilização de Aço

RESUMEN

Marco de trabajo basado en BIM para la evaluación de la deconstructibilidad de estructuras de acero

Las instalaciones que han caído en desuso, deterioro o abandono son consideradas como bancos de materiales por la Economía Circular. Mediante la deconstrucción de estas instalaciones, dichos materiales pueden ser recuperados y posteriormente reintroducidos en el entorno construido, ya sea reciclándolos o reutilizándolos para la construcción de nuevos edificios. La deconstrucción representa una oportunidad para aliviar parte de la carga que supone para el medio ambiente la extracción de materias primas para la industria de la construcción y por los residuos generados por demoliciones. El sector de Arquitectura, Ingeniería y Construcción (AEC) debe evolucionar en el camino para convertirse en una industria más limpia y competitiva y hacer la transición hacia un modelo circular.

El Diseño para la Deconstrucción (DfD, por sus siglas en inglés) es uno de los enfoques alineados con la Economía Circular que permitiría la recuperación de materiales una vez que un activo construido haya llegado al final de su vida útil. Los principios de DfD también podrían ser útiles en el análisis del potencial de deconstrucción de las estructuras existentes y para planificar el desmantelamiento de la instalación, independientemente de si fueron diseñadas inicialmente bajo DfD o no. De acuerdo con DfD, la metodología *Materials Passports* (Pasaportes de Materiales) establece las pautas para recopilar y manejar la información requerida en la ejecución de enfoques de diseño circular.

En el contexto actual, donde la adopción del modelo circular en AEC se ha convertido en un objetivo estratégico para Europa, *Building Information Modelling* (BIM) se ha concebido como un facilitador para la adopción de enfoques disruptivos, incluidos DfD y *Materials Passports*, y facilitador de la transición. de la industria AEC en un modelo circular. Esta investigación se centra en explorar cómo las capacidades BIM pueden respaldar la toma de decisiones, la evaluación y la planificación de la deconstrucción de estructuras de acero una vez que han llegado al final de su vida útil, y cómo la información se puede transferir al diseño posterior reutilizando el acero recuperado resultante. en la construcción de nuevas instalaciones bajo los principios del DfD y la metodología *Materials Passports*. Se propone un flujo de trabajo basado en BIM para la evaluación de la deconstrucción que aprovecha las funcionalidades de una herramienta de autoría BIM comúnmente utilizada en el diseño de estas estructuras. Además, se desarrolló un conjunto de indicadores para medir la deconstructibilidad de la estructura analizada y una aplicación para asistir en la evaluación y planificación de la deconstrucción basada en los parámetros de los objetos BIM. La aplicabilidad del flujo de trabajo y la aplicación propuestos se demuestra a través de un estudio de caso.

Palabras clave: BIM, Economía Circular, Deconstrucción, Materials Passports, Reutilización de Acero

ABSTRACT

Facilities that have fallen into disuse, disrepair or abandonment are considered as banks of materials by the Circular Economy. Through the deconstruction of these facilities, such materials can be reclaimed and posteriorly reintroduced into the built environment, either by recycling or reusing them for the construction of new buildings. Deconstruction represents an opportunity to alleviate part of the burden that the extraction of raw materials for construction and the waste generated by demolition poses to the environment. The Architecture, Engineering and Construction (AEC) sector must evolve in the road to becoming a cleaner and more competitive industry and transitioning into a circular model.

Design for Deconstruction (DfD) is one of the approaches aligned with Circular Economy that would enable the recovery of materials once a constructed asset has reached its end of service life. DfD principles could also be helpful in the analysis of the deconstructability potential of existing structures and to plan the facility decommission, regardless if they were initially designed under DfD or not. In line with DfD, the Materials Passports framework sets the guidelines to collect and handle the information required in the execution of circular design approaches.

Within the current context, where the adoption of Circularity in AEC has become a strategic goal for Europe, Building Information Modelling (BIM) has been envisioned as an enabler for the adoption of disruptive approaches, including DfD and Materials Passports, and facilitator on the transition of the AEC industry into a Circular model. This research focuses on exploring how BIM capabilities can support the decision making, assessment and planning of the deconstruction of steel structures once they have reached the end of their service life, and how the information can be transferred to the subsequent design reusing the resulting reclaimed steel into the construction of new facilities under the DfD principles and the Materials Passports framework. A BIM-based workflow for the deconstructability assessment that takes advantage of the functionalities of a BIM authoring tool commonly used in the design of these structures is proposed. Additionally, a set of indicators to measure the deconstructability of the analyzed structure and an application to assist on the deconstructability assessment and planning based on BIM objects' parameters were developed. The applicability of the proposed workflow and application is demonstrated through a case study.

Keywords: BIM, Circular Economy, Deconstruction, Materials Passports, Steel Reuse.

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1. INTRODUCTION

Architecture, Engineering, and Construction (AEC) Industry faces a formidable challenge: becoming a sustainable business. Achieving this goal requires answering several questions, including: How to manage and reduce the waste generated by the construction activities? How to minimize the alterations to the environment caused by these activities? How to reduce the cost of scarce and energy-intensive materials? How to take advantage of unused constructed assets? In the search for solutions to these problems, AEC has turned its interest into the Circular Economy (CE). Under the CE approach, renewable materials and energy are preferred, natural systems are preserved and enhanced, and waste and negative impacts are reduced during the design phase (Acharya et al., 2018). However, the shift into this model requires a systemic transformation of the industry (Kirchherr et al., 2017). The adoption of innovative strategies, methods and technologies can propel this so much needed change. One of such strategies is the reclamation for reuse and recycling of materials that already form part of the built environment from structures that have fallen into abandonment or that for any other reason must be demolished. Recycling and reusing would help to reduce and alleviate the environmental damage created by the extraction of raw materials required for new constructions and, at the same time, reduce material costs and waste volumes. Steel structures, particularly, have a great potential to become exploitable material banks. Through a well-planned deconstruction process, much of the steel from these structures could be recovered and reincorporated in future constructions.

Building Information Modelling (BIM) methodology comprises technologies, processes and policies (Succar et al., 2012) intended to manage the information generated during the lifecycle of a building, using object-based digital models of the building. BIM tools and its capabilities, as many research works suggest (Akanbi et al., 2019; Akinade et al., 2017; ARUP, 2016; Heinrich and Lang, 2019; Ness et al., 2015; Nizam et al., 2018), can be facilitators for the introduction of Circular Economy oriented approaches in the AEC industry, including Design for Deconstruction (DfD). The studies on the integration between BIM and circular approaches have mostly focused on supporting processes during the early stages of the building lifecycle (i.e. design, preconstruction analyses). However, as the methodology gains terrain in academia and practice, BIM-based applications to assist operating and decommissioning of buildings are being proposed and implemented (Iacovidou and Purnell, 2016; van den Berg et al., 2020; Volk et al., 2014).

1.1. Objectives

This research explores how BIM can be leveraged in the deconstruction assessment, planning and execution, for steel structures at the end of their service life, and the subsequent reuse of the reclaimed steelwork in new constructions designed under the DfD principles. It aims to generate BIM-based tools and workflows relevant for steel structures deconstruction practice. To achieve this objective, the research should accomplish the following specific goals:

- Propose a BIM-based workflow to support deconstruction potential assessment and planning processes for existing steel structures, and subsequent reuse of the reclaimed steelwork.
- Propose guidelines that enable practitioners to generate 4D BIM models useful to assess the viability and plan the deconstruction of an existing steel structure.

- Create a support application that automates the assessment of the deconstruction potential of steel structures for reuse of the reclaimed steelwork through the analysis of parameters contained in a BIM model of the steel structure.

1.2. Thesis organization

This document contains six chapters. Following the introduction, Chapter 2 presents a literature review on the Circular Economy, its fundamental principles, and the barriers and benefits of its integration into the construction sector. Then, it focuses on one of the design approaches aligned with CE: Design for Deconstruction and its principles, followed by an introduction to the Materials Passports traceability tool, a structured approach for data collection for material reuse purposes. This chapter also explores the steel reuse practice, and previous studies regarding BIM uses in circularity and material reuse.

Chapter 3 relates the methodological approach of this research work, its scope, key assumptions, and constraints. This chapter also contains the description of the BIM environment selected, the exploration of the BIM tools and programming tools used to develop an application created to aid in the automatization of the proposed workflow.

Chapter 4 details the proposed BIM-based framework for deconstructability assessment of steel structures, and defines the concepts behind the Deconstructability Score, an indicator of the Deconstructability potential of the structure. This chapter also contains a description of the information requirements and the specifics on how BIM can assist the deconstruction of steel structures and how the information output of this process could be later utilized in the design phase of new structures using reclaimed steel.

Chapter 5 contains a description of the case study developed. The BIM model of an existing steel structure was chosen to validate the framework applicability and demonstrate the application's use.

At last, Chapter 6 collects the conclusions drawn from the research work and the implications for future research.

2. LITERATURE REVIEW

2.1. Circular Economy and Construction

Growing environmental awareness has driven Architecture Engineering and Construction (AEC) Industry to look for alternative approaches that enable reductions on the environmental impact generated by buildings throughout their whole lifecycle. In the road to becoming a more environmentally friendly activity, this industry has turned its attention to the Circular Economy (also referred to as Loop Economy in the literature). From the many definitions given throughout the existing literature regarding Circular Economy, Kirchherr et al. (2017) conceptualized it as "*an economic system that replaces the traditional "end-of-life" concept with reducing, alternatively reusing, recycling and recovering materials in production, distribution and consumption processes*", aiming to accomplish sustainable development. For the AEC industry, the adoption of this system promises to alleviate part of its impact on the environment through reductions on raw material extraction and waste generation but also represents an opportunity to achieve leaner processes and lower construction costs.

The Circular thinking in construction considers existing buildings and infrastructure as vast banks of materials to take advantage of, once they have reached the end of their service life (EOSL). It promotes the extension of the life of materials through their reuse and reincorporation into the value chain, resulting in reduced extraction and consumption of resources and energy, and at the same time, reduced waste emissions. It also encourages, whenever feasible, the refurbishment of the existing built environment (which comprises buildings, infrastructure for transportation, telecommunications, energy, water, and waste management systems) to extend its service life or to adapt it to new functions, as an alternative to demolition. Similarly, encourages the use of energy obtained from renewable sources, and the preservation and enhancement of natural systems (Acharya et al., 2018).

The first ideas regarding the Circular Economy model date back to 1976, when W. Stahel proposed the concept of economy in loops. Then, the "Cradle to cradle" design protocol, developed in the 1980s by W. McDonough and M. Braungart, built on top of the loop concept and set the basis for the Circular approach. Particularly in the European Union, the promotion of Circular Economy principles and efforts for their adoption in different industrial sectors have been pursued since 2014, as part of the Europe 2020 strategy for sustainable growth. In the communication "Towards a circular economy: A zero waste programme for Europe", the European Commission (2014) emphasized the need for changes in value chains to transition into a more circular economy and the benefits these systemic transformations could bring to the European economy. More recently, the European Commission (2020) reaffirmed the pivotal role of Circular Economy on their strategy to achieve a climate-neutral, resource-efficient, and competitive economy by 2050. Moreover, it identified the AEC industry as one of the critical value chains that require urgent, comprehensive, and coordinated actions to speed up their transformation into a circular model.

In the AEC sector, several research projects, included the ones funded by the European Commission under the Horizon 2020 Research and Innovation Programme (such as BAMB[1] and CINDERELA[2]) have started to work towards the development of methodologies and tools that address the barriers to the adoption of Circularity in the European AEC industry. These projects strive to encourage and normalize the use of reclaimed materials through the study, development and dissemination of innovative design approaches, construction methods, materials, deconstruction techniques, and alternative business models. Reversible buildings design, Design for Deconstruction (DfD, further discussed in section 2.2), are some of such approaches, is gaining momentum in the academy and practice.

2.1.1. Benefits from the adoption of Circular Economy principles in the AEC industry

Contrasting with the mainstream ideology based on the linear model of resource consumption, which day by day has proven to be unsustainable (not only in terms of economic growth but also in natural resources use), the adoption of a circular approach by the AEC industry promises environmental and economic benefits. The extent of such positive impacts would depend on the reach and scale of the circular approach adoption within the AEC industry. Being this industry the largest consumer of raw materials, the circular approach could help reduce the pressure that the ever-growing demand of materials for construction activities puts on the natural resources. Reducing waste, improving efficiency and minimizing the intake of raw materials required by construction activities would preserve natural resources. The Ellen MacArthur Foundation (2019) estimates a reduction of up to 2 billion tonnes of CO_2 emissions per year by 2050. This reduction stems from a reduced demand of new materials if the AEC sector widely adopts circular measures (such as circular oriented design, waste elimination, reuse and recycle of materials, and the introduction of new business models).

A significant positive effect derived from Circularity is the reduction of the volumes of construction and demolition waste (CDW) that would end up in landfills. Taking into account that CDW constitutes 35% to 40% of urban solid waste and only 20 to 30% of this is recycled or reused (Ellen MacArthur Foundation, 2019; European Commission, 2020), the reduction (or ideal elimination) of CDW would drastically reduce the volume of waste to be handled. Direct results of this would be lower energy consumption, reduced greenhouse gas emissions, and monetary saving linked to waste management activities. This waste reduction would also favour safeguarding, restoring and increasing the ecosystems and industry resilience (ARUP, 2016).

In terms of economic benefits, for example, the European Commission Directorate-General for Research and Innovation (2017) estimates potential annual net savings per year of up to €600 billion for European industries through the implementation of measures for waste prevention, eco-design, and reuse. Circular Economy would also help organizations to hedge against volatility in the prices of commodities such as copper and steel, and rebalance flows of goods, scrap, and used products (Geng et al., 2019). However, as explained by Ghisellini et al. (2018), more research must be oriented to quantify at different levels

1 Buildings As Material Banks (BAMB) is an EU funded project that aims to develop methodologies and tools that enable the shift to a circular building sector, such as reversible building design and circular building assessment.

2 CINDERELA Consortium aims to develop and demonstrate new circular economy business models based on waste-to-resource opportunities.

the possible economic benefits that the implementation of Circular Economy measures might bring to the construction industry.

2.1.2. Barriers for the adoption of Circular Economy in the AEC industry

Circular Economy offers an attractive area for industrial innovation and investment within the AEC industry. However, as Blériot et al. (2017) concluded, the investment in Circular Economy oriented actions is still limited, restraining the implementation of circular measures. The European Commission (2014) also acknowledges that the financial sector often does not provide for investment in innovation and resource efficiency improvements. Instead, circular economy exemplar projects are typically funded by public or private organisations solely through internal capital budgets (Acharya et al., 2018). Overcoming these barriers requires the development and adoption of innovative financial instruments, business models (such as public-private partnerships) and removing obstacles stemming from current legislation or inadequate enforcement (European Commission, 2015).

The European Environment Agency (2020) points out the price competition with virgin alternatives as one of the main obstacles for the uptake of circular economy actions. The price gap between these products is still considerable. Although some measures such as tax benefits for circular economy products or businesses, tax increases on undesirable waste streams, tax reductions on the use of secondary materials, and tax reductions for companies that share, repair, and recycle (Ellen MacArthur Foundation, 2019) are being implemented, these are still not the norm and have not managed to reduce this price gap.

Mindsets and lack of awareness also represent a significant impediment for the adoption of Circularity. In the specific case of the steel industry, Ness et al. (2015) suggest the mindsets and approaches from all the steel chain stakeholders (steel companies, designers, constructors, customers), need to change to give more emphasis to steel reuse and think of their products as assets to be conserved. Cruz Rios (2019) points out that research has focused on the operational phase of the asset's lifecycle, neglecting other phases (i.e. material extraction, construction, demolition, disposal of waste), therefore limiting the knowledge creation and dissemination regarding material reuse. There is also a lack of basic knowledge from architects, engineers and owners regarding the Circular design approaches. Kirchherr et al. (2017) argue that practitioners not fully grasping the Circular Economy concepts is a barrier to advances in the field. The European Commission (2015) acknowledges the transition to a Circular Economy requires a qualified workforce with specific skills; therefore, efforts must be made to encourage education and training aligned with circular thinking.

2.2. Design for Deconstruction

Design plays a significant role in enabling Circularity. The Design for Deconstruction approach (DfD, also referred to as Design for Disassembly or Dismantling) is one of the design tendencies aligned with Circular Economy concepts that has started to gain ground in the AEC sector. This approach aims to generate design solutions that enable the deconstruction (or disassembly) and recovery of the building components once its service life is over, through the process of deconstruction, which is defined by ISO 20887 (2020) as the "*non-destructive taking-apart of construction works, or constructed asset into (its) constituent materials or components*". Thomsen et al. (2011) extend the concept into a phased process: a first phase that consists in the planning and execution of the deconstruction per se, and a second phase that entails *“the continued use of the deconstructed components and materials in other buildings or in other functions at the highest possible level”*.In this way, the materials reclaimed through deconstruction can be reused in new constructions, serving the same or similar purpose, consequently reducing the need for recycling or discarding, and reducing the intrinsic burden imposed on the environment by the extraction of natural resources and the manufacture or recycling of materials required for new constructions.

Crowther (2005) proposed a set of recurring principles that provide the foundation of the DfD approach, which are listed and classified by their relevance to reuse in Figure 1. Applying these DfD principles during the design strives to ease recovery and reintroduction of materials into the built environment, once the building has reached the end of its service life. The application of these principles during the design development stage or to assess existing structures (regardless these were initially designed under the DfD approach or not), for future disassembly (Crowther, 2001) strives to reduce the need for destructive demolition, generation of CDW, and increase the recovery of materials, either by facilitating reclamation of materials for recycling, remanufacturing of components, reusing of parts or the disassembly and relocation of the whole building.

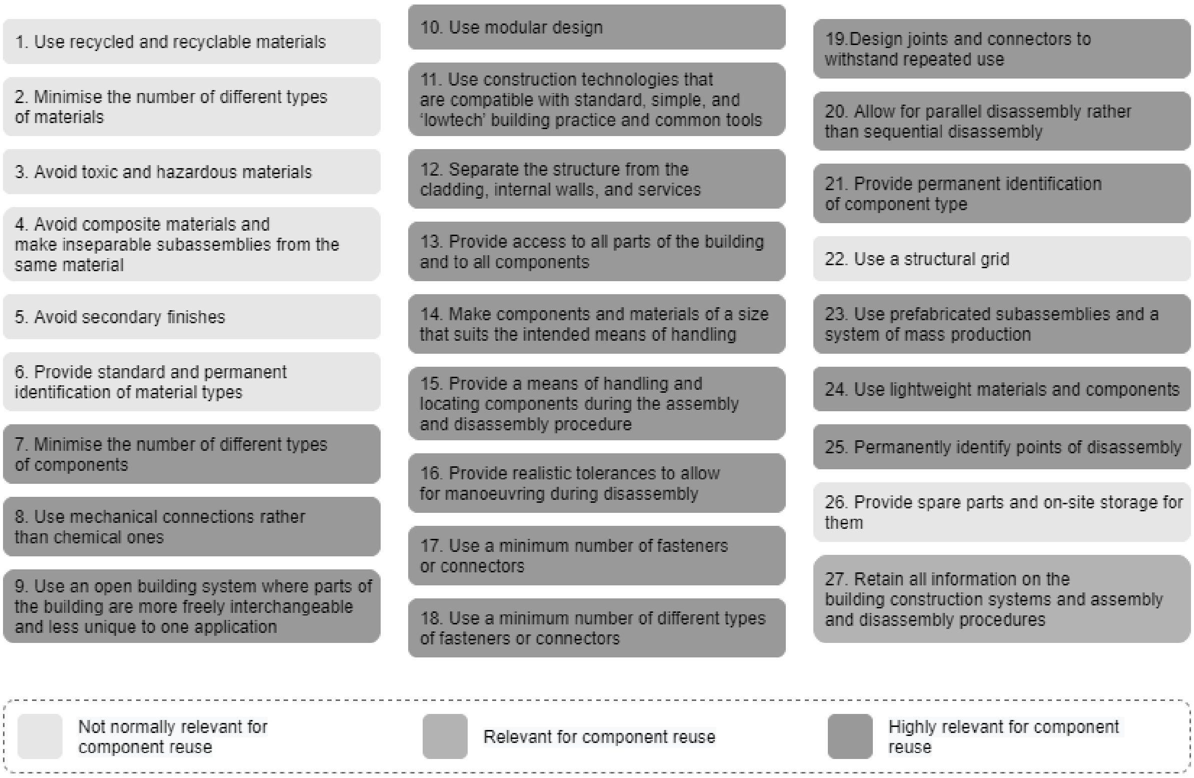

Figure 1: Principles of design for disassembly.
Based on Crowther (2005).

The DfD approach also relies on the theory of layers, proposed by F. Duffy and later expanded by S. Brand, which considers the building not as a single entity, but as a collection of layers with defined functions and expected service life (see Figure 2). This theory considers that the interfaces between these layers are primary points of deconstruction (Crowther, 2001) and should be designed to facilitate the appropriate disassembly. This layered conceptualization of a building would also allow extending the service life of the building by modifying or substituting the layers with shorter service life (i.e.

services, space plan and stuff) without the need of replacing the more long-lived ones. Alternatively, as explained by Jensen et al. (2019), enable the possibility of making selective repairs and upgrades during its operational stage, which allows for repurposing or modifying the constructed asset, extending its service life.

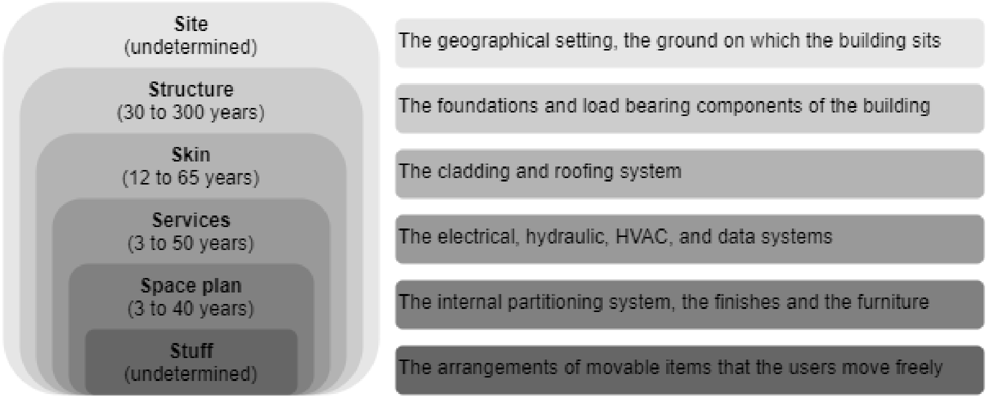

Figure 2: Building layers.
Based on Crowther (2001).

Although there has been a recent ramp-up in the interest in DfD and other Circular approaches in the AEC industry (Ghisellini et al., 2018), the implementation of this approach is still scarce. Akinade et al. (2019) identified the main barriers to the adoption of DfD practices, specifically in the UK industry through a series of focus groups and literature review. Their findings are shown in Table 1. These have a direct correlation with the barriers encountered for the CE adoption in the AEC industry.

DfD has a short history in terms of standardization. The recently published first edition of ISO 20887:2020 "Sustainability in buildings and civil engineering works — Design for disassembly and adaptability — Principles, requirements and guidance" provides general guidelines for the integration of DfD and DfA (Design for Adaptability) into the design practice. This standard document also defines several principles that aim to increase the potential for disassembly and adaptability of a constructed asset (summarized in the following table), provides guidance on the formulation of performance indicators for each of these principles.

Table 1: Main barriers to DfD adoption.
Taken from Akinade et al. (2019).

Group		Identified barriers
Lack of stringent legislation for DfD	1	Lack of Government legislation for deconstructed facilities.
	2	Design codes generally favour specifying new materials.
	3	Low Building Research Establishment Environmental Assessment Method (BREEAM) point for DfD.
Lack of adequate information in building design	4	Lack of information about recoverable materials.
	5	Lack of disassembly information.
	6	Inadequate information about cost-effective material separation methods.
Lack of large enough market for recovered components	7	No standardisation and grading system for salvaged materials.
	8	Perceived perception and risks associated with reclaimed materials.
	9	Low-performance guarantees for recovered materials.
	10	Degraded aesthetics of salvaged materials.
	11	Damage or contamination of materials during recovery.
	12	Storage consideration for recovered materials.
	13	Transportation considerations for recovered materials.
	14	No information exchange system for salvaged materials.
	15	Cost of product re-certification.
Difficulty in developing a business case for DfD	16	Additional costs of design that make the project more expensive.
	17	Insurance constraints and legal warranties of reclaimed materials.
	18	DfD will increase the design time.
	19	Changing industry standards and construction methodology.
	20	Believe that DfD could compromise building aesthetics and safety.
	21	Overall benefit of DfD may not happen after a long time.
Lack of effective DfD tools	22	Lack of DfD analysis methodologies.
	23	Existing DfD tools are not BIM compliant.
	24	No tools for identifying and classifying salvaged materials at the end-of-life.
	25	Performance analysis tools for end-of-life scenarios are lacking.
	26	Limited visualisation capability for DfD.

Table 2: ISO 20887:2020 DfA and DfD principles

Category	Principle	Description
Adaptability	1. Versatility	The constructed asset should be designed to accommodate different uses in a single space, with minor and reversible adaptations, resulting in reduced required area, cost and resource consumption.
	2. Convertibility	Spaces in the constructed asset can accommodate changes in the user needs through usually irreversible modifications.
	3. Expandability	The design should consider allowance so the constructed asset's spaces, features, capabilities and capacities can be easily modified in the future.
Disassembly	1. Ease of access to components and services	Components and connections design should ensure accessibility and visibility to promote ease of disassembly.
	2. Independence	Elements that make up the facility should be designed so they can be removed or upgraded without affecting other parts or systems performance.
	3. Avoidance of unnecessary treatments and finishes	Only finishes with essential purposes, such as fire insulation and corrosion protection, should be used; otherwise, materials should be used with their natural finish.
	4. Supporting circular economy business models	Constructed asset's components selection should favour future reuse, recycling, remanufacturing, and refurbishing.
	5. Simplicity	The design solutions selected for the constructed asset should minimize the number of components and diversity of materials
	6. Standardization	The asset's design should minimize customization and incorporate the use of standard components to favour simplicity, interchangeability, adaptability and material optimization.
	7. Safety of disassembly	Any component of the constructed asset should count with a disassembly plan that provides enough documentation to support a safe disassembly for future reuse or recycling.

2.3. Materials passports

One of the axes of the research work by the BAMB project is the development of guidelines to create data sets containing defined properties of a material for their present use, recovery, and reuse. This tool for material traceability is known as Materials Passports (MP). It would facilitate material circularity by standardizing and centralizing information about product use and reuse that are usually not available in other initiatives/documents /databases (Mulhall et al., 2017) and is generally required by circular approaches, including DfD. As explained by Lang (2019), the holistic and structured approach of Materials Passports intends to bridge the information gap that currently exists between the diverse actors within the construction value chain at the different stages of a facility's lifecycle and can be used to support various assessment, including LCA and LCC. The information in each MP spans from initial characteristics (such as manufacturer, origin, production date, expected service life) to the actual characteristics of the component/material after use (transport, disassembly and handling instructions, exposition to hazardous chemicals during its service life).

Materials Passports proposes a structured approach for data collection, relying on five different hierarchy levels (see Figure 3) and four categories of properties. The higher level, building level, as explained by Heinrich and Lang (2019), can be used for a holistic evaluation of non-material factors, such as energy performance. Meanwhile, the component and material levels define the value for recovery of the material. The four categories of properties defined in MP are 1) physical, 2) chemical, 3) process and 4) biological. Figure 4 provides an overview of the aspects included in each group, which set a template to manage and check the completeness of information required for the information needed by circular solutions. MP would gather information from different standardized sources, including Environmental Product Declarations (based on ISO 14025 and EN 15804), CE Marking Declarations (based on EU construction products regulation 305/2011, and for the specific case of structural steel components on the harmonised standard EN 1090-1:2009+A1:2011), Safety Data Sheet (International Hazard Communication Standard) (Debacker and Manshoven, 2016). Appendix 1 shows a more detailed list of data requirements proposed by the Materials Passports framework. From this detailed list, the properties of interest specifically for steel circularity are discussed in section 4.2.3.

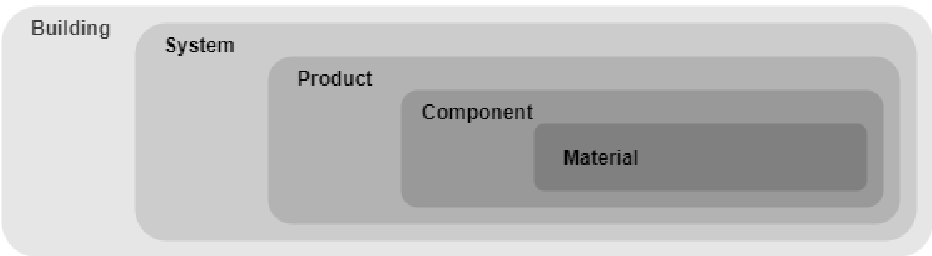

Figure 3: Hierarchy levels of product composition in the Materials Passports framework. Heinrich and Lang (2019).

Figure 4: Overview of properties classification in the Materials Passports framework. Based on Heinrich and Lang (2019).

2.4. Steel reuse

Steel, being one of the most commonly used construction materials, requires a significant amount of natural resources for the extraction of its raw inputs, production, casting, and transportation before becoming part of the built environment. To give an idea of the environmental impact of steel production, the activities related to the iron and steel industry accounted for 63 million tonnes of CO_2 equivalent in Europe during 2017, which represent 17% of the total annual emissions from industrial processes (Eurostat, 2019). However, steel is also one of the materials that offer more opportunities for reincorporation into the built environment by recycling or reusing, providing ample opportunity to reduce the intrinsic impact of its use. Steel recycling and reuse are measures adopted by the AEC industry consistent with the circular thinking, being nowadays, the recycling of steelwork and scrap resulting from demolition the most common alternative to reincorporate it into the built environment (see Figure 5).

Reusing steel reclaimed from the deconstruction of existing buildings should be favoured over recycling since the energy and resource consumption for steel reuse is lower. At least 4,272,000 MJ/ton are saved when choosing to reuse steel just by skipping the melting process. If the transportation distance to the reuse site is shorter than the ones to the production facility and the new construction site, the savings in transportation are also significant. These asseverations are backed by the results of Ness et al. (2015) work, where they compared the embodied energy of a structure built totally with recycled steel elements vs the same structure built using exclusively reused steel parts.

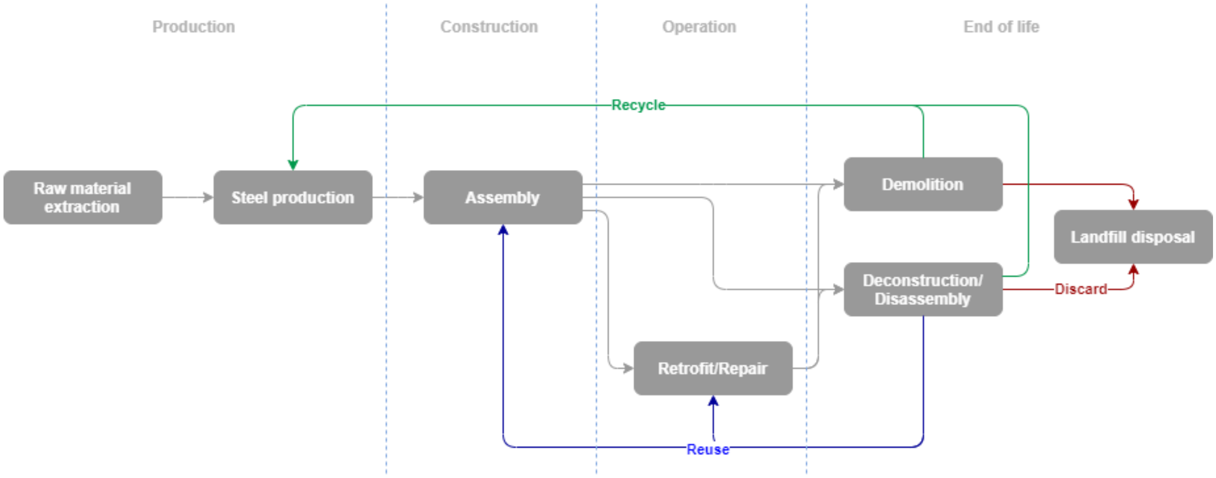

Figure 5: Steel life cycle, according to the Circular Economy model.

Rossetti (2017) exemplifies steel structures versatility and ease for reuse with the case of an RAF Hangar built in the Netherlands in 1942, demounted and rebuilt in 1958 to serve as an airport, and more recently in 2015, reused as a bus terminal. Research projects such as PROGRESS[1] and REDUCE[2] that aim to

1 PROvisions for a Greater REuse of Steel Structures (PROGRESS) is an EU funded project under the Research Fund for Coal and Steel (RFCS), with the goal of providing methodologies, tools and recommendations on reusing steel-based components from existing and planned buildings

2 REuse and Demountability Using steel structures and the Circular Economy (REDUCE) is an EU funded project for the development, testing and design, fabrication and detailing guidance of new demountable, composite floor systems.

develop guidelines for the reuse of steel, have studied several successful cases produced between 2017 and 2020 in several European countries. These case studies include the relocation of warehouse buildings, repurposing of a hydraulic testing laboratory into a five-storey office building, and the utilization of innovative composite flooring systems.

There is a significant amount of steel contained in the built environment. Still, there is no measure of the steel potentially suitable for reclamation and reuse in new constructions. Rosseti (2017) estimates that up to 50% of the steel in structural elements of abandoned structures could be reused. Meanwhile, a smaller portion of claddings can be reclaimed for reuse. Ajayabi et al. (2019) consider the estimation of stocks of building products and their possible release rates as fundamental for enabling circularity in the built environment. Through the REBUILD[1] project, efforts are being made to develop methods to help develop catalogues with the number of buildings, their ages, construction type and product/material choices, to quantify the stock of different material stocks (including steel) contained in standing buildings.

2.4.1. Benefits of steel reuse

In terms of environmental benefits, the reuse of steel translates into a significant reduction of carbon emissions, resource, and energy savings. Vares et al. (2018) estimated that when the steel is reused for the construction of a building, the carbon emissions are 12% lower than the ones resulting from construction with recycled steel. Pongiglione and Calderini (2014) estimated 30% savings in material consumption if the steel trusses reclaimed from an abandoned industrial complex were reused in the construction of a close-by railway station in Genoa, Italy. The energy consumption and CO_2 emissions reduction might surpass this 30%, considering the savings achieved in transportation and construction processes. PROGRESS (2020a) reported an estimated decrease of 56% on the embodied and operational emissions over the lifecycle of a warehouse and offices building, which had to be deconstructed and relocated 1.6km from its original position.

The economic benefits derived from steel reuse must be evaluated on a case by case basis. However, some indexes found throughout the literature regarding the economic benefits attained by projects that used reclaimed steel show there is a significant reduction in costs. ARUP (2016) reported that savings in material costs could be up to 25% per tonne of steel compared to conventional sources when incorporating reused and recycled steel into the construction. PROGRESS (2020b) reports cost reductions up to 50% in high eaves portal frame structures based in several case studies published as a result of their research in different European countries.

2.4.2. Barriers to steel reuse normalization

The main barriers that hinder the normalization of reusable steel are related to information gaps, market characteristics, and quality assurance. Vares et al. (2018) identified as a barrier for mainstreaming reuse the lack of coordination and integration between stakeholders in the supply chain, limiting the information about available components from executed, planned, and on-going

[1] REgenerative BUILDings and products for a circular economy (REBUILD) is a UK based research project oriented develop techniques for remanufacturing products from buildings at end of service life (EoSL) than can be used for future deconstruction and product re-use.

demolitions/deconstructions that could be reused in new construction. Densley (2017) suggested a database of suppliers and section availability as a means to overcome this breach in the information flow in the procurement of reusable steel. Densley also points out that designers do not receive education and clear guidance on how to include and adapt reusable steel into their projects. Cai and Waldman (2019) also conceptualized a business model based on a bank of materials and components reclaimed from deconstructed structures to enable their reuse and recycling. This strategy would rely on a centralized database containing the information regarding these materials and components, to make it available to the stakeholders in the different links of the supply chain.

The perceived increase in difficulty and cost when compared to traditional construction and demolition techniques from contractors and clients also limits the reuse of steel. PROGRESS (2020b) reports that steel contractors are reluctant to work on projects using reclaimed structural elements since they do not want to sacrifice production efficiency based on this belief. Dunant et al. (2017) found through a survey that 56% of the respondents, regardless their experience on steel reuse, consider it extends the duration of the deconstruction and construction, and also increases the cost of the project. However, in this same study, respondents with experience on steel reuse had positive experiences in the execution of projects that incorporated reuse of steel.

Market barriers start with the preference for virgin materials. This limited demand, added to the disarticulated supply chain, hampers the regularization and profitability of steel reuse (Densley Tingley et al., 2017). Regardless of the environmental benefits and the possible savings in costs, the scepticism from the consumers drives them to prefer new or recycled steel over reusable steel. There is a generalized lack of confidence in the quality and structural properties of the reclaimed steelwork. In some cases, clients consider reused steel as “inferior” and refuse it or demand a discount (Dunant et al., 2017). There are also concerns regarding whether reclaimed materials have reduced performance and meet statutory standards (Ajayabi et al., 2019) and the safety risks their use might involve. However, the EN 1090-1 and 1090-2 European Standards in force (EN 1090-1, EN 1090-2) do not clarify or comment on special requirements for the design and execution of steel structures using reclaimed steel components and whether additional considerations for CE marking apply to reclaimed steelwork.

2.5. Building Information Modelling

Building Information Modelling (BIM), as a methodology, is conceptualized as a set of interacting policies, processes and technologies that enable throughout the building’s lifecycle the management of the essential building design and project data in digital format (Succar et al., 2012). This methodology has been envisioned as having the potential to redefine the way buildings are designed, constructed, managed, and decommissioned and as the enabler for the adoption of disruptive approaches in the AEC industry. This section focuses on defining some of the fundamentals of this methodology and how it could enable and support DfD practices.

2.5.1. BIM dimensions

The concept of BIM dimensions has been used to theorize how BIM models evolve through the project lifecycle, and the layers of information are incorporated into them during the model development. (See Figure 6). The third dimension, as explained by MacPartland (2017), refers to the basic modelling workflow where objects with graphical and non-graphical information are created in the information model and shared within a Common Data Environment (CDE).

The fourth dimension refers to the modelling workflow where information regarding the time is linked to the objects within the shared information model. From these 4D models, practitioners can 1) plan construction and identify beforehand potential bottlenecks in the schedule, 2) improve the communication among stakeholders to get their input regarding community concerns, 3) manage the site logistics, 4) coordinate the work of different trades, 5) monitor construction progress (Eastman et al., 2011). The fifth dimension of BIM adds another layer of information to the model: the cost. The cost data, together with the quantities derived from the 3D objects and the integration of rules, enable the estimation of construction costs and scenarios exploration, resulting in more competitive cost management (Charef et al., 2018).

There is a lack of consensus regarding what constitutes the dimensions beyond the fifth one, as noted by Charef et al. (2018). Bertin et al. (2019) define the sixth dimension as the one covering the data related to sustainability. Other authors, like McPartland (2017), attribute this dimension to the Facility Management related information. Nical and Wodynski (2016) acknowledge both definitions are correct and overlapping since the use of BIM in facility management practices is oriented to improve the building's efficiency, influencing its lifecycle performance, therefore its sustainability. In broader terms, the sixth dimension could be defined as the one that gathers the information throughout the project lifecycle.

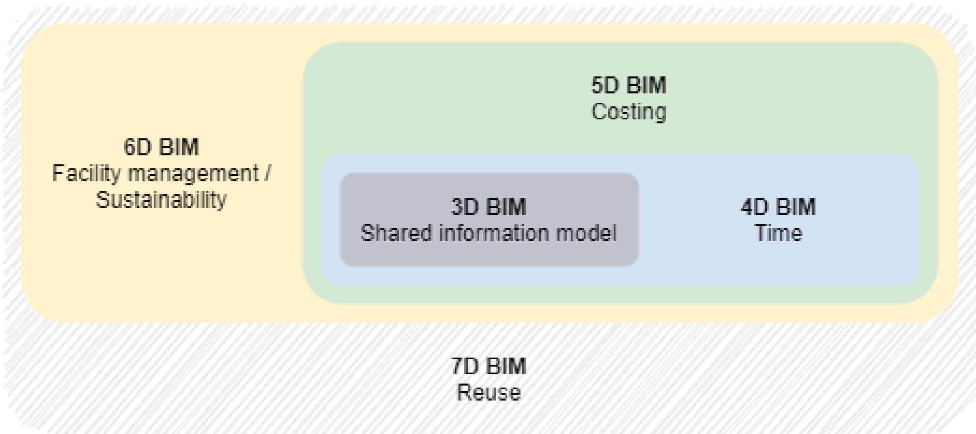

Figure 6: Theorized BIM dimensions.

Other dimensions after the 6th one have been theorized. Charef et al. (2018) proposed the definition of an End of Life (EOL) BIM dimension. This dimension would refer to an additional set of data that can be used to support decision-making for component selection during the design process, and facilitate the deconstruction process, once the asset reaches the end of its service life. Jensen et al. (2019) also define the 7th dimension as the one that allows the integration of data into the model that enables future disassembling and reuse of the building elements.

2.5.2. BIM uses

Through research and practice, the usefulness of BIM in several processes has been identified. These applications are known as BIM uses and have been defined as "*method(s) of applying BIM during a facility's lifecycle to achieve one or more specific objectives*" (Kreider and Messner, 2013). One of the popularized BIM uses frameworks, proposed by Kreider and Messner (2013), popularly known as Penn State Uses, describes a set of uses classified by their purpose during the planning, design, construction and operation stages of the building lifecycle. However, it does not consider the BIM uses during the facility's end of life.

Succar et al. (2016) described an extensive list of possible uses of BIM models, organizing them into three categories: general model uses (those "*applicable across varied knowledge domains, industries, and information systems*"); domain model uses, which collate the applications specific for AEC industry; and custom model uses, which are tailored to the particular requirements of a project, client or market. However, within this list, it is only considered the demolition planning, as the use of BIM to plan or monitor the demolition of existing structures, not specifying the deconstruction planning and material reuse planning as possible BIM uses.

2.5.3. BIM uses for Material Reuse

Several research works and publications acknowledge the pivotal role BIM methodology might play in nurturing material circularity in the AEC industry. This section summarizes some of the uses explored by different research works analyzed during the literature review stage of this research, focusing on those that study the possible applications of BIM at approaches that enable the reuse of materials reclaimed at the end of life of facilities.

Akinade et al. (2017) reviewed existing DfD practices and tools available to assist DfD and conducted focus group discussions with professionals currently using BIM in their projects. Their work concluded that most of the analyzed DfD tools are not BIM compliant and are missing essential features for deconstruction planning. One of the outcomes of their investigation is a set of functionalities from BIM that can be leveraged for DfD practices. The ways BIM could aid DfD practice include: 1) enabling improved collaboration among stakeholders, 2) allowing the visualization of deconstruction processes, 3) facilitating the quantification of recoverable materials, 4) assisting the deconstruction plan development, 5) running performance analysis and simulate the end of life alternatives 6) allowing better management of information throughout the whole lifecycle of the building.

BIM models have also been used to estimate the life cycle performance of buildings. For example, Akanbi et al. (2018) developed a mathematical model for the assessment of the whole-life performance of a building, using information retrieved from a BIM model. Nizam et al. (2018) proposed a BIM-based tool to estimate the embodied energy (EE) of a building.

Geldermans (2016) identified BIM as a potential base for developing tools to systematically control and record data on the materials and products used for the construction of buildings, including their composition, supply chain, and properties. These tools would ensure a source of high-quality data for facilitating and sustaining circular processes. Heinrich and Lang (2019) also emphasize the primordial role of BIM on the practice of reversible and circular design. Together with other methodologies and technologies, such as Geoinformation Systems (GIS), Augmented Reality (AR), Internet of Things (IoT) and Artificial Intelligence (AI), BIM plays the role of an enabler for a successful transition to a circular model.

BAMB project has also explored the alignment of the Materials Passports and BIM as part of their research work. The Materials Passport Framework considers BIM as a capable container and vehicle of information for DfD and other design approaches aligned with Circular Economy. However, the lack of standardization of the information content of BIM objects, the use of more than one model, not updating the as-designed models into as-built, and the lack of update during facility management, are identified by Mulhall et al. (2017) as setbacks to the effective integration between BIM models and Materials Passports. Kovavic et al. (2019) described a proof of concept for the compilation of Materials Passports into BIM models for LCA assessment and Urban Mining strategies.

Akanbi et al. (2019) proposed a theoretical Disassembly and Deconstruction Analytics System (D-DAS) that aims to analyse the de-constructability of a design through a plugin developed for Revit 2017 using the tool’s SDK and Visual C# programming language. The output of the plugin would be an audit report on the estimated demolition waste generated at the end of life of a modelled building. The report would serve as a decision-making support tool on the material selection process.

Throughout the literature, there is scarce evidence regarding the practical implementation of BIM uses in the execution of deconstruction processes. Van den Berg (2019) studied the applications of BIM in demolition and deconstruction projects through empirical evidence. This research concluded that BIM could support activities in deconstruction projects, specifically to provide insights on the existing building conditions to help deconstruction planning, label reusable building elements and generate deconstruction simulations. Akbarnezhad et al. (2014) proposed an algorithm to quantify and analyse the effects of various alternative deconstruction strategies might have on cost, energy use and carbon footprint, assisted by information retrieved from a BIM model into an excel spreadsheet.

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3. METHODOLOGY

3.1. Research scope and limitations

This research work focuses in exploring the ways BIM can be leveraged to assist the deconstruction processes of steel structures once they have reached the end of their service life (EOSL), and the subsequent reuse of the reclaimed steelwork in the design of new facilities. The research work is divided into four phases:

Phase 1: An extensive literature review, focusing on the state of the art of the following topics: 1) Circular Economy in construction, 2) Design for Deconstruction, 3) Steel Reuse, 4) Building Information Modelling uses, especially in the context of Circular Economy. During this stage, the need for a structured approach to managing the information required for steel reuse purposes in BIM was identified. The Materials Passports framework was selected to fill this gap. In parallel, an exploration of the chosen BIM environment and the documentation available for the tools available in this environment was performed.

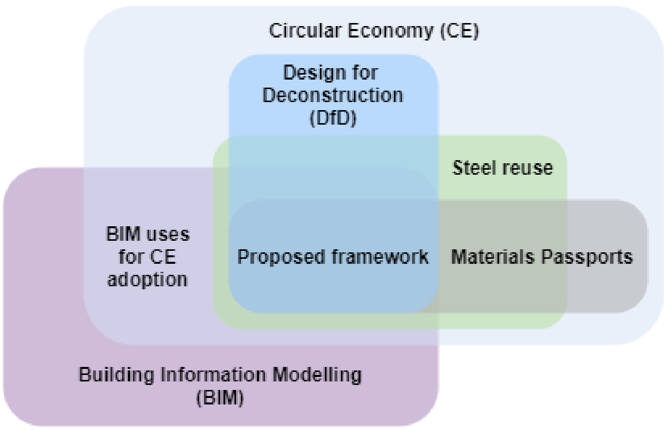


Figure 7: Venn diagram of Literature review axial topics.

- **Phase 2:** Formulation of the BIM-based framework for deconstructability assessment of steel structures, based on the findings from stage 1. This stage also included the development of an application in line with the selected BIM tool, that aims to automate part of the steps proposed for the assessment.
- **Phase 3:** the development of a case study used to validate the applicability of the proposed framework and test the application operation.
- **Phase 4:** formulation of results and conclusions derived from the research work.

A particular limitation of this research work is that it focuses solely on the structural layer of the building, specifically on the structural steel elements recovery. Other layers of the building (see section 2.2) are currently not included in the analysis. The quantification of economic and environmental benefits generated by the deconstruction of the facility subject of analysis, and from the reuse of the reclaimed material in new constructions, were also excluded from this research's scope.

3.2. Key assumptions

In contrast to previous works, such as Akinade et al. (2015) and Akanbi et al. (2019), aimed to determine the Deconstructability of a building right from the design stage, this research focuses on other stages of the lifecycle of the building. It aims to assess the Deconstructability and reuse potential of existing steel structures, including those that have been abandoned and for any reason must be decommissioned. This research assumes these facilities represent possible banks of materials for new constructions, whether these were designed under the DfD approach or not.

These research endeavours also merge the analysis of the Deconstructability and Reuse potential into a single indicator, and assume that the reusable parts are going to be used in a unique new structure. However, in practice, steelwork reclaimed from a structure might end up being used in more than one project. This research differs by considering an existing structure as a source of reclaimed material for one or more new structures. Similarly, it assumes that a single new construction project can use reclaimed steel from different deconstructed structures. Therefore, it is necessary to separate the deconstructability assessment and planning from the reuse ones. It is also assumed that the BIM model from the existing structure and the new structure can be created asynchronously and by different stakeholders.

Given the lifespan of steel structures and that BIM methodology is a relatively recent development, this research assumes the analysed structure might not count with a BIM model. Therefore, it becomes compulsory to generate a BIM model, gather and input the required data to support the deconstruction assessment and decision making.

The proposed framework excludes steel bridges as suitable sources of material for reuse. Steel reclaimed from bridges is not suitable for reuse, since it has been exposed to multiple cycles of loading and unloading and therefore, fatigue might provoke cracks that impede salvaging it for reuse as structural elements in new constructions.

This research excludes from the analysis all the steel in the form of concrete reinforcement bars. This assumption is based on the fact that reclaimed bars are in most cases unsuitable for reuse purposes, due to the damage caused on the bars during the recovery process. Also, the distribution and quantity of steel contained in reinforced concrete elements of existing structures is usually unknown, which precludes the generation of accurate models and makes it difficult to know the exact quantity of steel that can be recovered.

3.3. Framework development

From the findings of the literature review, a framework for the deconstructability assessment of steel structures was proposed. The framework leverages the BIM functionalities to support contractors and owners on the decision making and planning of deconstruction activities, integrating the Material Passports methodology for the management of data required for reuse purposes. Chapter 4 describes in detail the proposed framework, including the characterization of the as-is process of deconstruction and reclamation of steel structures, the factors that influence the selection of the EOL scenario for the steelwork and the proposed to-be process with the introduction of BIM-based assessment.

3.4. Application development

As previously stated in the research objectives, this work aims to provide tools to automatize as far as possible the process required to assess the de-constructability potential of an existing structure and the selection of parts for reuse within a BIM environment. To achieve this goal, an application was developed in Visual Studio, using the C# programming language, which is an object-oriented programming language developed by Microsoft Corporation, widely used for the development of different types of applications. Following the Tekla Developer Guidelines and the examples provided by Tekla Developer Center, the application was built taking as starting point a Windows Forms App (.NET Framework) template. To enable the application to work with Tekla Structures version 2019i, the Tekla Open API v2019.1.50434 package was installed. Other packages used for the development of the application are listed in Table 3. These are open-source packages available to download through the NuGet Package manager of Visual Studio.

Table 3: NuGet extensions used for the development of the application

Extension name and version	Authors	Function
ClosedXML 0.95.3	Botha, Francois;	Read, manipulate and write Excel files.
DocumentFormat.OpenXML	Microsoft Corporation	Open-source library for working with Open XML documents
System.IO.Packaging	Microsoft Corporation	To support the storage of multiple data objects in a single list.
Tekla Open API v2019.1.50434	Trimble Solutions Corporation	Interact with models and drawings in Tekla Structures.

3.4.1. Selected BIM tool

For this research work, Tekla Structures 2019i was the BIM tool selected to develop the case study, since it is one of the most popular BIM authoring tools used for steel structures design and detailing nowadays. The research explored the support documentation of the Tekla Structures, including manuals, guides, and tutorials regarding modelling steel structures and managing information in the BIM models developed in this authoring tool. This exploration was oriented to understand how Tekla Structures could facilitate inclusion into BIM models of data required by the Materials Passports framework for deconstruction and reuse processes, how this data could support the deconstruction assessment and planning, and how the information could be transferred for the reuse of the reclaimed steelwork. An exploration of the Tekla Open API, which allows users and developers to create apps and plugins that add new functionalities to the Tekla Structures software, extending its basic capabilities, complements the study.

3.4.2. Selection of object types

In Tekla Structures, the fundamental model entity is a part. These model objects represent actual building objects (i.e. beams, columns, slabs, footings and so on) that can be further detailed. For objects with complex geometries, Tekla Structures introduced a particular category of parts, which are denominated items. Figure 8 shows the hierarchy of model objects in Tekla Structure. For the purposes of this research, only the model objects that can be built out of steel in the real world are considered and highlighted in light blue in this same figure.

These objects can be clustered to generate assemblies. Assemblies represent more complex objects that are usually custom elements fabricated for the project. In the case of steel objects, assemblies are defined when the user creates single workshop welds or bolts to join parts together, or when applying automatic connections that create workshop welds or bolts.

3.4.3. Properties selection

Each of the model objects within the model has a defined set of basic properties. Figure 9 shows the basic properties applicable to each of the object types selected for the analysis. The correlation of each type with entity types defined by the IFC Schema is also shown in the figure. As acknowledged by the Materials Passports (Luscuere et al., 2019; Mulhall et al., 2017) the information required for reuse purposes might not always be already contained in BIM models, mostly when these models have not been updated during the operational phase of the building. Therefore, it is necessary to review the attributes already contained in the selected BIM tool(s) and develop a list of the ones required to cover. The properties from the selected parts already existent in Tekla Structures were matched with the data requirements of the Material passports framework. These properties were also compared to the ones existing in the different properties sets defined in the IFC schema (Appendix 1 shows the complete list).

Tekla allows users to assign new property fields to model objects. These are known as User Defined Attributes (UDAs). UDAs can be used for filters, reports and drawings. To allow the user to input the custom attributes to the parts needed for the analysis, a file containing the additional User-Defined Attributes was created. Appendix 2 contains the script included in this file. The inclusion of this file into the model folder creates a new tab into Tekla Structures UDAs dialogue, named “Steel Deconstruction Attributes” where the user can access the set of properties explicitly created to record the additional data required by the Materials Passports framework. The attributes are also accessible through Tekla’s inquiry command, organizer window and other native reporting tools.

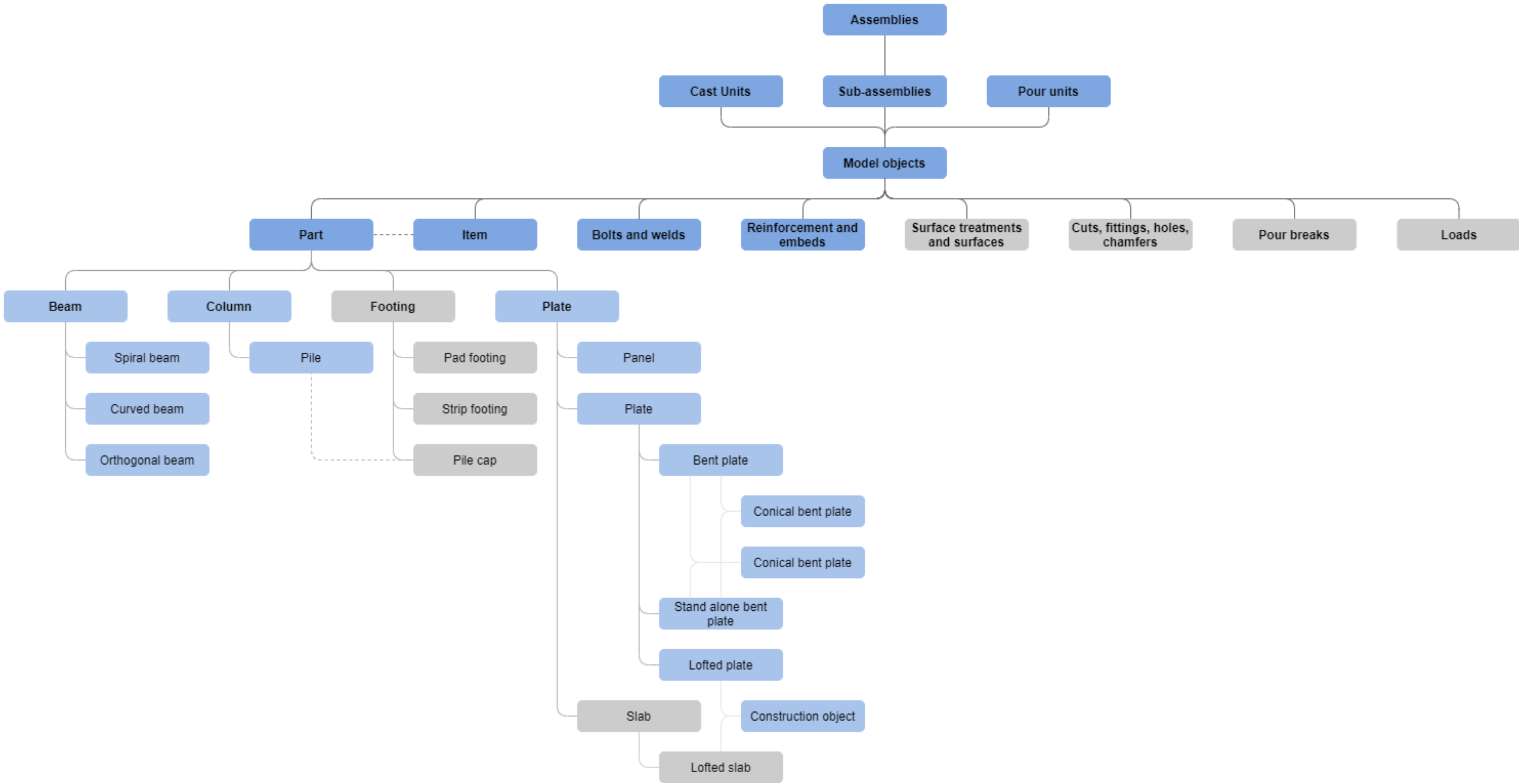


Figure 8: Tekla Structures model object classification

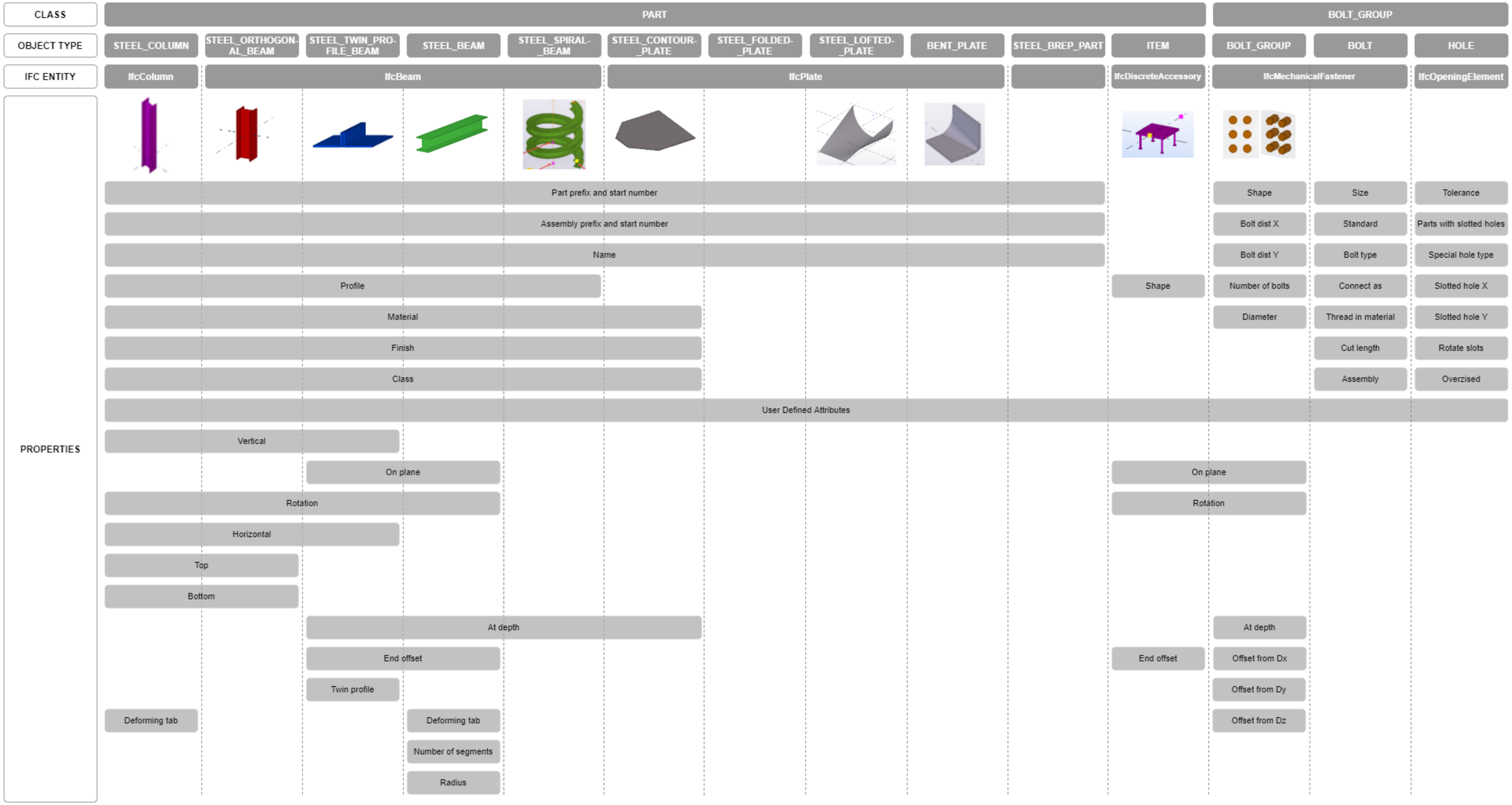


Figure 9: Object properties in Tekla Structures.

3.4.4. Application operations

The application starts by checking the connection with a model and the Tekla Structures Version. If the connection with the model is successful, the application interface window, similar to the one shown in Figure 10, appears in the screen. Otherwise, the user is alerted with an error message and the application closes. In that case, the user must check if the model file is open, and the running version of Tekla Structures is 2019i.

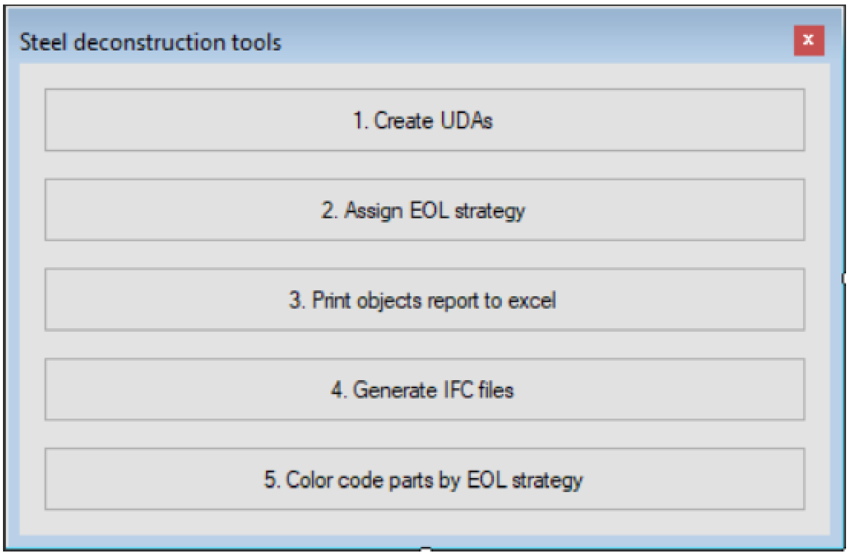


Figure 10: Application interface

Each of the buttons included in the application graphical user interface (GUI) performs a specific action. To accomplish each of the defined action, the application runs several interconnected classes, each of them performing a specific operation. In C#, each class is a data structure that collects various data members and functions to create or modify objects. Appendix 3 presents the complete script developed for each of the application classes.

The application creates five different lists of steel model objects. Each of the lists corresponds to the five model classes selected for the analysis, which contain the objects with types that can represent steel elements within the structure (see Table 4). These lists are created using the ModelObjectEnumerator class from Tekla's API, which allows iterating through object instances in the model based on the object type, through a while loop, as shown in Figure 11.

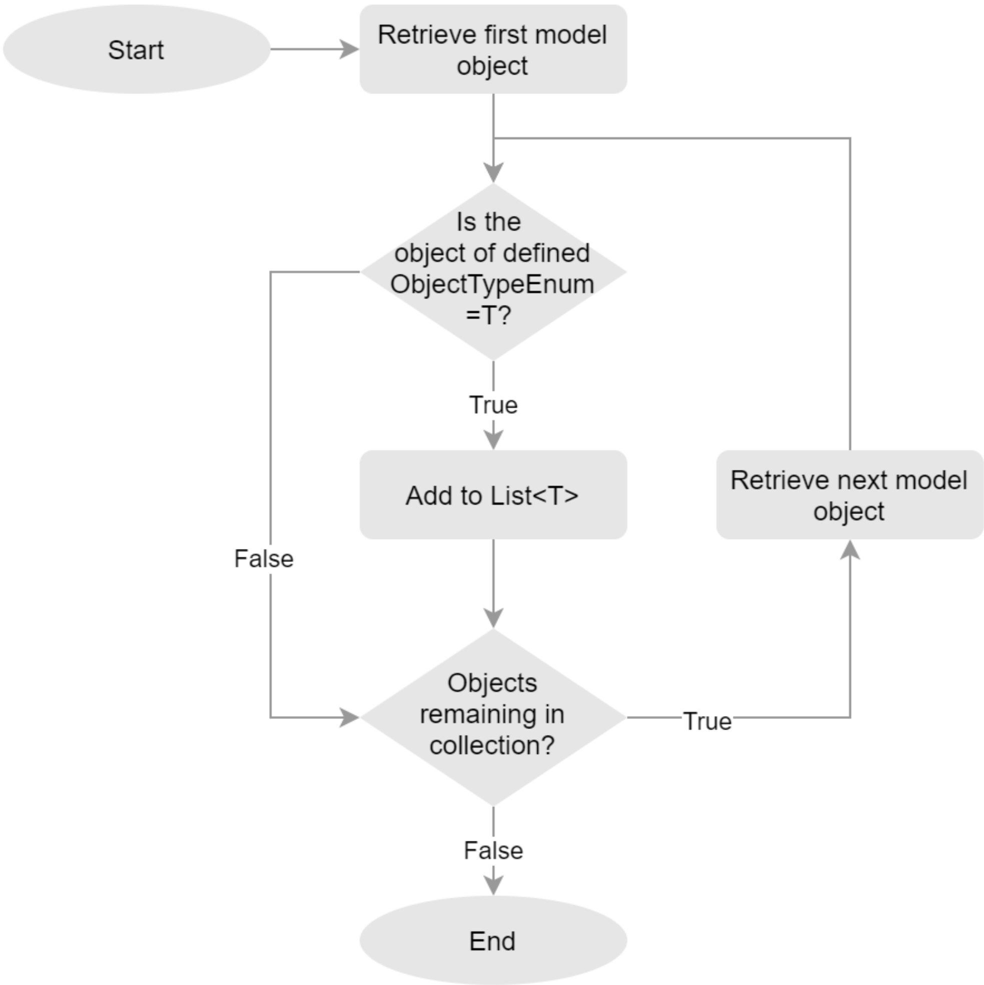


Figure 11: ListCreation extension method flowchart.

Table 4:Tekla Structures model object classes and types included in the application

Class	Model Object Type Enumerator	Enumerator Value	Description
Assembly	ASSEMBLY	9	Selects the parent assembly instances.
BoltGroup	BOLT_ARRAY	15	Selects single instances or arrays of bolts, holes or studs.
	BOLT_CIRCLE	16	Selects polar array instances of bolts, holes or studs.
	BOLT_XYLIST	17	Selects bolts, holes or studs grouped for any shape different to a rectangular array or polar array.
Connection	CONNECTION	24	Selects the connection element groups.
CustomPart	CUSTOM_PART	43	Selects the custom part objects included in the model.
Part	BEAM	1	Gets instances of type beam. This type includes beams, columns, panels and strip footings.
	BENT_PLATE	61	Selects the instances of curved plates joining 2 part faces.
	CONTOURPLATE	3	Selects plates with an outline defined by the user.
	LOFTED_PLATE	69	Selects the transitions, rolled plates, warped plates and plates with a double-curve.
	POLYBEAM	2	Selects beams with several segments, either straight or curved. Also includes columns modelled as a poly beam.
	SPIRAL_BEAM	62	Selects spiral beams.

By using a conditional statement, the application filters out the elements with a material type different to steel, based on the MATERIAL_TYPE property of each model object contained in the lists. By default, Tekla Structures provides five material types (i.e. steel, concrete, reinforcing bars, timber and miscellaneous). The MATERIAL properties from each object category were not selected as an argument to filter the elements since usually there might be more than one string, corresponding to the different grades of steel that could be present in the model subject of analysis. Hence, it is a precondition that the material type should be appropriately assigned to each object in order to be included in the automatic analysis. Also, objects with illegal materials (i.e. material grade not defined in the matdb.bin file or materials with incomplete definition) assigned will not be included in the analysis.

Once these five steel model object lists have been generated, the application sorts the objects into four lists, according to the value set for the "EOL_SCENARIO" attribute (i.e. reusable objects, recyclable objects, disposable objects, and objects without an assigned EOL Scenario). The flowchart illustrating the process to create the list of objects with "REUSABLE" value is shown in Figure 12. The same flow is followed for "RECYCLABLE", "DISPOSABLE" and "UNASSIGNED" values.

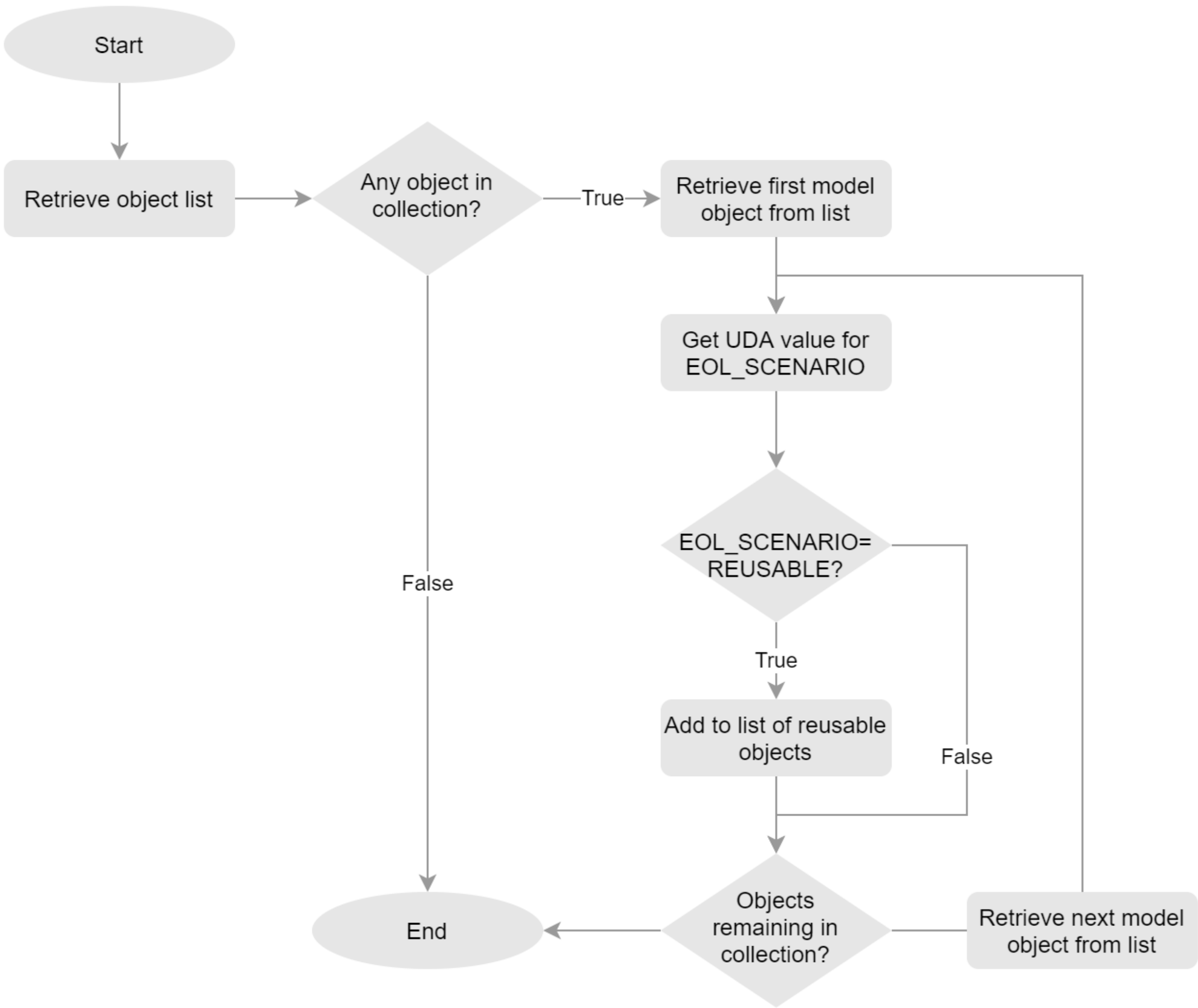


Figure 12: AllReusable class

These lists are used to perform the actions assigned to each button:

1) **Creation of User Defined Attributes (UDAs)** for the introduction of Materials Passports related properties. The application generates a set of custom properties listed in Appendix 2 for each of the model object types selected for the analysis. These properties can be included and visualized in the Organizer window of Tekla Structures and exported as part of the reports generated in Tekla or by the application. Figure 13 portrays the process performed by the class created to perform this action.

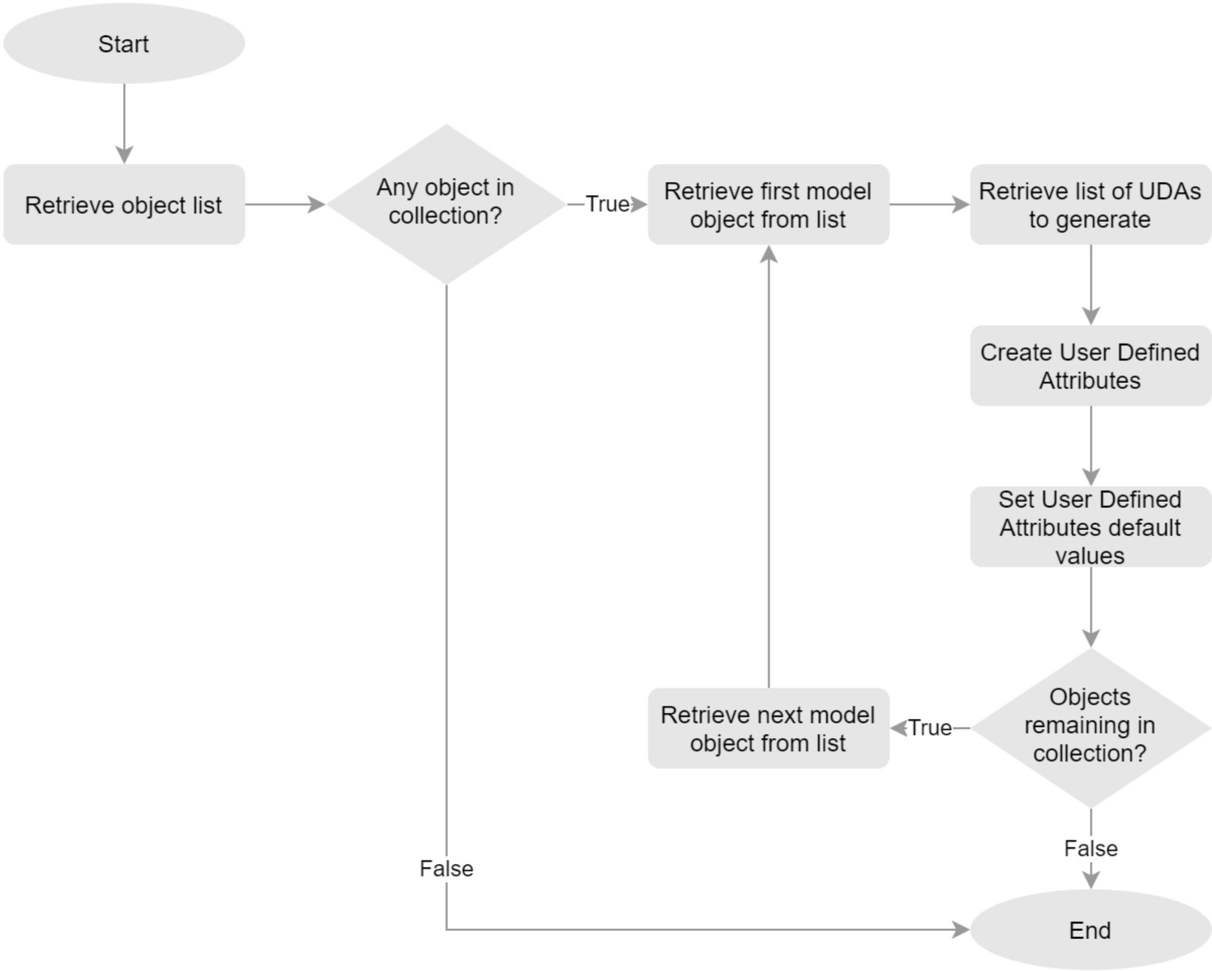


Figure 13: CreateUDAs class flowchart.

2) **Automatic assignation of End of Life (EOL) scenario for each object** included in the analysis, based on the parameters of each instance. The application assigns one of the EOL strategies (i.e. Reusable, recyclable, disposable) to each of the objects included in the steel object lists. To accomplish this operation, the application follows a set of rules created, taking into consideration the properties described in Table 5 to determine the corresponding scenario for each part. The user can manually override within Tekla Structures' UDA dialogue the values assigned by the application if desired. If the data required to sort the object is not available, or the weight of the object is zero, the application assigns the value "UNASSIGNED" to the current object. Once the application sets the values for all analyzed objects, a message box informs the user that the operation has been successful.

Table 5: Properties considered for the End of life scenario assignment

Variable/ property name	Description	Variable type	Default value	Possible values
User-Defined Attribute				
CORROSION	Indicates the assessed corrosion level of the surface of the steel part	String	string.Empty	"HIGH" "MODERATE" "LOW" "NEGLIGIBLE" string.Empty
DEFORMATION	Indicates the assessed grade of deformation on the part before the deconstruction process.	String	string.Empty	"HIGH" "MODERATE" "LOW" "NEGLIGIBLE" string.Empty
EOL_SCENARIO	States the selected end of life scenario for the part. Can be assigned either by the application or overridden by the user.	String	"UNASSIGNED"	"REUSABLE" "RECYCLABLE" "DISPOSABLE" "UNASSIGNED" string.Empty
FIRE_EXPOSURE	Records if the steel part has been exposed to fire during the constructed asset service life.	String	string.Empty	"YES" "NO" string.Empty
HAZARDOUS	Specifies if the part has been exposed to or contains traces of toxic or hazardous materials.	String	string.Empty	"YES" "NO" string.Empty
RADIOACTIVE	Indicates the exposition to radioactive materials and the possible presence of radionuclides on the steel part.	String	string.Empty	"YES" "NO" string.Empty
Tekla Structures Report Property				
WEIGHT_NET	Returns the weight of the part after holes and cuts have been subtracted from the primitive part volume.	Double	NA	>= 0

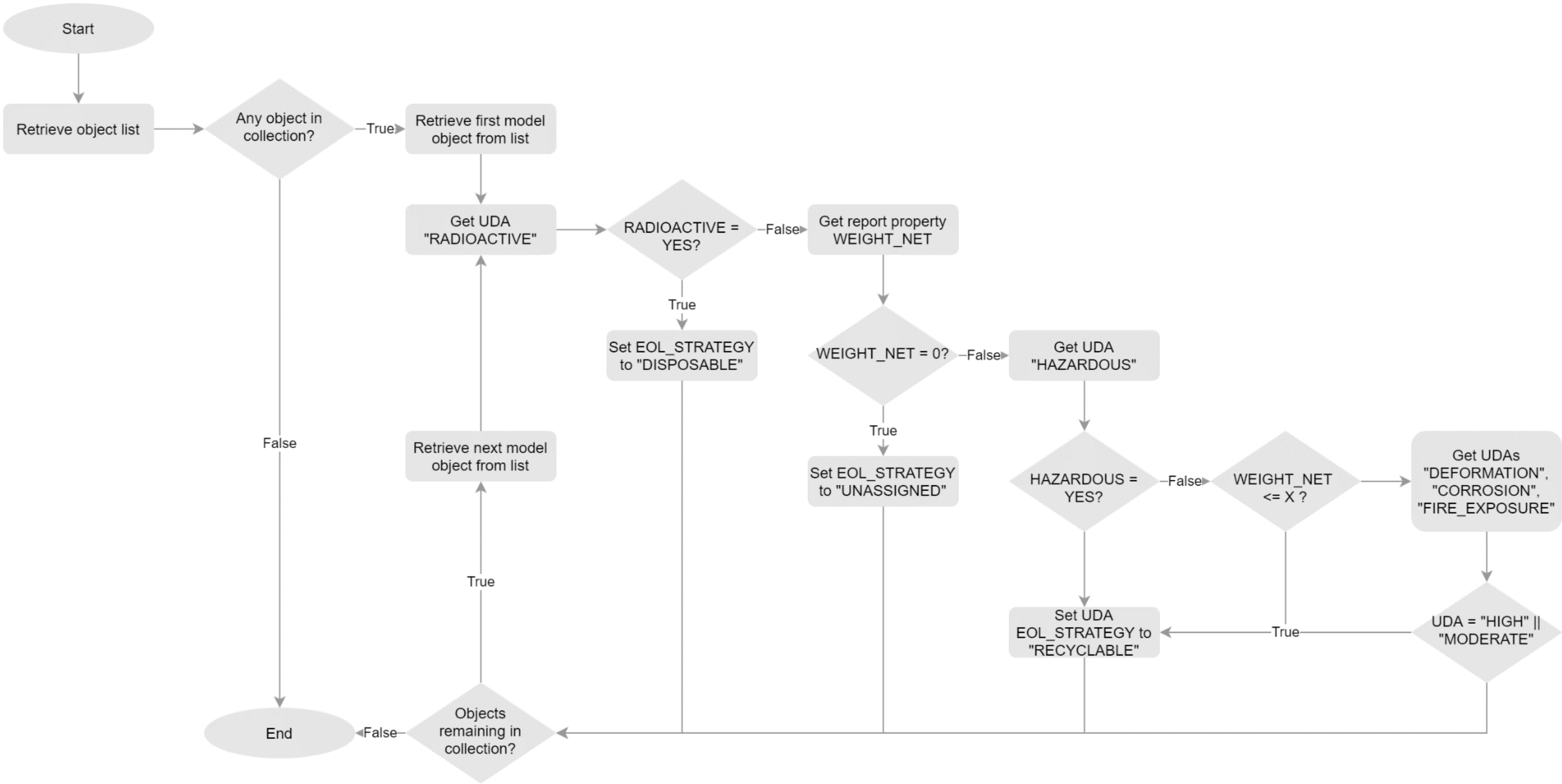


Figure 14: Assign EOL_SCENARIO class flowchart.

3) **Calculation of the Deconstructability Score and reporting** with the information retrieved from the BIM model of the existing structure, the application calculates the indicators proposed in this research (deconstructability score, reusable, recyclable and disposable steel ratios; for more detail see section 4.2.3.1). To do so, the application must fetch from the BIM model the report properties and UDAs of the steel parts subject of analysis, and calculate the total weight of objects by their end of life scenario (see Figure 15). As output, it generates a .xlsx file which contains several spreadsheets reporting a) the De-constructability Score calculated for the model, b) the proportion of reusable, recyclable and disposable steel c) a list of all the parts used for the analysis categorized by object type d) individual lists of the reusable, recyclable and disposable parts, with their corresponding properties. To account for possible errors, the application also generates within the report a spreadsheet containing 1) objects that do not have a defined end of life scenario assigned, and 2) objects with weight equal to zero. Once the application concludes the operation, it opens the resulting spreadsheet, saved in a folder created inside the model directory. A sample of the report is provided in Appendix 4.

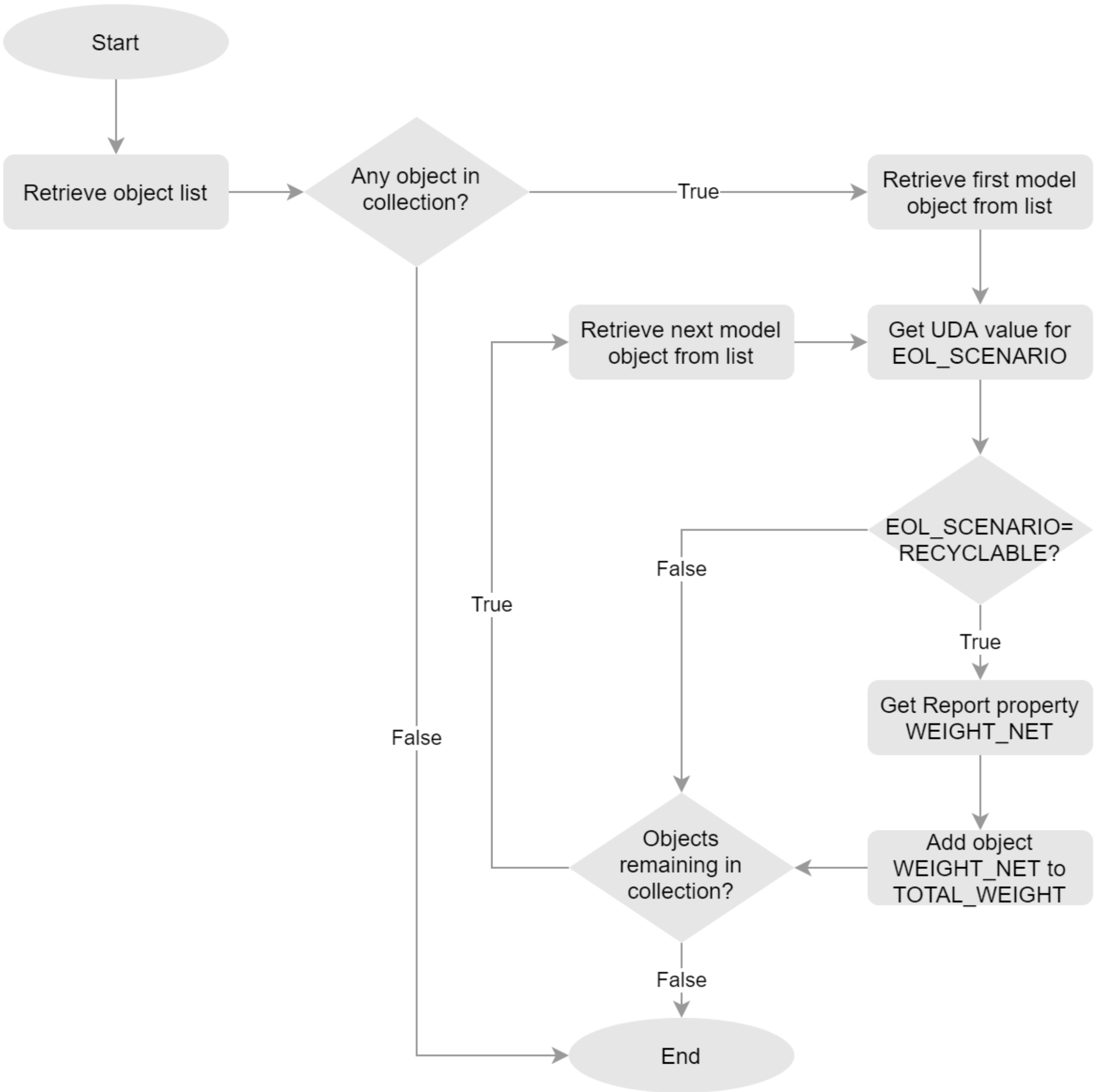


Figure 15: Calculate total weight class flowchart.

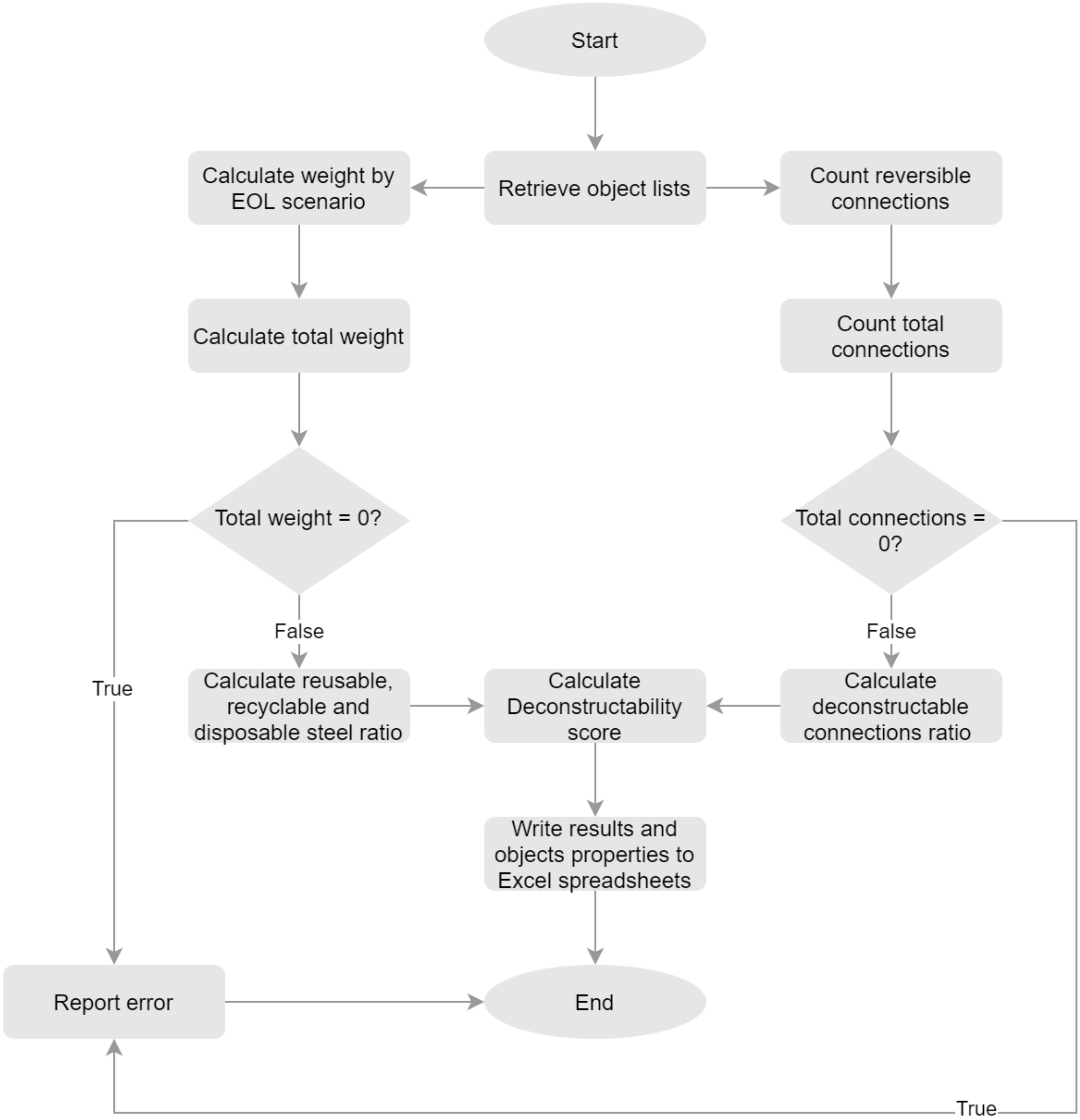


Figure 16: Deconstructability score calculation flowchart.

4) **Create a set of .ifc files from the assemblies with parts deemed as reusable**, which are saved in a folder within the model directory. The IFC export settings are managed by a specific class (shown in Figure 17). A second class is in charge of gathering the objects and exporting the .ifc files into a new folder in the model directory. These .ifc files can later be inserted as reference models to compare the geometry of the reclaimed steelwork available and the parts required for the new structure.

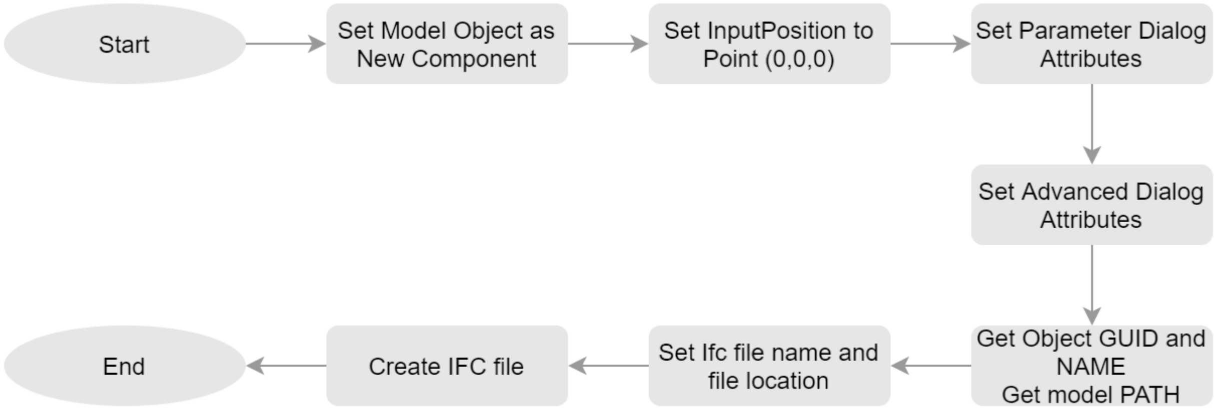


Figure 17: IfcSettings class flowchart.

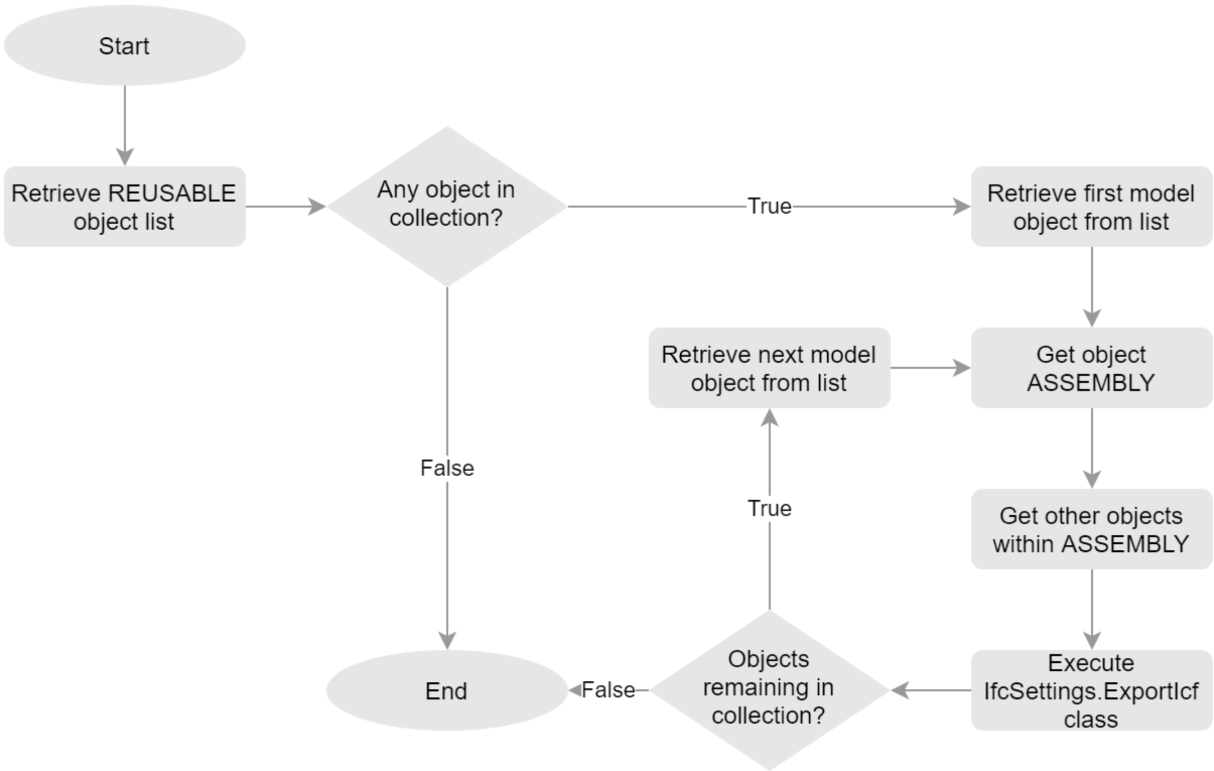


Figure 18: ExtractIfcFiles class flowchart.

5) **Assign a colour schema to the model objects according to their EOL scenario:** to help visualize in the model the objects considered as reusable, recyclable or disposable in the view of the BIM model. The application does so by modifying the object class attribute of each analysed element, according to their EOL_SCENARIO value, following the process illustrated in Figure 19. The next table enumerates the classes and corresponding colours assigned to each object.

Table 6: Object class by EOL_SCENARIO value

EOL_SCENARIO string value	Object Class string value	Colour
REUSABLE	3	Green
RECYCLABLE	6	Blue
DISPOSABLE	9	Magenta
UNASSIGNED	1	Gray

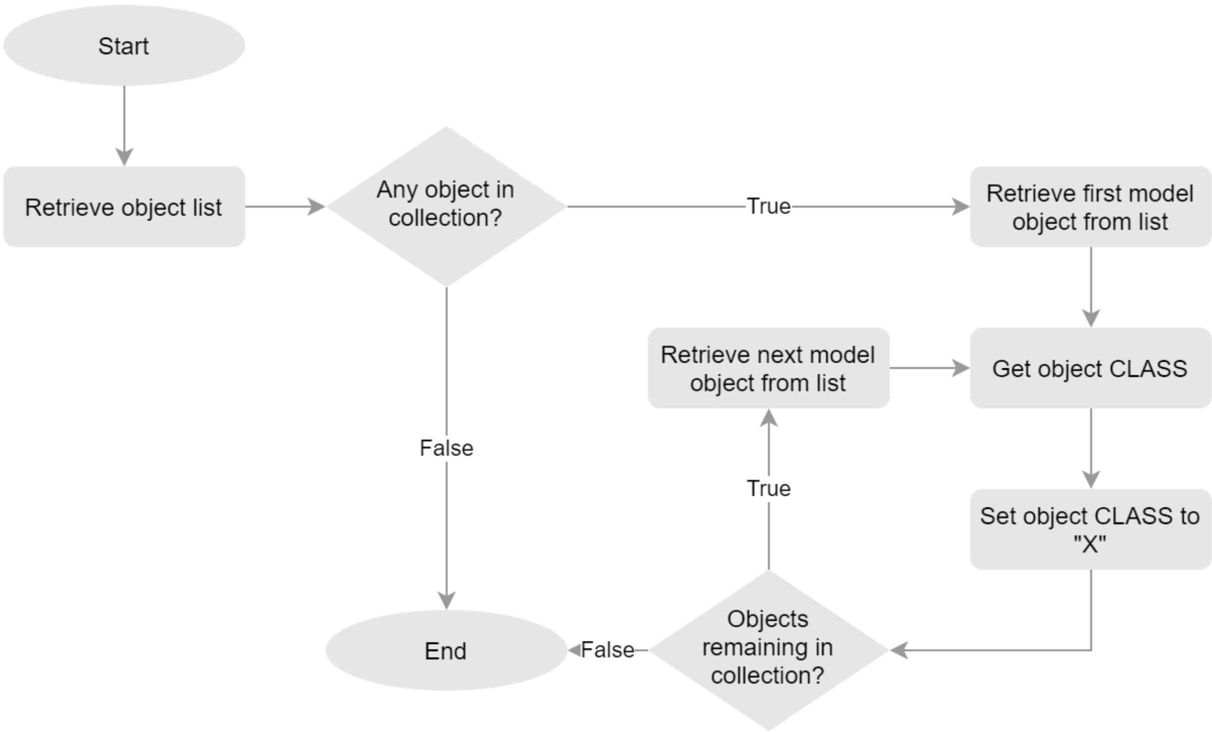


Figure 19: FilterByEol class flowchart.

3.4.5. Identified limitations

During the development and testing of the application, some limitations were identified.

- Material grades without a definition (known in Tekla Structures as Illegal material grades) are not considered within the analysis performed by the application since, by default, they are not assigned to any of the material types considered in Tekla Structures. Therefore, any error regarding material grade assignation within the model should be corrected by the user to avoid possible calculation errors. Also, any missing profile definition affects the calculation of the weight of the object. The application includes a list of objects that might generate errors, either by unassigned values or by having a weight equal to 0 (which stems from an undefined profile or undefined material grade). However, it cannot assign the correct material type or retrieve the profile definition of these objects automatically.

- The application is version specific, i.e. it works only with Tekla Structures 2019i. To enable the application to run with newer versions of Tekla Structures, the Tekla Open API package within the Visual Studio project file should be updated in Visual Studio and test the build of the application after this update. However, full compatibility might not be accomplished by differences with other versions of the Tekla Open API.
- The application cannot include in the calculation BREP objects present in the model. Therefore, all BREP objects, which could be item or extrusion type objects generated during the import of geometries from other BIM tools formats or .ifc files, must be converted into Tekla structures model objects. This step is necessary for Tekla to calculate the attributes of the object, including its weight.
- Tekla Structures objects of the spiral beam type cannot be exported as parts in .ifc format. Connections and details might also present problems with this type of objects.
- Every time the “CreateUDAs” and “AssignEol” class are executed, the script overwrites the values input by the user for the EOL_SCENARIO property. To address this issue, an additional parameter that records if the EOL_SCENARIO was automatically or manually assigned could be integrated into the code, to overlook those introduced manually by the user.
- The developed code integrates guard statements and assertions to deal with bugs and exceptions identified during the development and testing of the application. However, this does not mean all bugs have been addressed since some scenarios might not have been tested.

4. BIM-BASED DECONSTRUCTABILITY ASSESSMENT OF EXISTING STEEL STRUCTURES

4.1. Introduction

As discussed in section 2.2, the underlying principles of DfD have seldom been applied in projects until recent years, and still, there has been a low level of adoption within the current practice. This fact represents a challenge for implementing deconstruction as a strategy to decommission of existing facilities, since many of them were not designed having in mind how they were going to be managed at the end of their service life, being the usual decision to demolish them once they reach this point, opting out the deconstruction as a viable alternative. Nevertheless, this does not mean that such assets are not suitable to undergo a deconstruction process to salvage materials that can be later reincorporated to the built environment.

Vares et al. (2018) identified the need for a framework to assess potential deconstruction and reuse cases, specifically for existing industrial buildings and warehouses with steel sandwich panels and load-bearing structures with standardized dimensions, connections, joints, and steel structures as modular elements. Akanbi et al. (2019) also highlighted the need for quantitative approaches to estimate how much material could be recoverable at the end of a facility's service life. Volk (2017) identified the value of BIM models in reducing the uncertainty associated with deconstruction processes and acknowledges the use of BIM for operative deconstruction support is inexistent yet. Akinade et al. (2019) identified amongst the perceived barriers to the adoption of DfD the lack of tools for identifying and classifying salvaged materials at the end of life stage of an asset, and the lack of BIM compliant DfD tools. Volk et al. (2014) also recognize that deconstruction processes could benefit from up-to-date and accurate information contained in BIM models.

The present framework for Deconstructability Analysis of existing steel structures under BIM tries to fulfil these needs by proposing guidelines that leverage the capabilities of currently available BIM tools for assessing, planning and controlling deconstruction processes of existing steel structures once they have fallen in abandonment and disrepair. The Deconstructability potential of the structure is assessed by calculating an indicator named Deconstructability Score, that takes into consideration several factors (discussed in section 4.2.3.1) to quantify the portion of the structure potentially reusable, seizing the parametric nature of the objects from a BIM model of the facility object of study. This research goes a step further by exploring the ways the information flow could continue and support the design of new structures using the reclaimed steel, product of the deconstruction process, with the aid of BIM tools and aligned with the DfD principles. A workflow for the effective integration of BIM in the deconstruction processes has been proposed.

4.1.1. As-is steel reclamation and reuse process

Before proceeding to the description of the proposed workflow, it is necessary to characterize the as-is-process of the steel reclamation for reuse through the deconstruction of a steel structure. The first step in the typical process (shown in Figure 20), as described by Brown (2019) is a preliminary evaluation of the structure. The deconstruction contractor must assess how demountable is the structure, the state of the material, the expected cost of demolition, based mostly on previous experiences and estimations.

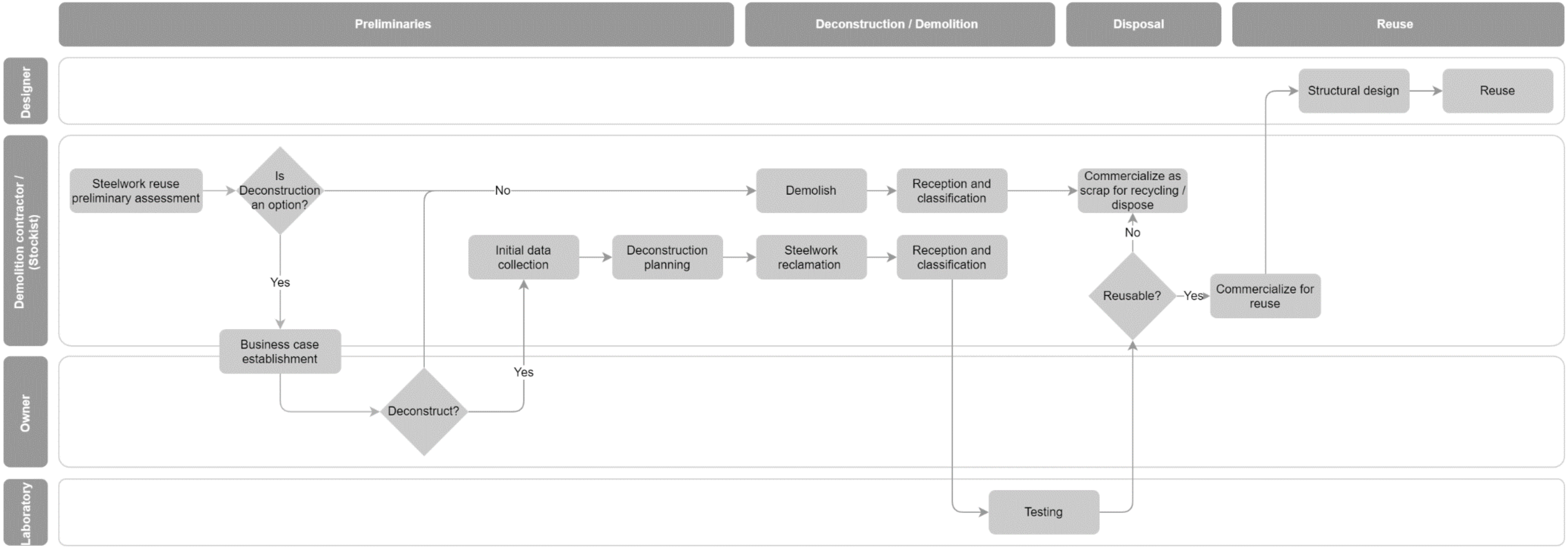


Figure 20: As-is steel structure reclamation process map

Then a business case is established between the owner and the contractor. If both agree and decide to continue with either a total or selective deconstruction of the constructed asset, the first collection of data of the possible reclaimed parts is performed, and the deconstruction is planned. Otherwise, the asset is demolished.

If the path followed is the deconstruction of the facility, once the disassembly has started, the reclaimed pieces are grouped by structural function and size, then tested to determine the mechanical properties of the steelwork and those approved can be commercialized for reuse; else, the steelwork is sold as scrap for recycling or disposed of in a landfill. The material sold for reuse should be accompanied by a declaration of the material properties issued by the stockholder (i.e. CE marking within the European Union). The subsequent design with reused assemblies is performed by designer taking into consideration the determined mechanical properties through the testing of the reclaimed steel selected, or conservative assumptions about these characteristics.

4.2. BIM uses in the context of deconstruction assessment of steel structures

BIM would allow deconstruction contractors to:

1. Obtain more accurate estimations of the quantities of material to be reclaimed from the future deconstruction of the steel structure.
2. Develop more detailed and achievable deconstruction execution plans, by enabling enhanced communication and collaborative analysis, to define the most suitable strategies to reclaim potentially reusable steelwork.
3. Enable traceability of steelwork and data transference of information required for the deconstruction and posterior reuse of steelwork.

A reengineered process of the reclamation and reuse process of existing steel structures, that integrates BIM uses, with an emphasis in the deconstructability assessment is proposed. The to-be process is synthesized in Figure 21, and Figure 22 shows the detailed process map. Each stage is described in the following sections of this chapter.

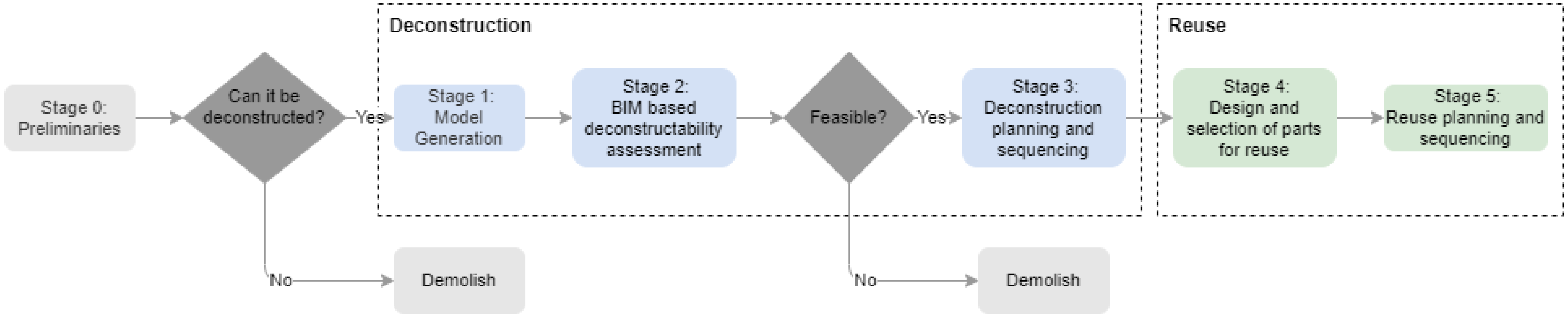


Figure 21: Deconstruction assessment and planning synthesized To-be process map

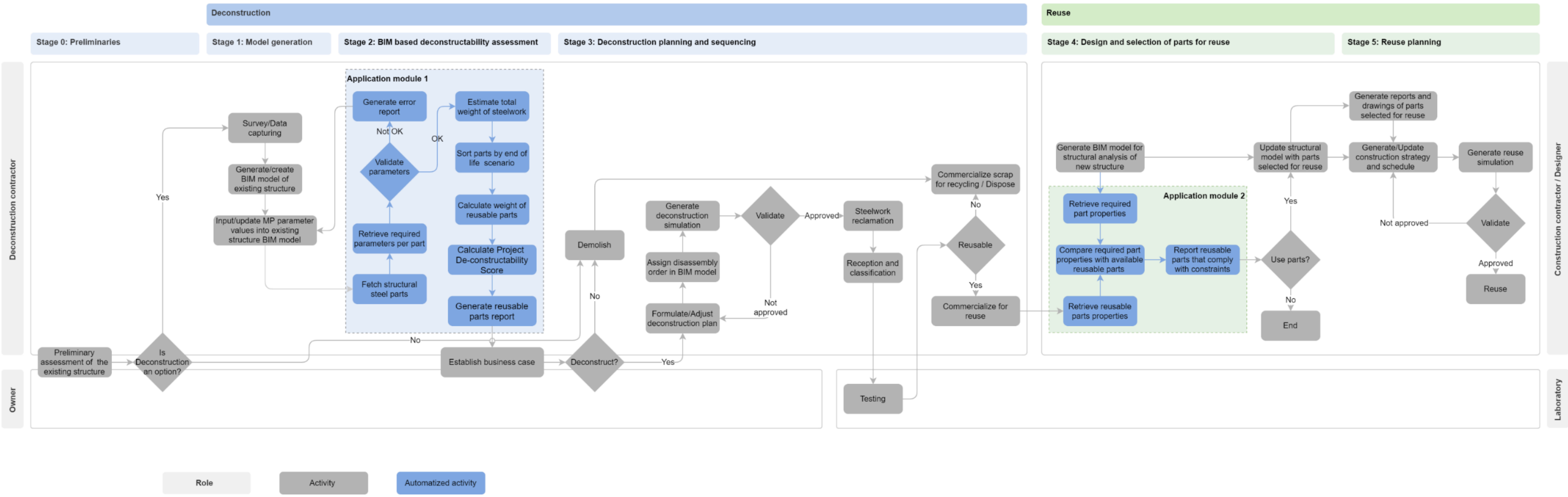


Figure 22: Proposed process map

4.2.1. Stage 0: Preliminaries

Before making any decision regarding the strategy to be implemented for the structure's end of life management strategy, it is essential to gather and analyse information to create an ample picture of the conditions of the constructed asset and the structural steel contained, intending to define whether the facility's deconstruction is a viable option. At the building level, the minimum characteristics required to perform a preliminary assessment of the viability of the deconstruction of the facility is:

1) Building dimensions.
2) Ownership.
3) Date of construction.
4) Building typology and construction technology.
5) Changes of use during its service life.
6) Estimated volumes of materials contained.
7) Availability of drawings, as-built plans, technical specifications, or any other pertinent existing documentation, including any digital model that might have been elaborated from the facility subject of analysis.
8) Records of relevant events during the facility's operation such as significant modifications, earthquakes, fires, damages due to war, floods.
9) Information regarding its physical context and possible influence on neighbour facilities.
10) Presence of hazardous or radioactive materials in the constructed asset.

It is also vital to define the value of the deconstruction process and why it is preferred over traditional demolition. By default, (as discussed in section 2.1.2) both owners and contractors do not attempt to deconstruct and recover building elements for reuse, since it is perceived as a complex and lengthy operation with a low economic return. However, economic benefits obtained from the deconstruction have been proven (ARUP, 2016; PROGRESS, 2020b, 2020a, 2020c). Under a circular economy model, the social and environmental benefits also have to be accounted for, including the generation of jobs and businesses, diversion of building waste from landfills, reductions in pollution.

4.2.2. Stage 1: BIM model generation

Once it has been decided to perform the total or selective deconstruction of the constructed asset, it is necessary to count with a comprehensive BIM model of the structure, which is the pivotal point of the proposed workflow. However, before starting with the modelling process, the way it will be carried out and managed should be clearly defined through a BIM Execution Plan (BEP). So far, guidelines available for the creation of BEPs encompass the use of BIM on the design, construction and operational phases of the building, overlooking the end of life stage. For deconstruction uses, this document should at least state:

- Project overview
- Expected BIM model uses (site planning, quantification, visualization, communication, trade coordination, 2D documentation, demolition planning, deconstruction planning).
- Involved roles and their respective responsibilities.
- Minimum Level of Detail of the model objects.

- Information requirements (concordant with Materials Passports data requirements for reuse purposes).
- BIM tools and data capturing methods to assist the process.
- Coordinate system, units and tolerances to be adopted.
- Expected deliverables and milestones.

4.2.2.1. Initial survey/data capturing and creation of the BIM model of the existing structure

As acknowledged by Volk et al. (2014), BIM is still seldom used for facility management, and most of the existing constructed assets have not been documented into BIM models. They also point out there are scarce cases where BIM models have been developed for specific uses during the asset lifecycle. There are currently several techniques that enable surveying and capturing data from existing buildings, and the subsequent generation of BIM models. Some of these techniques are:

1) **Modelling based on as-built plans:** the most common practice usually involves using as-built drawings to model the existing structure. As-built plans might not exist or might not represent the actual construction since changes during the lifespan of the facilities are seldom documented. Therefore, it becomes necessary to verify the actual conditions on-site and do not rely solely on the available plans.
2) **Modelling based on site measurements:** whenever the original drawings are not available, the dimensions of the elements have to be collected on-site. This option is a time-consuming and error-prone process.
3) **3D point cloud-assisted modelling (scan-to-BIM):** This approach results more valuable when there is no updated documentation available and consists of generating a model of the asset based on laser scans performed in various locations of the facility. However, these scans only represent surfaces and have to be converted into as-is BIM models through the manual input of model objects.
4) **Automatic model generation:** more recent research has explored the possibility of automatizing the creation of BIM models taking as departure point 2D CAD plans and elevations, such as the one proposed by Bortoluzzi et al. (2019) or laser scans and imagery like the one presented by Xiong et al. (2013). Nevertheless, these are usually still experimental approaches, and the quality of the output still has to be verified by the modeller.

The means used to generate the model may vary, and more than one technique could be selected to perform the survey of the constructed asset to be studied, to try to overcome the drawbacks of each technique. The selection of the approach is influenced by the availability of tools, time and cost. Whichever is the path taken to generate the model, the result must represent the geometry and size of the elements and connections that make up the structure subject of analysis, according to the requirements stated in the BEP. The objects modelled should count with enough level of detail, in order to enable the proper calculation of material volumes and provide data for the decision on the end of life scenario. Based on the BIMForum LOD interpretation of AIA schema, modelled objects should count with at least a LOD 350, which means that they should be *"graphically represented as specific systems, objects, or assemblies from which quantity, shape, size, location, and orientation can be measured directly"*.

As acknowledge by Morganti et al. (2019), many existing structures might contain components and profiles that are not commercialized nowadays or contain bespoke elements. Therefore, it also becomes necessary to develop a comprehensive library of BIM objects that represent these components. Another consideration to be taken during the BIM model creation is that all objects modelled must be created under their respective categories or types. Failing to do so, leads to inaccuracies in calculations, especially when using automatic analysis tools for LCA, or other purposes, including the proposed Deconstructability assessment.

4.2.2.2. Collection of relevant information into the BIM model of the existing structure

During the model generation process, the information required for deconstruction and reuse purposes should be gathered and input into the model. Alternatively, if an asset model exists and has been maintained during the constructed asset's lifecycle, this model could be the starting point for the Deconstructability assessment. This model should be checked to verify if the model objects count with enough level of detail, if all the structural elements have been included and modelled under their specific object type, and materials have been appropriately assigned to each of them. Then, it should be enriched and updated with the data required for the identified uses, including the data requirements from Materials Passports.

It is also essential to provide a consistent numbering and identification system for deconstruction, transport, stocking and reuse of the reclaimed steelwork, as it is for fabrication, shipping and erection of steel structures. Thus, it is necessary to provide each of the instances subject of analysis in the BIM model a unique code of identification. The importance of this unique ID relies on enabling the traceability of the steel parts for deconstruction and reuse purposes through the different BIM models that could be developed through the building lifecycle (i.e. existing structure model, new structure model, as-built model). Most BIM tools already set a global unique identification code to each of the instances that make up the BIM model, based on the IFC GUID. Whether this identification code or another one is going to be adopted, should be stated in the BEP and followed during the creation of drawings and reports to ensure the model object traceability.

In the field, it is required to provide standard and permanent identification of all the parts from the analysed structure, concordant with the coding adopted in the BIM model. Crowther (2005) suggests the use of non-removable and non-contaminating identification marks on the parts to allow for future sorting. As discussed in section 2.5.3, other means like RFID and NFC tags could be utilized for identification of parts. However, these tags could be accidentally damaged or removed and might represent a higher cost, if the means required to support this identification system are not available. Another limitation of these means is their expected lifetime. For example, current RFID tags have an expected lifetime of up to 7 years, just a fraction of the usual building service life of 50 years (Jensen et al., 2019).

4.2.3. Stage 2: Deconstructability Assessment

Ideally, during the deconstruction of a steel structure, every part could be recovered and posteriorly reused. However, in practice, not all the steelwork can be destined for reuse and subsequently reincorporated into the built environment (Wang et al., 2018). Several factors determine whether steelwork can be reused as-is, with minor rework or remediation, sent to recycling as scrap or disposed of in a landfill. The latter being the less desirable scenario following the Circular Economy thinking. Three possible end of life scenarios (i.e. reuse, recycle, dispose of, as depicted in Figure 5) have to be considered and, based on the available information, one of them must be defined for each structural member of the analysed constructed asset's steel structure, taking into consideration these factors.

The factors identified throughout the literature as relevant to define the End of Life scenario and how they affect the deconstructability and reusability potential of the steelwork are described below, following the Materials Passports schema:

Building level

1) **Building morphology:** The morphology of the facility affects the Deconstructability of its steel structure. The more complex the geometry of the structure is, the more complex the deconstruction process becomes. Simple shapes, such as industrial warehouses made with portal frames, have a higher reuse potential because elements forming the frame are fewer, with a lower number of connections, reducing the chance of damage during the deconstruction process (Vares et al., 2018) than more complex structures. Hradil et al. (2019) analysed three different frames typically found in industrial buildings (welded-tapered, hot-rolled and truss girders), discovering differences in the reuse potential by individual parts, but none when reusing complete frames.
2) **Building age:** Structures built before 1970 are considered as not suitable for reclamation of steel for reuse purposes. This limit, as explained by Brown et al. (2019), relates to the material properties assumed by modern design standards. From 1970, steel was considered as part of the Eurocode programme and the development of product and design standards. Therefore, it is compulsory to know at least the date of construction of the building, if the fabrication date of the individual steel parts is undeterminable.
3) **Fire exposure:** Steel's mechanical properties might be significantly altered by the exposition to fire. Therefore, it is crucial to determine if any fire occurred during the service life of the facility. If this happened, determine if the whole facility or just sections of it have been affected and if individual members have resulted with damages or bending. Visual inspection and measurements of the members affected by the fire can provide information on the effects on the steel physical properties. For the evaluation of the damages on steel members and the stability and safety of the whole structure, Tide (1998) proposed categorizing these elements based on the member's geometry changes:

   Category 1: includes "*straight members*", or members with negligible deformations, which were not subjected to elevated temperatures and maintained most of their physical properties.

   Category 2: members noticeably deformed, that could still be repaired for reuse, if economically feasible.

   Category 3: members with severe deformations and effects on their physical properties.

   For elements classified into category 2, further study of the mechanical properties is suggested through testing, to quantify the changes in the steel's physical properties and to determine if the steelwork is still suitable for reuse or if it should be destined for recycling.

Component level

Physical properties:

Dimensions

a) Weight: equipment to be used in the deconstruction process sets a limit on the weight of the steel parts than can be recovered as a whole. On the opposite end of the spectrum, the smaller and lighter pieces could be considered by the deconstruction contractor as scrap and better suited for recycling than reusing.

b) Measurements: Similarly, the size of elements to be recovered for reuse is limited by the capacity of the equipment that will assist the deconstruction and transportation of reclaimed steel (if the pieces are to be relocated). Therefore, a maximum length and width of recoverable elements and measures to deal with elements that might surpass these limits should be defined.

Structural data

c) Load bearing: the function of the steel element and whether it was a load-bearing member should be stated, to preliminarily determine if it is suitable for reuse or not and whether additional testing is required to decide its end of life scenario. Structural steel elements reclaimed from bridges have been subject to repeated loading and might present fatigue cracking, which makes them unsuitable for structural reuse.

d) **Yield and Ultimate strength:** of the reclaimed steelwork also determine its reusability potential and its possible future uses. To determine the yield and ultimate strengths of steelwork, and demonstrate the adequacy to be incorporated as structural steel members, destructive tests should be executed on samples of the recovered parts, following the methods provided by EN 1090-2. Once these properties have been determined, the elements should be sorted according to the results obtained into reusable and recyclable elements.

Other factors:

a) **Type of existing connections:** for deconstruction and reuse purposes, reversible connections are preferred since these connections allow to be assembled and disassembled multiple times with a minor risk of damaging the material or the connector itself (Jensen et al., 2019). In the specific case of steel, for DfD, the use of bolted connections and other mechanical connectors (such as post-tensioned moment connectors and clamped friction connectors) is encouraged. Bolts and other fasteners themselves can be deemed as non-reusable since it is hard to identify if these elements have exceeded its yield point. However, when compared to the total weight of the structure, the total weight of these elements is insignificant. Other of the disadvantages of bolted connections is that patching the holes might be required for reuse.

On the contrary, chemical connections, such as welded connections, have adverse effects on the material surrounding the connection area. Basta et al. (2020) mention heat affected zones, cracks formation, welded parts distortion after welding, and poor welding, as issues that affect the reusability of steelwork with welded connections. The occurrence of any of these issues should be identified and reported. Another disadvantage of welded connections when compared against bolted connections, as reported by Silverstein (2009), is the occurrence of brittle failures, which means welds can break without warning during the deconstruction execution, making compulsory the constant support of lifting equipment to ease the load on the connections during the whole process, increasing the deconstruction cost of structures with welded connections.

b) **Deformations:** before and after the deconstruction has been executed, the deformations and distortions present in the steelwork must be measured and recorded. These deformations could be the result of fire exposure, impacts prior to or during the deconstruction process, plastic failure or damages produced during the deconstruction process.

Chemical properties:

Chemical composition:

1) **Steel chemical composition:** since it affects the weldability of the steelwork, should also be known for reuse purposes, in case the new connections require welding. Therefore, the Carbon Equivalent Value (CEV), if known, should be declared as part of the information for reusable assemblies, as reference for welding procedures planning.
2) **Surface coatings and treatments:** The importance of identifying and recording the type of surface treatment applied to the steelwork lies in the effect that these previous treatments might have on the choice of future treatments and coatings if the steelwork is going to be reused and the remediation measures that might have to be performed before its reuse or recycling. Coatings that can be easily removed or separated from the surface of the steelwork favour its circularity. However, for reuse purposes, ISO 20887:2020 suggests the use of the material with its "*natural state*" finish and only using coatings for corrosion protection and fireproofing purposes.

Health and safety:

3) **Toxicity:** If steelwork has been exposed to toxic or hazardous materials (such as lead-based paintings, lead-tin alloys and mercury) its reuse is not advised, and additional considerations and measurements should be taken before proceeding for recycling, since traces of the materials could be transferred to the recycled steel. DfD encourages to avoid the use of toxic and hazardous materials in the finishes applied to steelwork since this will reduce the potential for contaminating the material destined for recycling, and will reduce the potential for health risks that might otherwise discourage disassembly (Crowther, 2005).
4) **Radioactivity:** if steelwork has been exposed to radioactive substances, as is the case of steel reclaimed from nuclear power plants, industrial research irradiator activities, teletherapy, industrial radiography, medical equipment, gauges, logging, or other sources (Foulke, 2008), it might pose adverse health effects on workers and future occupants of the constructed asset where the steelwork is reused since it can carry radionuclides. Especial measures should be taken to handle and dispose of these steel elements, but in general, its reuse or recycling is not advised, unless it is recycled and reused within the nuclear sector (Hrncir et al., 2013).
5) **Corrosion:** Steelwork with significant loss of section due to corrosion is deemed as unsuitable for reuse and should, therefore, be destined for recycling or disposal. The presence of corroded areas of the steel part should be assessed and recorded. Parts with negligible or low corrosion levels can be reused since the reduction of the thickness of the steel is minimal, and the geometry and mechanical properties of the part have not been significantly affected.

4.2.3.1. Deconstructability Score

As a means to measure the deconstructability of the analysed structure for reuse, a set of indicators is proposed. These indicators would serve as a support for the deconstruction contractor and the owner when deciding on whether to deconstruct the asset, by indicating the portions of the structure weight that are potentially reusable, recyclable or disposable, based on the parameters of each modelled object. For each object that represents a steel element, a set of properties has been defined within the BIM model. The ones of interest for the calculation of the Deconstructability Score are weight, connection type and end of life scenario assigned to the object (which derives from the assessment performed by the contractor or the automatic tool proposed). To quantify the extent to which the structure subject of analysis can be recovered for reuse, the following variables and equations are defined (equation 4.1):

$$W = w_1 + w_2 + w_3 \tag{4.1}$$

where

w_1: $total\ weight\ of\ reusable\ elements$;

w_2: $total\ weight\ of\ recyclable\ elements$;

w_3: $total\ weight\ of\ discarded\ elements$;

W: $total\ weight\ of\ steel\ elements$;

R_1: $Reusable\ steel\ ratio$ (equation 4.2);

$$R_1 = \frac{w_1}{W} \tag{4.2}$$

R_2: $Recyclable\ steel\ ratio$ (equation 4.3);

$$R_2 = \frac{w_2}{W} \tag{4.3}$$

R_3: $Disposable\ steel\ ratio$ (equation 4.4);

$$R_3 = \frac{w_3}{W} \tag{4.4}$$

Connections between elements are also to be accounted for as a factor to measure the Deconstructability of the pieces selected as reusable.

c_1: $reversible\ connections\ (bolts, fasteners, other\ special\ connections)$;

c_2: $non\ reversible\ connections\ (welded\ connections)$

C: $total\ number\ of\ connections$ (equation 4.5);

$$C = c_1 + c_2 \tag{4.5}$$

$D_C: Deconstructable\ connections\ ratio$ (equation 4.6).

$$D_C = \frac{c_1}{C} \tag{4.6}$$

Being the maximum value 1, when all the connections considered in the analysis are reversible, so all their connections can be easily disassembled. Then, the Deconstructability Score would be defined, according to equation 4.7:

$$D_S = R_1 * D_C \tag{4.7}$$

This indicator supports the decision-making process by giving a notion of how “deconstructable” the analyzed structure is. The higher the score calculated, the higher the deconstructability potential of the steel structure and the higher the amount of steel that can be recovered for potential reuse. However, this score, by no means, is intended to be the sole factor to take into consideration when deciding on whether to deconstruct or not. As previously stated in section 3.2, site-specific factors such as storage area availability, manoeuvring area, are not considered into the calculation of the proposed Deconstructability Score. However, these, together with economic and technical factors, cannot be neglected and should be regarded as constraints for the decision making and posterior planning. Ultimately, the decision will rely on the experience and interests of the stakeholders.

4.2.3.2. Reporting

Once the steelwork has been classified according to their EOL scenario in the BIM model and the decision to deconstruct the structure has been taken, it is necessary to report on the properties of the reusable parts and assemblies. These reports should present the available information required for reuse purposes of the steelwork deemed as reusable.

When more than one deconstruction project is executed, or in the case the quantity of steelwork is significant, a report might become unsuitable for the task, and a data management system might be required. The complexity of the system to control the inventory of parts available for reuse will vary depending on the number of stakeholders involved in the reclamation/reuse processes, the volume of steel and the technologies selected to support the process. Ideally, to manage the information generated, the resulting reports should be input into a shared database. Managing the data of one or more deconstructed structures in a shared database could enable the implementation of innovative business models that foster the reuse of materials and components, such as the ones proposed by Cai and Waldmann (2019), through better articulation between the supply chain stakeholders.

4.2.4. Stage 3: Deconstruction planning and sequencing

Volk (2017) asseverates deviations in time and cost in deconstruction projects can be explained by the uncertainty generated by mass deviations and insufficient building documentation. A reduced uncertainty would allow creating plans and baseline schedules with higher chances of successful execution. The implementation of BIM on deconstruction projects can help manage the uncertainty associated to these endeavours, through more accurate estimations of volumes of materials resulting of the deconstruction processes, improved planning of resources and site utilization, and enhanced communication among stakeholders.

BIM supports the site layout planning, selection of the equipment and strategies to be implemented, foreseeing possible dangers and planning safety measures. For deconstruction processes that have to be performed in spatially limited sites, the execution of a detailed plan becomes essential for the success of the project. It is significant to consider space availability (or limitations) for the execution of works and storage of material and debris. Usually, structural elements should be dropped to the ground and transported to a storage place (Pongiglione and Calderini, 2014) within a site. These areas should be shown within the site layout created in the BIM model. When the site does not provide enough space to stockpile debris and reclaimed material, an additional area destined for these purposes should be guaranteed. The expected cost of transportation, rental and other expenses derived from securing these additional areas should be accounted into the cost estimate of the deconstruction project.

Risk zones related to equipment required for the deconstruction process (such as cranes) can also be delimited in the BIM model through the use of volumes that represent the reach or manoeuvring area required by this equipment. Other risk factors to be taken into account for the site planning, including existing electricity transmission cables and equipment, pipelines, neighbouring structures and zones with hazardous materials, must be demarcated in the model.

4.2.4.1. 4D deconstruction simulation

Deconstruction is usually performed in several stages, following the logic planned by the layer theory (see section 2.2). Deconstruction routines depend on the type, accessibility and number of connections a building object has with other objects (van den Berg, 2019) and its focus mainly on efficiently recovering the elements that have value for reuse. Depending on the selected BIM tools, it is possible to produce detailed simulations of the deconstruction processes. However, as explained by van den Berg (2019) the resulting simulations should be considered as a communication aid on the planning of deconstruction sequence and to identify possible conflicts, and by no means as a strict portrayal of the deconstruction process.

Within most BIM tools, it is also possible to implement filters and visualize the parts according to their end of life scenario attribute, either isolating them or visualizing them in different colours. These functionalities can be leveraged to better visualize and identify the reusable elements within the facility, allowing improved analysis of the strategies to be implemented. Location-based planning can also be implemented within BIM models. By taking advantage of these filtering, phasing and visualization tools, the deconstruction contractor can plan the execution of the deconstruction works and decide on the most suitable strategies for removal of the steelwork, since clusters of reusable elements might be more attractive to deconstruct than objects that are isolated when performing selective deconstruction.

4.2.5. Stages 4 and 5: Reuse

In the same way that BIM can be seized for the deconstruction of existing structures, so it can be done during the design and preconstruction stage of projects where steel is going to be reused. Several BIM uses can be applied during the reuse stage, including the structural design, 2D drafting of connections and modifications to the reusable parts, the transference of information for the future, generation of simulations and support the coordination of strategies for construction.

A significant part of the future deconstructability potential of any structure depends on the decisions taken during the design stage. To ensure that the new structure designed with steel sourced from the deconstruction of other structures can also be deconstructed, the structural designer has to take into consideration the principles proposed by DfD during the design and detailing of the structure. As mentioned before, in section 2.2, DfD suggests preferring the use of mechanical connections over chemical ones (Crowther, 2005) to ease the separation of elements and reduce the damage that could be generated during the posterior deconstruction process. Then, the welded connections of otherwise demountable parts are not advised since they limit the practicability of future deconstruction. Bolted connections or other mechanical connectors that allow the disassembly of the pieces with a minor loss of material and deformations during the deconstruction process should be preferred. ISO 20887:2020 also suggests the consolidation of connector types and sizes to reduce the need for multiple tools during the deconstruction process.

The structural design process assumes typically that the elements will be fabricated as required (Dunant et al., 2017). However, when designing with reused elements, an exact match of the geometrical and mechanical properties between the needed part and the parts available might not always be possible. Therefore, the designer should choose parts that satisfy the structural requirements and can be easily adapted to fit the desired dimensions. From the list of reusable elements available, the ones that comply with the criteria determined by the designer can be compared to the required piece to select the best fit. Leveraging the capabilities of most BIM tools, a visual comparison of the geometry of the proposed part against the required one can be performed, which could simplify the process of part selection. A straightforward way of achieving this is by inserting the reusable part geometry through the use of a .ifc file as a reference into the BIM model generated for the structural design and 2D drafting of the new structure, in the same position of the part subject of analysis. Suppose the designer decides to incorporate reclaimed steelwork into the design of the new structure, shop drawings detailing the modifications required for its reuse must be produced.

If the existing connection parts are to be used, these should be inspected and tested before its incorporation in the design. Additionally, the connections between structural members should be exposed wherever possible and have enough space to perform future deconstruction. In most BIM tools, oriented to structural design, connections can be designed and detailed, including the required buffer or clearance zones for deconstruction. A soft clash check can be performed to verify that enough space is left to allow the future disassembly of the connections and its parts. As requested by the MP, the instructions for the assembly and future disassembly of the connections also should be included or linked to the object, especially for non-standard connections.

The set of parts available for reuse should be updated continuously, incorporating the steelwork reclaimed from every deconstruction or demolition performed and available for the reuse into the selected data management schema. Similarly, the steelwork elements already selected for reuse or sold should be removed from the list of parts available, to avoid that any of them is selected more than one time for one or different projects.

Materials Passports also requires as part of the information for reusable components, the development of plans and instructions for their reuse. These documents should be developed and included as part of the documentation linked to the BIM object that represents the actual reclaimed steelwork. BIM can also be seized to develop 4D models for the planning of the construction and deconstruction of the new structure.

5. CASE STUDY

5.1. Overview

The proposed framework applicability was tested on a remodelling project executed in France between 2015 and 2019. This project included the construction of several steel structures that would modify the aspect of two existing buildings, built during 1983. One of such structures is a tower located between the two buildings that would extend the usable area and communicate both towers on different levels. For this case study, only the steel objects that make up the tower were taken into consideration for the analysis of the deconstructability and reuse potential. The choice of bolted connections for the construction of the tower structure favours its Deconstructability once it reaches the end of its service life.

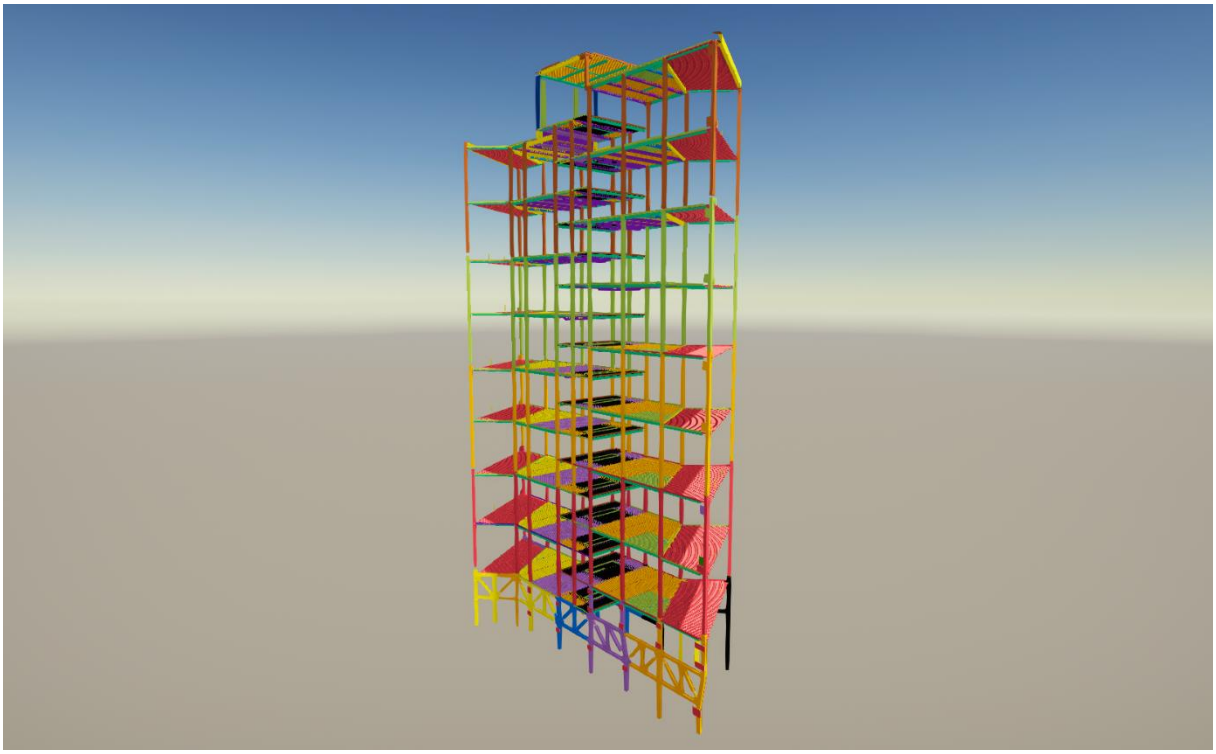


Figure 23: 3D view of the tower BIM model

5.1.1. BIM model assessment

As input for the assessment, a Portuguese company provided a BIM model developed for structural design use. The structure of the tower, together with other steel elements corresponding to modifications made on the façade and rooftops of the existing buildings were modelled in Tekla Structures. The model objects of the tower were separated from the other structures. A total of 16,322 model objects were analysed, including columns, beams, plates, bolts and studs. No custom parts were included in the model.

During the revision of the model, it was found that many model objects were not adequately modelled (missing material assignation, illegal profiles, incorrect model object type), so it was crucial to amend them to give no chance to mistakes in the subsequent analysis. Therefore, the following amendments on the provided model were done to ensure integrity in the data input for the deconstructability assessment and avoid possible errors on the output:

1. **Completing the definition of material grade or assigning the correct material type to model objects:** since the inclusion of objects into the analysis made by the application is defined by the material type assigned to each object. A first iteration of the analysis left 9,518 of the 16,322 steel model objects out of the scope of the calculations performed because the material was erroneously applied or the material grade definition was not complete.
2. **Substituting objects erroneously modelled:** since the classification and assignment of the EOL_SCENARIO values also depends on the type of the BIM object. Then, the objects identified as being modelled in the incorrect type category had to be substituted. The use of objects of type column to represent shear studs and bolts, instead of objects of type bolt, exemplifies this situation. This error caused the rules defined in the application for the objects within the class BOLT_GROUP were not applied to these objects. Instead, the rules defined for the class PART were applied, and the application set the EOL_SCENARIO for the elements as REUSABLE, instead of RECYCLABLE.
3. **Retrieving missing profile definitions:** to ensure the weight of all the modelled objects is calculated and taken into account while computing the indicators described in section 4.2.3. In the initial analysis of the model, only 6,804 out of the 16,322 steel model objects had a net weight equal to 0.

5.2. Material Passports data gathering

Given the model was used for structural analysis, coordination during design and 2D drawing generation, the model did not count with information beyond the required for these uses. Once most of the inconsistencies on the material assignation found in the model were solved, the User Defined Attributes needed to input the MP data not included in Tekla’s default were created with the aid of the application developed. The data required for the MP was obtained from different sources, including handling guides, environmental product declarations, and other publicly available documents regarding structural steel. For the model used for the case study, the data had to be retrieved, and then input by the user into the UDAs generated for the objects by the application, resulting in a cumbersome, error-prone and lengthy process. As explained in section 3.4 of this document, the importance of the data contained in these parameters considered by the MP, relies on enabling the transference of data for the reuse stage, if the deconstruction of the structure is deemed as feasible. This data will also serve as the base for the deconstructability analysis performed by the application.

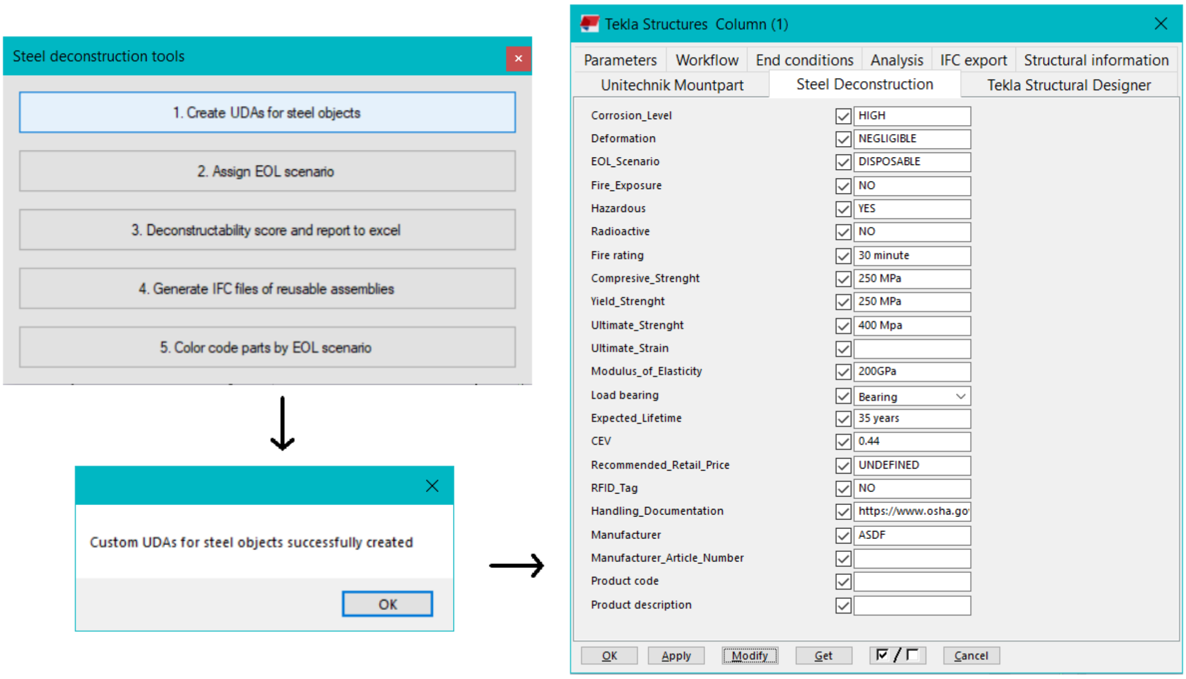


Figure 24: Steel deconstruction and reuse attributes in Tekla's UDA dialogue

5.1. End of life scenario assignation

The possible end of life scenario for all the steel pieces was automatically assigned using the function within the application, following the conditions defined in section 3.4.4. In this case, given the absence of toxic materials in the finishes of the steel parts and exposure to radioactive materials, none of the elements was discarded by the application for these reasons. However, to exemplify and test the function of the rules contained in the script, the parameters of 4 parts were changed, so the EOL_SCENARIO was set to DISPOSABLE for these elements (Figure 25).

The user can override the EOL scenario suggested by the application manually. To demonstrate this and take into consideration the geometric complexity of the column and beam assemblies in the first level of the structure, the EOL_SCENARIO values for these objects were modified from "REUSABLE" (when automatically assigned by the application) to "RECYCLABLE", since non-standard and complex shapes reuse is more complicated and infrequent than standard sizes and shapes, being the usual decision of the deconstruction contractor/stockist to sell these as scrap for recycling (see Figure 27). The following table, extracted from the report generated by the application, shows the number of model objects included in the analysis and classified according to their EOL_SCENARIO value.

Table 7: Total of objects per EOL scenario

	Total	Reusable	Recyclable	Disposable	Unassigned
Bolt groups	2,089	NA	-	-	2,089
Custom parts	-	-	-	-	-
Parts	14,233	2,762	11,451	4	16
Total	**16,322**	**2,762**	**11,451**	**4**	**2,105**

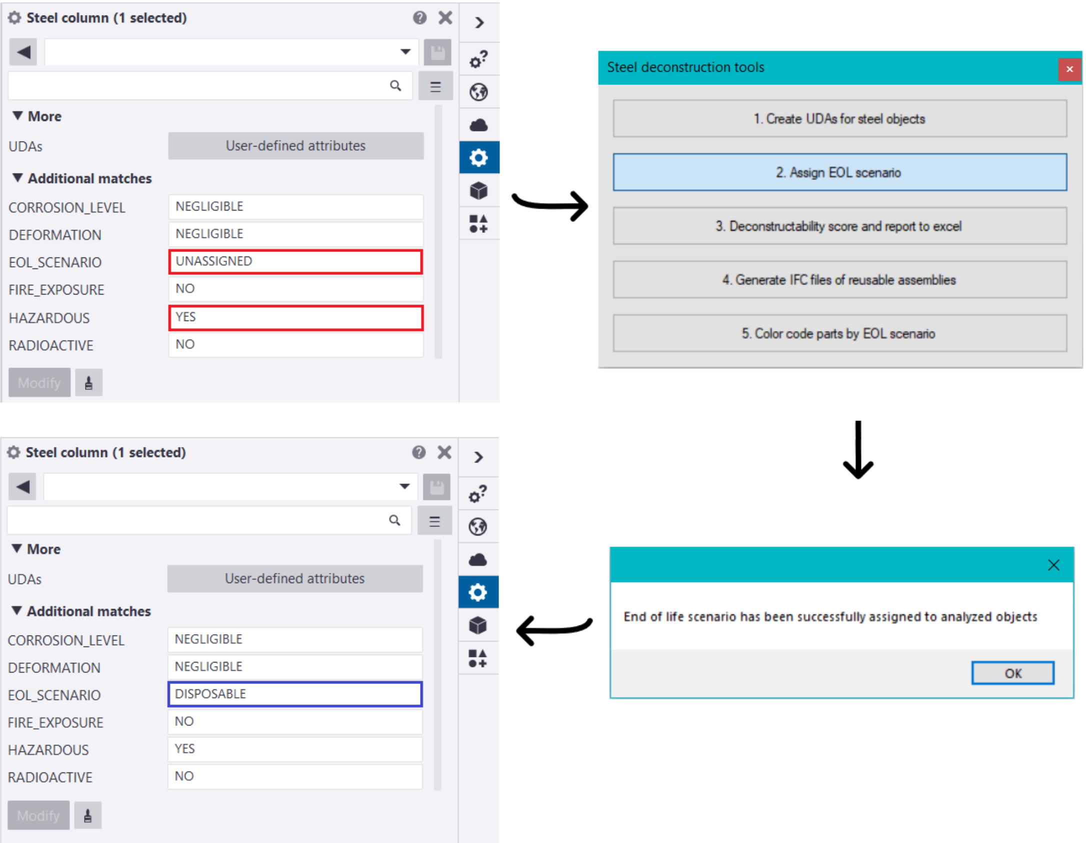


Figure 25: EOL Scenario assignation

5.2. Deconstructability assessment

With the EOL_SCENARIO values assigned to all the steel model objects, the Deconstructability Score calculation and report generation class of the application was executed. All the connections in the structure are bolted; then, the deconstructable connections ratio is 1. The results obtained are shown in the following tables, and an extract of the report is included in Appendix 4.

Table 8: Steel weight by end of life scenario

Concept	Calculated value	Unit
Reusable weight:	191,193.79	kg
Recyclable weight:	59,033.71	kg
Disposable weight:	308.51	kg
Unassigned weight	-	kg
Total weight of analysed objects:	250,536.02	kg

Table 9: Deconstructability indicators calculated for the structure

	Calculated value
Reusable steel ratio	0.76
Recyclable steel ratio	0.24

Disposable steel ratio	0.00
Deconstructable connections ratio	1.00
Deconstructability score:	0.76

The reusable elements consist of columns and beams, including their connection plates, which can be posteriorly removed or modified according to the future design. In the case of the recyclable portion of the structure, it is mostly the material contained in a steel-concrete composite slab, in the form of shear studs and steel decking.

5.3. Visualization of objects according to their EOL Scenario

The application modified the visual representation of the objects included in the analysis. Reusable objects are shown in green, recyclable in yellow, disposable in magenta, and unassigned in grey. Figure 26 shows the complete model after the application function has been executed, and the view has been updated. For the sake of clarity, Figure 27 shows a close-up of some of the objects in the lower level of the structure, where the values of EOL_SCENARIO of some objects were modified to show the representation of disposable elements.

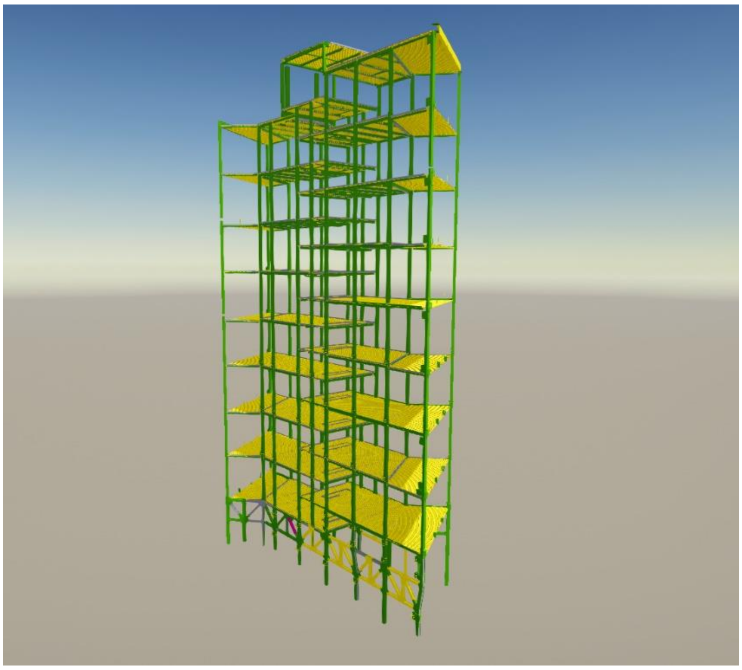


Figure 26: Modified 3D view of the BIM model.

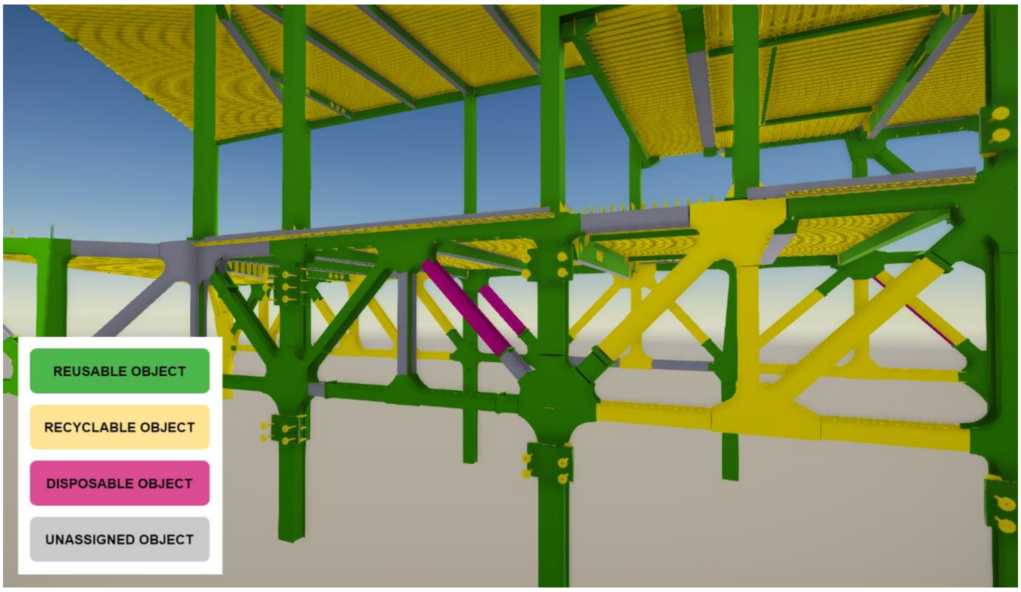
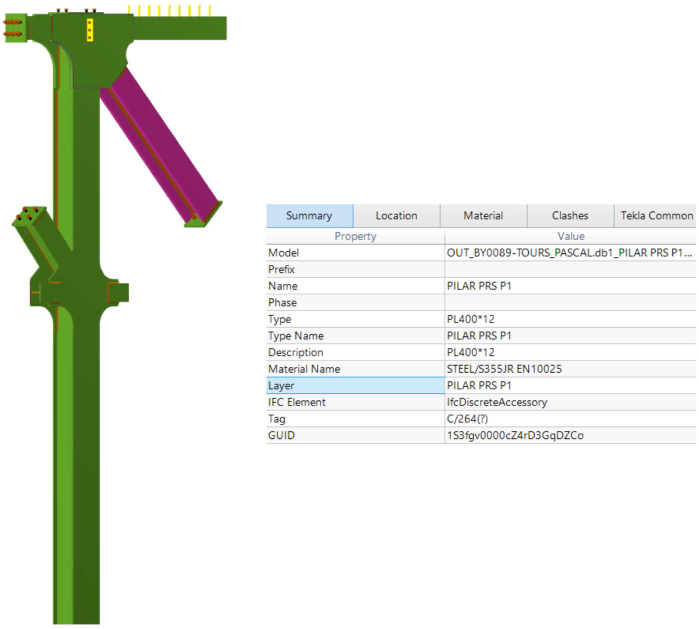


Figure 27: Close-up of the modified 3D view.

5.4. Output for reuse phase

From the model, a set of .ifc files were generated; each one represents an assembly that contains parts recoverable for reuse. It also includes the rest of parts that conform the assemble, with the same colour coding implemented to distinguish the recyclable, disposable and unassigned parts from the reusable ones.



Property	Value
Model	OUT_BY0089-TOURS_PASCAL.db1_PILAR PRS P1...
Prefix	
Name	PILAR PRS P1
Phase	
Type	PL400*12
Type Name	PILAR PRS P1
Description	PL400*12
Material Name	STEEL/S355JR EN10025
Layer	PILAR PRS P1
IFC Element	IfcDiscreteAccessory
Tag	C/264(?)
GUID	1S3fgv0000cZ4rD3GqDZCo

Figure 28: Generated .ifc files sample

The .ifc files generated were located automatically by the application in a folder within the model directory. These files, together with the spreadsheet containing the list of reusable objects, could be later used by the designer as a source of information for the design during the reuse stage. The .ifc format was chosen since Tekla, and other BIM tools allow the insertion of these files into other BIM models generated in Tekla, to serve as reference and source of information for design, coordination and other uses. Using .ifc files of the reusable parts instead of a native format from Tekla (or another authoring tool) also ensures interoperability between different BIM authoring tools. In the specific case of Tekla, these files can also be converted into model objects, retaining the properties from the original object. However, the user must take care of defining the correct object conversion settings for the IFC conversion process (i.e. defining the correct IFC entity type and target native part type, map the IFC properties to the correct Tekla property or User Defined Attribute), mainly when the .ifc file used as a reference has been generated by a different BIM authoring tool, to ensure that all the information is transferred from the source to the target object.

6. CONCLUSIONS AND FUTURE DEVELOPMENTS

Deconstruction of steel structures and the posterior reuse of the reclaimed steelwork can be a way to reduce the environmental impact of the construction industry and take advantage of materials already contained in the built environment. Although in current practice the reuse of steel elements is still scarce, the deconstruction and reuse of steel structures might increase as Design for Deconstruction (DfD), and other circular economy approaches gain terrain in the AEC sector. It became evident throughout the literature review a scarcity of studies oriented towards identifying ways BIM can support deconstruction and other strategies to decommission buildings at their end of service life, and more importantly, research on practical approaches and tools to assist this process. Most of the research has focused on the use of BIM in the initial stages of the building lifecycle and more recently in the facility management applications, but overlooked the asset demolition or deconstruction once they reach the end of life stage.

The developed research proposes a structured BIM-based approach to support the assessment, planning and execution of deconstruction of existing steel structures, based on a workflow and an application that take advantage of the Tekla Structures capabilities to be incorporated into the deconstruction assessment of steel structures. Both would help practitioners achieve more accurate estimates of material to reclaim, make informed decisions on the strategy implemented to decommission the structure, provide better visualization and traceability of the reusable elements within the constructed asset, and enable the management of information required for the deconstruction and posterior reuse of reclaimed steelwork. A set of indicators were proposed as an aid for decision making, by providing an "at a glance" measure of the portion of steel that could be recovered through the reusable steel ratio and recyclable steel ratios, and the ease of deconstruction through the deconstructable connections ratio and the deconstructability score.

The developed application is a useful and straightforward tool to help practitioners on the assessment of the deconstructability of a steel structure under the BIM environment. It helps the user to define custom attributes that will contain information pertinent for deconstruction and reuse purposes. Based on the parameters of the BIM model objects, it suggests an End of Life (EOL) scenario for each of the steel parts that make up the structure. It also calculates the proposed indicators and generates lists of parts classified according to the assigned EOL scenario. As a way to transfer information for the reuse phase, the application can generate a set of .ifc files containing the information of the assemblies and parts deemed as reusable. Finally, it can also modify the visual representation of parts according to their EOL scenario in the 3D view of the model.

A major constraint in the development of this research was the possibility to find a real-life case of a deconstruction project to test and validate the whole workflow in real time. Deconstruction projects are quite scarce, and during the current context induced by the COVID-19 pandemic, even more challenging to access. Therefore, it was not possible to find a case study where the deconstruction assessment and reuse workflow could be implemented in real time. The structure chosen for the case study, though, proves the usefulness of the framework and the developed tool on the assessment of the future deconstructability of existing structures. It also provided insight on the importance of consistency on the modelling procedures and categorization of objects, to fully grasp the capabilities of the BIM tools and applications developed to perform automatic analysis under BIM environments.

Another problem encountered during the conducted research was the lack of consistency and adherence to standards on the BIM modelling practice. On the model used to test the application, many of the objects were not modelled under their right category or with the inappropriate assignation of material properties. Incipient standardization regarding the management of information and requirements for deconstruction and reuse purposes was another limitation faced during the development of the research. By the time this research was performed, ISO 20887 had just been released. Many of the instruments proposed for DfD and other Circular approaches, including Materials Passports, are still in development or in the prototype phase. EN 1090 standard series do not count, at the moment, with clear definitions concerning the incorporation of reclaimed steelwork into new constructions.

This research focused merely on the constructed asset's structural layer. However, it can be modified and scalable to other layers of the building. The focus of the selected BIM tool drove this decision since Tekla Structures is aimed at the development of structural models, and does not provide tools to model the architectural and MEP components of the building. Further development of the proposed framework could be done on the incorporation of the excluded layers of the building into the analysis, as well as structural elements built with other materials, for a more comprehensive analysis of the Deconstructability and reuse potential of the constructed asset components. The extraction of data from BIM models created on environments with more wide-ranging modelling tools, or from .ifc files to perform the deconstructability analysis can be explored.

Given the allowed time to develop the research and the limitations on the programming skills and experience of the researcher, it was not possible to develop the automatized part selection module of the proposed application. This second module of the application would assist the process of reuse planning. It would have to be able to read the report generated by the first application or the selected database solution chosen to manage the data of the reclaimed steelwork, and create a list of reusable parts that comply with a set of parameters so that the user can select the best fit for the part subject of analysis. It would also allow the user to insert the IFC files of the shortlisted pieces as a reference object in the model of the new structure. In that way, the user would be able to compare the geometry of the required part with the ones listed as suitable and select.

Further work could also focus on formulating more efficient ways to manage the information required by Materials Passports and other instruments oriented to Circular approaches, within BIM models associated with other tools. The amount of data required by the Materials Passports framework is significant, and inserting all the information into all the modelled objects in a BIM model might become a cumbersome and error-prone activity. To add to the issue, the introduction of all the data into a BIM model increments the size of the model file considerably, making it more challenging to open and manage. Based on these shortcomings, it is advised to manage the additional information in external databases and link the information with the use of the selected part unique identifier.

The influence of the geometry of an assembly as a determining factor on the decision to reuse or recycle is still not included in the script developed for the application. How to take into consideration the geometrical complexity of the part into the analysis could improve the proposed assessment tool. The application of geometrical optimization methods for the design of new structures in a BIM environment can be another research direction to explore. This integration could be achieved through the development of a tool that applies the best fit for a determined steel part in a BIM model given a list of reusable steel elements, through an iterative process that selects the part with higher geometrical resemblance from the range. Also, the incorporation of AI into the BIM-based design workflow of new buildings using reusable steelwork could be studied. AI has the potential to serve as a means to automatize the selection of reusable parts from a catalogue and the generation of shop drawings containing modification required to reincorporate steelwork into new structures.

This research represents a small, yet certain step in the direction of fully seizing BIM capabilities for deconstruction assessment, planning and execution. There is a vast potential for research and development on the uses of BIM as a means to support deconstruction, reuse of materials and other circular economy oriented actions that will help AEC sector get closer to become a sustainable industry.

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LIST OF ACRONYMS AND ABBREVIATIONS

3D	3rd dimension of BIM.
4D	4th dimension of BIM.
5D	5th dimension of BIM.
6D	6th dimension of BIM.
7D	7th dimension of BIM.
AEC	Architecture, Engineering and Construction
AI	Artificial Intelligence
AIA	American Institute of Architects
API	Application Programming Interface
BAMB	Buildings as Material Banks
BEP	BIM Execution Plan
BIM	Building Information Modelling
BREEAM	Building Research Establishment Environmental Assessment Methodology
BREP	Boundary REPresentation
C#	C-Sharp programming language
CAD	Computer Aided Design
CDE	Common Data Environment
CDW	Construction and Demolition Waste
CE	Circular Economy
CE marking	Certification mark that indicates conformity with relevant EU legislation applicable to a product.
CEV	Carbon Equivalent Value
DfA	Design for Adaptability
DfD	Design for Deconstruction (or Disassembly)
EE	Embodied Energy
EOL	End of Life
EOSL	End of Service Life
EU	European Union
FM	Facility Management
GIS	Geoinformation Systems

GUI	Graphical User Interface
GUID	Global Unique Identifier
IFC	Industry Foundation Classes
IoT	Internet of Things
ISO	International Organization for Standardization
LCA	Life Cycle Analysis
LCC	Life Cycle Costing
LOD	Level of Detail
MP	Materials Passports
NFC	Near Field Communication
PROGRESS	PROvisions for a Greater REuse of Steel Structures, EU funded research project
RAF	Royal Air Force
REBUILD	REgenerative BUILDings and products for a circular economy
REDUCE	REuse and Demountability Using steel structures and the Circular Economy, EU funded research project
RFID	Radio Frequency Identification
SDK	Software Development Kit
UDAs	Tekla Structures' User-Defined Attributes
UK	United Kingdom

APPENDIXES

APPENDIX 1: MATERIALS PASSPORTS, TEKLA STRUCTURES AND IFC PROPERTIES FOR REUSE

	Materials Passports property	Tekla Structures Default Property Name	IFC Property Name	IFC Property Type	C# variable type
1	Physical				
1.1	Dimensions				
	Measurements	Various, depending on the object type			
	Weight	WEIGHT_NET		IfcMassMeasure	Double
	Area	AREA_NET		IfcAreaMeasure	Double
	Volume	VOLUME_NET	VolumeValue	IfcVolumeMeasure	Double
	Density	MATERIAL.PROFILE_DENSITY MATERIAL.PLATE_DENSITY	MassDensity	IfcMassDensityMeasure	Double
1.2	Structural data				
	Compressive strength				
	Load bearing	LOAD_BEARING	LoadBearing	IfcBoolean	Normalized string
	Stability	ND	ND		
	Resistance	ND	ND		
	Others				
	Yield strenght	ND	YieldStress	IfcPressureMeasure	Double
	Ultimate strenght	ND	UltimateStress	IfcPressureMeasure	Double
	Ultimate strain	MATERIAL.POISSONS_RATIO	UltimateStrain	IfcPositiveRatioMeasure	Double
	Modulus of elasticity	MATERIAL.MODULUS_OF_ELASTICITY	HardeningModule	IfcModulusOfElasticityMeasure	Double
1.3	Building physics				
	Energy and thermal performance	NA	NA		
	Transparency	NA	NA		

Materials Passports property	Tekla Structures Default Property Name	IFC Property Name	IFC Property Type	C# variable type
Hygroscopicity	NA	NA		
Sun insulation and transfer	NA	NA		
Fire protection				
Fire rating	FIRE_RATING	FireRating	IfcLabel	String
Ventilation and airtightness	NA	NA		
Daylighting and illumination properties	NA	NA		
Others	ND	ND		
1.4 Resistance and rigidity				
Expected lifetime	ND	ExpectedServiceLife	IfcTimeDuration	Double
Tensile strength	ND	TensileStrength	IfcPressureMeasure	Double
Testing	ND	ND		
1.5 Optical				
Colour			IfcPresentationItem	
Structure	NA			
Surface				
Transmission	NA	NA		
Transparency	NA	NA		
Reflectivity	NA	NA		
Others	ND	ND		
1.6 Actively beneficial functions				
Cleans air	ND	ND		
Ease of recycling and reuse	ND	ND		
Others	ND	ND		
1.7 Others				
Deformation	ND	ND		
2 Chemical				
2.1 Chemical composition				
Carbon Equivalent Value (CEV)	ND	ND		

	Materials Passports property	Tekla Structures Default Property Name	IFC Property Name	IFC Property Type	C# variable type
2.2	Health and safety				
	Maintenance	ND	ND		
	Beneficial functions	ND	ND		
	Product certification and labels	ND	ND		
	Building certification	ND	ND		
	Emissions	ND	ND		
	Material Composition				
	Toxicity	ND	ND		
2.3	LCA - Environmental assessment				
	Emission trading	ND	ND		
	Resource taxation	ND	ND		
	Others	ND	ND		
2.4	LCC - Life Cycle Costing				
	Recommended retail price per unit	ND	ND		
	Manufacturing costs	ND	ND		
	Costs for maintenance and operation	ND	ND		
	Cleaning	ND	ND		
	Energy	ND	ND		
	Water	ND	ND		
	Upkeep	ND	ND		
	Others	ND	ND		
	Costs for service models	ND	ND		
	End of life costs	ND	ND		
	Transportation and handling costs	ND	ND		
	Potential incomes depending on reuse scenarios	ND	ND		

	Materials Passports property	Tekla Structures Default Property Name	IFC Property Name	IFC Property Type	C# variable type
	Lifespans and durability	ND	ND		
	Tax benefits	ND	ND		
	Warranties	ND	ND		
	Availability of spare parts	ND	ND		
	Others	ND	ND		
2.5	SCLA - Social Life Cycle Assessment				
	Child labour	ND	ND		
	Fair salary	ND	ND		
	Forced labour	ND	ND		
	Health and safety	ND	ND		
	Transparency	ND	ND		
	Community engagement	ND	ND		
	Corruption	ND	ND		
	Supplier relationships	ND	ND		
	Others	ND	ND		
2.6	Resistance and stability				
	Corrosion	ND	ND		
2.7	Lifespan and durability				
2.8	Material criticality				
2.9	Recycling and reuse potentials				
	End of life scenario	ND	ND		
2.10	Others				
3	Process				
3.1	Product labels and certifications				
	Indications and assessment	ND	ND		
	Test methods	ND	ND		
3.2	Registration	ND	ND		
3.3	Policy	ND	ND		
3.4	Standards and codes	ND	ND		

	Materials Passports property	Tekla Structures Default Property Name	IFC Property Name	IFC Property Type	C# variable type
3.5	BIM	ND	ND		
3.6	IoT and blockchain	ND	ND		
3.7	Actors	ND	Actor	IfcActor	
3.8	Transportation and logistics				
	Dimensions and weight	Several, depending on the object type	Several, depending on the object type		
	Required vehicles	ND	ND		
	Required labour and costs	ND	ND		
	Required tools	ND	ND		
	Health and safety requirements	ND	ND		
	Storage requirements	ND	ND		
	Material flow analysis	ND	ND		
	Information flows	ND	ND		
	Supply chain				
	Corporate Social Responsibility	ND	ND		
	Responsibilities	ND	ND		
	Supply chain mapping	ND	ND		
	Transport distances	ND	ND		
	Carbon footprint	ND	ND		
	Reverse logistics and take-back systems	ND	ND		
	Risk assessment	ND	ND		
	Others	ND	ND		
	Traceability				
	RFID tags	ND	ND		
	Barcodes	ND	ND		
	Others	ND	ND		
	Packaging	ND	PackagingCareType		

	Materials Passports property	Tekla Structures Default Property Name	IFC Property Name	IFC Property Type	C# variable type
	Handling instructions				
	Documentation	ND	ND		
	Hazard classes	ND	ND		
	Restrictions	ND	ND		
	Others	ND	ND		
	Others	ND	ND		
3.9	Ownership				
3.10	Design for disassembly and reversible structures	ND	ND		
3.11	Installation, use and extraction instructions	ND	ND		
3.12	Function	ND	ND		
3.13	Unique identifiers				
	Product/Brand name	PRODUCT_NAME	ModelLabel	IfcLabel	Normalized String
	Manufacturer's name/details	ND	Manufacturer	IfcLabel	Normalized String
	Manufacturer's article number	PRODUCT_CODE	ArticleNumber	IfcIdentifier	Normalized String
	Temporal Information				
	Production date	ND	ProductionYear	IfcLabel	Date
	Expected lifetime	ND	ExpectedServiceLife	IfcTimeDuration	Double
	Year of data set	ND	ND		
	GTIN or EAN number	ND	GlobalTradeItemNumber	IfcIdentifier	Normalized String
	CAS number	ND	ND		
	Product main function	PRODUCT_DESCRIPTION	ND		
	Product properties	PRODUCT_DESCRIPTION	ND		
	Product picture	ND	ND		
	Product complexity	ND	ND		
	Others				

	Materials Passports property	Tekla Structures Default Property Name	IFC Property Name	IFC Property Type	C# variable type
	Global Unique Identifier	GUID	GUID	IfcGloballyUniqueId	Normalized String
3.14	Material flows				
	Input flows	ND	ND		
	Output flows	ND	ND		
	Potential use scenarios	ND	ND		
	Others	ND	ND		
4	Biological				
4.1	Renewable/Non renewable	ND	ND		
4.2	Untreated/treated	ND	ND		
4.3	Recycling and reuse potentials	ND	ND		
4.4	Others	ND	ND		

APPENDIX 2: STEEL DECONSTRUCTION AND REUSE APPLICATION CODE

```
**********************************************************************************
Program.cs
**********************************************************************************
using System;
using System.Windows.Forms;

namespace WFA_Thesis
{
    static class Program
    {
        /// <summary>
        /// The main entry point for the application.
        /// </summary>
        [STAThread]
        static void Main()
        {
            Application.EnableVisualStyles();
            Application.SetCompatibleTextRenderingDefault(false);
            Application.Run(new Form1());
        }
    }
}
```

```
*********************************************************************************
Form1.cs
*********************************************************************************
using System;
using System.Diagnostics;
using System.Windows.Forms;
using Tekla.Structures.Model;
using Tekla.Structures.Model.UI;
using Color = Tekla.Structures.Model.UI.Color;

namespace WFA_Thesis
{
    public partial class Form1 : Form
    {
        public static readonly Model CurrentModel = new Model();
        public Form1()
        {
            //Check connection to model before loading GUI
            InitializeComponent();

            if (!CurrentModel.GetConnectionStatus())
            {
                MessageBox.Show(@"Failed to connect to Tekla Structures 2019i");
                Environment.Exit(-1);
            }
        }

        //Define button actions

        //Create UDAs and assign default values
        private void button1_Click(object sender, EventArgs e)
        {

            new CreateUDAs().AddBoltGroupCustomProperties(AllSteelObjectsInModel.AllSteelBoltGroups());

            new CreateUDAs().AddCustomPartCustomProperties(AllSteelObjectsInModel.AllSteelCustomParts());
            new CreateUDAs().AddPartCustomProperties(AllSteelObjectsInModel.AllSteelParts());

            MessageBox.Show(@"Custom UDAs for steel objects successfully created");
        }

        //Assign End of life scenario to each part based on their UDAs values
        private void button2_Click(object sender, EventArgs e)
        {
            new AssignEol().SetEOLBoltGroups();
            new AssignEol().SetEOLConnections(AllSteelObjectsInModel.AllConnections());
            new AssignEol().SetEOLCustomParts(AllSteelObjectsInModel.AllSteelCustomParts());
            new AssignEol().SetEOLParts();


            MessageBox.Show(@"End of life scenario has been successfully assigned to analyzed objects");
        }

        //Calculate Deconstructability score and report to Excel
        private void button3_Click(object sender, EventArgs e)
        {
            new PrintToExcel().PrintToExcelParts();
```

```
            }

            //Generate .ifc files of reusable objects
            private void button4_Click(object sender, EventArgs e)
            {
                var currentModelName = CurrentModel.GetInfo().ModelName;
                var currentModelPath = CurrentModel.GetInfo().ModelPath;


                new ExtractIfcFiles().ExtractIfcPart(AllReusable.AllReusableParts(), currentModelPath, currentModelName);
                new ExtractIfcFiles().ExtractIfcCustomPart(AllReusable.AllReusableCustomParts(), currentModelPath, currentModelName);


                MessageBox.Show(@"Ifc files from assemblies containing reusable parts have been generated");
            }

            //Color code parts based on their EOL Scenario assigned
            private void button5_Click(object sender, EventArgs e)
            {

                ModelObjectVisualization.ClearAllTemporaryStates();
                ModelObjectVisualization.SetTemporaryStateForAll(new Color(0, 0, 1));
                ModelObjectVisualization.SetTransparencyForAll(TemporaryTransparency.VISIBLE);

                try
                {
                    new FilterByEol().SetClass();

                    MessageBox.Show(@"Objects visual style modified. Refresh view");
                }
                catch (Exception ex)
                {
                    Trace.WriteLine(ex.InnerException + ex.Message + ex.StackTrace);
                }
            }

        }
    }
```

```
********************************************************************************
AllDisposable.cs
********************************************************************************
using System.Collections;
using System.Collections.Generic;
using System.Windows.Forms;
using DocumentFormat.OpenXml.Office.CoverPageProps;
using Tekla.Structures.Drawing;
using Tekla.Structures.Model;
using Connection = Tekla.Structures.Model.Connection;
using Part = Tekla.Structures.Model.Part;

namespace WFA_Thesis
{
    internal class AllDisposable
    {
        public static List<Assembly> AllDisposableAssemblies()
        {
            var allDisposableAssemblies = new List<Assembly>();
            var eolScenario = string.Empty;
            foreach (var assembly in AllSteelObjectsInModel.AllSteelAssemblies())
            {
                assembly.GetUserProperty("EOL_SCENARIO", ref eolScenario);
                if (eolScenario == "DISPOSABLE")
                {
                    allDisposableAssemblies.Add(assembly);
                }
            }

            return allDisposableAssemblies;
        }

        public static List<BoltGroup> AllDisposableBoltGroups()
        {
            var allDisposableBoltGroups = new List<BoltGroup>();
            var eolScenario = string.Empty;
            foreach (var boltGroup in AllSteelObjectsInModel.AllSteelBoltGroups())
            {
                boltGroup.GetUserProperty("EOL_SCENARIO", ref eolScenario);
                if (eolScenario == "DISPOSABLE")
                {
                    allDisposableBoltGroups.Add(boltGroup);
                }
            }

            return allDisposableBoltGroups;
        }

        public static List<Connection> AllDisposableConnections()
        {
            var allDisposableConnections = new List<Connection>();
            var eolScenario = string.Empty;
            foreach (var connection in AllSteelObjectsInModel.AllConnections())
            {
                connection.GetUserProperty("EOL_SCENARIO", ref eolScenario);
                if (eolScenario == "DISPOSABLE")
                {
                    allDisposableConnections.Add(connection);
                }
            }

            return allDisposableConnections;

        }

        public static List<CustomPart> AllDisposableCustomParts()
        {
            var allDisposableCustomParts = new List<CustomPart>();
            var eolScenario = string.Empty;
            foreach (var customPart in AllSteelObjectsInModel.AllSteelCustomParts())
            {
                customPart.GetUserProperty("EOL_SCENARIO", ref eolScenario);
                if (eolScenario == "DISPOSABLE")
                {
```

```
                    allDisposableCustomParts.Add(customPart);
                }
            }

            return allDisposableCustomParts;

        }

        public static List<Part> AllDisposableParts()
        {
            var allDisposableParts = new List<Part>();
            var eolScenario = string.Empty;

            foreach (var part in AllSteelObjectsInModel.AllSteelParts())
            {
                part.GetUserProperty("EOL_SCENARIO", ref eolScenario);
                if (eolScenario == string.Empty) continue;
                if (eolScenario == "DISPOSABLE")
                {
                    allDisposableParts.Add(part);
                }
            }

            return allDisposableParts;
        }

    }
}
```

```
*********************************************************************************
AllRecyclable.cs
*********************************************************************************
using System;
using System.Collections.Generic;
using Tekla.Structures.Model;

namespace WFA_Thesis
{
    class AllRecyclable
    {
        public static List<Assembly> AllRecyclableAssemblies()
        {
            var allRecyclableAssemblies = new List<Assembly>();
            var eolScenario = string.Empty;

            foreach (var assembly in AllSteelObjectsInModel.AllSteelAssemblies())
            {
                assembly.GetUserProperty("EOL_SCENARIO", ref eolScenario);
                if (eolScenario == string.Empty) continue;
                if (eolScenario == "RECYCLABLE")
                {
                    allRecyclableAssemblies.Add(assembly);
                }
            }

            return allRecyclableAssemblies;
        }


        public static List<BoltGroup> AllRecyclableBoltGroups()
        {
            var allRecyclableBoltGroups = new List<BoltGroup>();
            var eolScenario = string.Empty;

            foreach (var boltGroup in AllSteelObjectsInModel.AllSteelBoltGroups())
            {
                boltGroup.GetUserProperty("EOL_SCENARIO", ref eolScenario);

                if (eolScenario == "RECYCLABLE")
                {
                    allRecyclableBoltGroups.Add(boltGroup);
                }
            }

            return allRecyclableBoltGroups;
        }

        public static List<Connection> AllRecyclableConnections()
        {
            var allRecyclableConnections = new List<Connection>();
            var eolScenario = string.Empty;

            foreach (var connection in AllSteelObjectsInModel.AllConnections())
            {
                connection.GetUserProperty("EOL_SCENARIO", ref eolScenario);
                if (eolScenario == "RECYCLABLE")
                {
                    allRecyclableConnections.Add(connection);
                }
```

```
                }

                return allRecyclableConnections;
            }

            public static List<CustomPart> AllRecyclableCustomParts()
            {
                var allRecyclableCustomParts = new List<CustomPart>();
                var eolScenario = string.Empty;

                foreach (var customPart in AllSteelObjectsInModel.AllSteelCustomParts())
                {
                    customPart.GetUserProperty("EOL_SCENARIO", ref eolScenario);
                    if (eolScenario == "RECYCLABLE")
                    {
                        allRecyclableCustomParts.Add(customPart);
                    }
                }

                return allRecyclableCustomParts;
            }

            public static List<Part> AllRecyclableParts()
            {
                var allRecyclableParts = new List<Part>();
                var eolScenario = string.Empty;

                foreach (var part in AllSteelObjectsInModel.AllSteelParts())
                {
                    part.GetUserProperty("EOL_SCENARIO", ref eolScenario);
                    if (eolScenario == "RECYCLABLE")
                    {
                        allRecyclableParts.Add(part);
                    }
                }

                return allRecyclableParts;
            }

        }
    }
```

```
********************************************************************************
AllReusable.cs
********************************************************************************
```

```
using System;
using System.Collections.Generic;
using System.Windows.Forms;
using DocumentFormat.OpenXml.Office.CoverPageProps;
using Tekla.Structures.Model;

namespace WFA_Thesis
{
    class AllReusable
    {

        //Create list of reusable assemblies
        public static List<Assembly> AllReusableAssemblies()
        {
            var allReusableAssemblies = new List<Assembly>();
            var eolScenario = string.Empty;

            foreach (var assembly in AllSteelObjectsInModel.AllSteelAssemblies())
            {
                assembly.GetUserProperty("EOL_SCENARIO", ref eolScenario);

                if (eolScenario == "REUSABLE")
                {
                    allReusableAssemblies.Add(assembly);
                }
            }

            return allReusableAssemblies;

        }

        //All bolts are considered as non-reusable, therefore there is no method for list creation

        //Create list of reusable connections
        public static List<Connection> AllReusableConnections()
        {
            var allReusableConnections = new List<Connection>();
            var eolScenario = string.Empty;

            foreach (var connection in AllSteelObjectsInModel.AllConnections())
            {
                connection.GetUserProperty("EOL_SCENARIO", ref eolScenario);

                if (eolScenario == "REUSABLE")
                {
                    allReusableConnections.Add(connection);
                }
            }

            return allReusableConnections;
        }

        //Create list of reusable custom parts
        public static List<CustomPart> AllReusableCustomParts()
        {
            var allReusableCustomParts = new List<CustomPart>();
            var eolScenario = string.Empty;

            foreach (var customPart in AllSteelObjectsInModel.AllSteelCustomParts())
            {
                customPart.GetUserProperty("EOL_SCENARIO", ref eolScenario);

                if (eolScenario == "REUSABLE")
                {
                    allReusableCustomParts.Add(customPart);
                }
            }

            return allReusableCustomParts;
```

```
            }


            //Create list of reusable parts
            public static List<Part> AllReusableParts()
            {
                var allReusableParts = new List<Part>();
                var eolScenario = string.Empty;

                foreach (var part in AllSteelObjectsInModel.AllSteelParts())
                {
                    part.GetUserProperty("EOL_SCENARIO", ref eolScenario);
                    if (eolScenario == string.Empty) continue;
                    if (eolScenario == "REUSABLE")
                    {
                        allReusableParts.Add(part);
                    }

                }

                return allReusableParts;
            }


        }
    }
```

```
*********************************************************************************
AllSteelObjectsInModel.cs
*********************************************************************************
using System.Collections.Generic;
using System.Linq;
using Tekla.Structures.Model;

namespace WFA_Thesis
{
    //Defines the parts to be retrieved for the analysis
    class AllSteelObjectsInModel
    {
        public static readonly Model CurrentModel = new Model();

        //Get all steel assemblies
        public static List<Assembly> AllSteelAssemblies()
        {
            ModelObjectEnumerator.AutoFetch = true;
            var allAssemblies = CurrentModel.GetAllAssemblies()
                .Where(a => a.GetAssemblyType() == Assembly.AssemblyTypeEnum.STEEL_ASSEMBLY)
                .ToList();
            return allAssemblies;
        }

        //Get all bolt groups
        public static List<BoltGroup> AllSteelBoltGroups()
        {
            ModelObjectEnumerator.AutoFetch = true;
            var allBoltArrays = CurrentModel.GetAllBoltArrays()
                .ToList();

            var allBoltXyLists = CurrentModel.GetAllBoltXyLists()
                .ToList();
            var allBoltCircles = CurrentModel.GetAllBoltCircles()
                .ToList();

            var allSteelBolts = new List<BoltGroup>();

            allSteelBolts.AddRange(allBoltArrays);
            allSteelBolts.AddRange(allBoltXyLists);
            allSteelBolts.AddRange(allBoltCircles);

            foreach (var boltGroup in allSteelBolts)
            {
                var boltGroupMaterialType = string.Empty;
                boltGroup.GetReportProperty("MATERIAL_TYPE", ref boltGroupMaterialType);
                if (boltGroupMaterialType == "STEEL")
                {
                    allSteelBolts.Add(boltGroup);
                }
            }

            return allSteelBolts;

        }

        //Get all connections
        public static List<Connection> AllConnections()
        {
            ModelObjectEnumerator.AutoFetch = true;
```

```
            var allConnections = CurrentModel.GetAllConnections()
                .ToList();

            return allConnections;
        }

        //Get all custom parts with MATERIAL_TYPE="STEEL"
        public static List<CustomPart> AllSteelCustomParts()
        {
            ModelObjectEnumerator.AutoFetch = true;
            var allCustomParts = CurrentModel.GetAllCustomParts()
                .ToList();

            var allModeledCustomParts = new List<CustomPart>();
            allModeledCustomParts.AddRange(allCustomParts);

            var allSteelCustomParts = new List<CustomPart>();
            foreach (var customPart in allModeledCustomParts)
            {
                var customPartMaterialType = string.Empty;
                customPart.GetReportProperty("MATERIAL_TYPE", ref customPartMaterialType);

                if (customPartMaterialType == "STEEL")
                {
                    allSteelCustomParts.Add(customPart);
                }
            }

            return allSteelCustomParts;
        }

        //Get all parts with MATERIAL_TYPE = "STEEL"
        public static List<Part> AllSteelParts()
        {
            //BEAM includes curved beams
            //BEAM includes twin profiles
            ModelObjectEnumerator.AutoFetch = true;
            var allBeams = CurrentModel.GetAllBeams()
                .Where(b => b.Type == Beam.BeamTypeEnum.BEAM)
                .ToList();

            var allColumns = CurrentModel.GetAllBeams()
                .Where(b => b.Type == Beam.BeamTypeEnum.COLUMN)
                .ToList();

            var allSpiralBeams = CurrentModel.GetAllSpiralBeams()
                .ToList();

            //Get all plates (as Contour plates)
            var allContourPlates = CurrentModel.GetAllContourPlates()
                .Where(b => b.Type == ContourPlate.ContourPlateTypeEnum.PLATE)
                .ToList();

            //Get all plates (as unknown type plates)
            var allUnknownContourPlates = CurrentModel.GetAllContourPlates()
                .Where(b => b.Type == ContourPlate.ContourPlateTypeEnum.UNKNOWN)
                .ToList();

            //ContourPlateTypeEnum.SLAB are excluded from the analysis, considering these are concrete only elements
```

```

            var allBentPlates = CurrentModel.GetAllBentPlates()
                .ToList();

            var allLoftedPlates = CurrentModel.GetAllLoftedPlates()
                .ToList();

            //Create list of all parts
            var allModeledParts = new List<Part>();
            allModeledParts.AddRange(allBeams);
            allModeledParts.AddRange(allColumns);
            allModeledParts.AddRange(allSpiralBeams);
            allModeledParts.AddRange(allContourPlates);
            allModeledParts.AddRange(allUnknownContourPlates);
            allModeledParts.AddRange(allBentPlates);
            allModeledParts.AddRange(allLoftedPlates);

            var allSteelParts = new List<Part>();
            foreach (var part in allModeledParts)
            {
                var partMaterialType = string.Empty;
                part.GetReportProperty("MATERIAL_TYPE", ref partMaterialType);
                if (partMaterialType == "STEEL")
                {
                    allSteelParts.Add(part);
                }
            }
            return allSteelParts;

        }

    }
}
```

```
********************************************************************************
AllUnassigned.cs
********************************************************************************
using System.Collections.Generic;
using Tekla.Structures.Model;

namespace WFA_Thesis
{
    class AllUnassigned
    {
        public static List<Assembly> AllUnassignedAssemblies()
        {
            var allUnassignedAssemblies = new List<Assembly>();
            var eolScenario = string.Empty;
            var weight = 0;
            foreach (var assembly in AllSteelObjectsInModel.AllSteelAssemblies())
            {
                assembly.GetUserProperty("EOL_SCENARIO", ref eolScenario);
                assembly.GetReportProperty("WEIGHT_NET", ref weight);
                if (eolScenario == "UNASSIGNED")
                {
                    allUnassignedAssemblies.Add(assembly);
                }
                if (eolScenario==null)
                {
                    allUnassignedAssemblies.Add(assembly);
                }
            }

            return allUnassignedAssemblies;

        }

        public static List<BoltGroup> AllUnassignedBoltGroups()
        {
            var allUnassignedBoltGroups = new List<BoltGroup>();
            var eolScenario = string.Empty;
            var weight = 0;
            foreach (var boltGroup in AllSteelObjectsInModel.AllSteelBoltGroups())
            {
                boltGroup.GetUserProperty("EOL_SCENARIO", ref eolScenario);
                boltGroup.GetReportProperty("WEIGHT_NET", ref weight);

                if (eolScenario == "UNASSIGNED")
                {
                    allUnassignedBoltGroups.Add(boltGroup);
                }

            }

            return allUnassignedBoltGroups;
        }

        public static List<Connection> AllUnassignedConnections()
        {
            var allUnassignedConnections = new List<Connection>();
            var eolScenario = string.Empty;
            var weight = 0;
            foreach (var connection in AllSteelObjectsInModel.AllConnections())
            {
```

```
                    connection.GetUserProperty("EOL_SCENARIO", ref eolScenario);
                    connection.GetUserProperty("WEIGHT_NET", ref weight);
                    if (eolScenario == "UNASSIGNED")
                    {
                        allUnassignedConnections.Add(connection);
                    }

                }

                return allUnassignedConnections;
            }

            public static List<CustomPart> AllUnassignedCustomParts()
            {
                var allUnassignedCustomParts = new List<CustomPart>();
                var eolScenario = string.Empty;
                var weight = 0;
                foreach (var customPart in AllSteelObjectsInModel.AllSteelCustomParts())
                {
                    customPart.GetUserProperty("EOL_SCENARIO", ref eolScenario);
                    customPart.GetUserProperty("WEIGHT_NET", ref weight);
                    if (eolScenario == "UNASSIGNED")
                    {
                        allUnassignedCustomParts.Add(customPart);
                    }
                }

                return allUnassignedCustomParts;
            }
            public static List<Part> AllUnassignedParts()
            {
                var allUnassignedParts = new List<Part>();
                var eolScenario = string.Empty;

                foreach (var part in AllSteelObjectsInModel.AllSteelParts())
                {
                    part.GetUserProperty("EOL_SCENARIO", ref eolScenario);
                    if (eolScenario == "UNASSIGNED")
                    {
                        allUnassignedParts.Add(part);
                    }
                }

                return allUnassignedParts;
            }


        }
    }
```

```
********************************************************************************
AssignEol.cs
********************************************************************************
using System.Collections.Generic;
using Tekla.Structures.Model;

namespace WFA_Thesis
{
    class AssignEol
    {
        public void SetEOLBoltGroups()
        {
            foreach (var boltGroup in AllSteelObjectsInModel.AllSteelBoltGroups())
            {
                var eolScenario = string.Empty;
                var hazardous = string.Empty;
                var radioactive = string.Empty;
                double weight = 0;

                boltGroup.GetUserProperty("EOL_SCENARIO", ref eolScenario);
                boltGroup.GetUserProperty("HAZARDOUS", ref hazardous);
                boltGroup.GetReportProperty("WEIGHT_NET", ref weight);

                if (radioactive != "YES")
                {
                    if (weight == 0)
                    {
                        boltGroup.SetUserProperty("EOL_SCENARIO", "UNASSIGNED");
                    }

                    else
                    {
                        if (hazardous != "YES")
                        {
                            boltGroup.SetUserProperty("EOL_SCENARIO", "RECYCLABLE");

                        }

                        else
                        {
                            boltGroup.SetUserProperty("EOL_SCENARIO", "DISPOSABLE");
                            boltGroup.SetUserProperty("COMMENT",

                                "Possible traces of toxic or hazardous materials. Might pose adverse effects to the health. Dispose properly");
                        }

                    }

                }

                else
                {
                    boltGroup.SetUserProperty("EOL_SCENARIO", "DISPOSABLE");
                    boltGroup.SetUserProperty("COMMENT",

                        "Possible radioactivity. Might pose adverse effects to the health. Dispose properly.");
                    boltGroup.Modify();
                }
            }
        }

        public void SetEOLCustomParts(List<CustomPart> customParts)
        {
            foreach (var customPart in customParts)
            {
                var corrosion = string.Empty;
                var deformation = string.Empty;
                var eolScenario = string.Empty;
                var fireExposure = string.Empty;
                var hazardous = string.Empty;
                var radioactive = string.Empty;
```

```
                double weight = 0;

                customPart.GetUserProperty("CORROSION_LEVEL", ref corrosion);
                customPart.GetUserProperty("DEFORMATION", ref deformation);
                customPart.GetUserProperty("EOL_SCENARIO", ref eolScenario);
                customPart.GetUserProperty("FIRE_EXPOSURE", ref fireExposure);
                customPart.GetUserProperty("HAZARDOUS", ref hazardous);
                customPart.GetUserProperty("RADIOACTIVE", ref radioactive);
                customPart.GetReportProperty("WEIGHT_NET", ref weight);


                if (radioactive != "YES")
                {
                    if (weight == 0)
                    {
                        customPart.SetUserProperty("EOL_SCENARIO", "UNASSIGNED");
                    }

                    else
                    {
                        if (hazardous != "YES")
                        {
                            if (weight <= 5)
                            {
                                customPart.SetUserProperty("EOL_SCENARIO", "RECYCLABLE");
                            }

                            else
                            {

                                if (deformation == "HIGH" || deformation == "MODERATE" || corrosion == "HIGH" || corrosion == "MODERATE" || fireExposure == "YES")
                                {
                                    customPart.SetUserProperty("EOL_SCENARIO", "RECYCLABLE");
                                }

                                else
                                {
                                    customPart.SetUserProperty("EOL_SCENARIO", "REUSABLE");
                                }


                            }
                        }

                        else
                        {
                            customPart.SetUserProperty("EOL_SCENARIO", "DISPOSABLE");
                            customPart.SetUserProperty("COMMENT",

                                "Possible traces of toxic or hazardous materials. Might pose adverse effects to the health. Dispose properly");
                        }

                    }

                }

                else
                {
                    customPart.SetUserProperty("EOL_SCENARIO", "DISPOSABLE");
                    customPart.SetUserProperty("COMMENT",

                        "Possible radioactivity. Might pose adverse effects to the health. Dispose properly.");
                    customPart.Modify();
                }
            }
        }

        public void SetEOLParts()
        {
            foreach (var part in AllSteelObjectsInModel.AllSteelParts())
            {
```

```
                var corrosion = string.Empty;
                var deformation = string.Empty;
                var eolScenario = string.Empty;
                var fireExposure = string.Empty;
                var hazardous = string.Empty;
                var radioactive = string.Empty;
                double weight = 0;

                part.GetUserProperty("CORROSION", ref corrosion);
                part.GetUserProperty("DEFORMATION", ref deformation);
                part.GetUserProperty("EOL_SCENARIO", ref eolScenario);
                part.GetUserProperty("FIRE_EXPOSURE", ref fireExposure);
                part.GetUserProperty("HAZARDOUS", ref hazardous);
                part.GetUserProperty("RADIOACTIVE", ref radioactive);
                part.GetReportProperty("WEIGHT_NET", ref weight);

                if (radioactive != "YES")
                {
                    if (weight == 0)
                    {
                        part.SetUserProperty("EOL_SCENARIO", "UNASSIGNED");
                    }

                    else
                    {
                        if (hazardous != "YES")
                        {
                            if (weight <= 5)
                            {
                                part.SetUserProperty("EOL_SCENARIO", "RECYCLABLE");
                            }

                            else
                            {
                                if (deformation == "HIGH" || deformation == "MODERATE" || corrosion == "HIGH" || corrosion == "MODERATE" || fireExposure == "YES")
                                {
                                    part.SetUserProperty("EOL_SCENARIO", "RECYCLABLE");
                                }

                                else
                                {
                                    part.SetUserProperty("EOL_SCENARIO", "REUSABLE");
                                }


                            }
                        }

                        else
                        {
                            part.SetUserProperty("EOL_SCENARIO", "DISPOSABLE");
                            part.SetUserProperty("COMMENT",
                                "Possible traces of toxic or hazardous materials. Might pose adverse effects to the health. Dispose properly");
                        }

                    }

                }

                else
                {
                    part.SetUserProperty("EOL_SCENARIO", "DISPOSABLE");
                    part.SetUserProperty("COMMENT",
                        "Possible radioactivity. Might pose adverse effects to the health. Dispose properly.");
                    part.Modify();
                }
            }
        }
```

```
        }
*********************************************************************************
CalculateWeight.cs
*********************************************************************************
namespace WFA_Thesis
{
    public class CalculateWeight
    {
        //Assemblies
        //Calculate all steel assemblies weight
        public double CalculateWeightAllSteelAssemblies()
        {
            double totalWeight = 0;
            foreach (var assembly in AllSteelObjectsInModel.AllSteelAssemblies())
            {
                double weight = 0;
                assembly.GetReportProperty("WEIGHT_NET", ref weight);

                totalWeight += weight;
            }

            return totalWeight;
        }

        //Calculate weight per EOL scenario for assemblies

        public double CalculateWeightAllReusableAssemblies()
        {
            double totalReusableWeight = 0;
            foreach (var reusableAssembly in AllReusable.AllReusableAssemblies())
            {
                double weight = 0;
                reusableAssembly.GetReportProperty("WEIGHT_NET", ref weight);

                totalReusableWeight += weight;
            }

            return totalReusableWeight;
        }

        public double CalculateWeightAllRecyclableAssemblies()
        {
            double totalRecyclableWeight = 0;
            foreach (var recyclableAssembly in AllRecyclable.AllRecyclableAssemblies())
            {
                double weight = 0;
                recyclableAssembly.GetReportProperty("WEIGHT_NET", ref weight);

                totalRecyclableWeight += weight;
            }

            return totalRecyclableWeight;
        }

        public double CalculateWeightAllDisposableAssemblies()
        {
            double totalDisposableWeight = 0;
            foreach (var disposableAssembly in AllDisposable.AllDisposableAssemblies())
            {
                double weight = 0;
                disposableAssembly.GetReportProperty("WEIGHT_NET", ref weight);

                totalDisposableWeight += weight;
            }

            return totalDisposableWeight;
        }

        public double CalculateWeightAllUnassignedAssemblies()
        {
            double totalUnassignedWeight = 0;
            foreach (var unassignedAssembly in AllUnassigned.AllUnassignedAssemblies())
            {
                double weight = 0;
```

```
                unassignedAssembly.GetReportProperty("WEIGHT_NET", ref weight);

                totalUnassignedWeight += weight;
            }

            return totalUnassignedWeight;
        }

        //BoltGroups
        //Calculate all steel bolt groups weight
        public double CalculateWeightAllBoltGroups()
        {
            double totalWeight = 0;
            foreach (var part in AllSteelObjectsInModel.AllSteelBoltGroups())
            {
                double weight = 0;
                part.GetReportProperty("WEIGHT_NET", ref weight);

                totalWeight += weight;

            }

            return totalWeight;
        }

        //Calculate weight per EOL scenario for bolt groups
        //All bolts are considered as non reusable
        public double CalculateWeightAllRecyclableBoltGroups()
        {
            double totalRecyclableWeight = 0;
            foreach (var recyclableBoltGroup in AllRecyclable.AllRecyclableBoltGroups())
            {
                double weight = 0;
                recyclableBoltGroup.GetReportProperty("WEIGHT_NET", ref weight);

                totalRecyclableWeight += weight;
            }

            return totalRecyclableWeight;
        }

        public double CalculateWeightAllDisposableBoltGroups()
        {
            double totalDisposableWeight = 0;
            foreach (var disposableBoltGroup in AllDisposable.AllDisposableBoltGroups())
            {
                double weight = 0;
                disposableBoltGroup.GetReportProperty("WEIGHT_NET", ref weight);

                totalDisposableWeight += weight;
            }

            return totalDisposableWeight;
        }

        public double CalculateWeightAllUnassignedBoltGroups()
        {
            double totalUnassignedWeight = 0;
            foreach (var unassignedBoltGroup in AllUnassigned.AllUnassignedBoltGroups())
            {
                double weight = 0;
                unassignedBoltGroup.GetReportProperty("WEIGHT_NET", ref weight);

                totalUnassignedWeight += weight;
            }

            return totalUnassignedWeight;

        }

        //Calculate custom parts weight
        public double CalculateWeightAllSteelCustomParts()
        {
            double totalWeight = 0;
```

```
                foreach (var customPart in AllSteelObjectsInModel.AllSteelCustomParts())
                {
                    double weight = 0;
                    customPart.GetReportProperty("WEIGHT_NET", ref weight);

                    totalWeight += weight;

                }

                return totalWeight;
            }

            //Calculate weight per EOL scenario for custom parts
            public double CalculateWeightAllReusableCustomParts()
            {
                double totalReusableWeight = 0;
                foreach (var reusableCustomPart in AllReusable.AllReusableCustomParts())
                {
                    double weight = 0;
                    reusableCustomPart.GetReportProperty("WEIGHT_NET", ref weight);

                    totalReusableWeight += weight;
                }

                return totalReusableWeight;
            }

            public double CalculateWeightAllRecyclableCustomParts()
            {
                double totalRecyclableWeight = 0;
                foreach (var recyclableCustomPart in AllRecyclable.AllRecyclableCustomParts())
                {
                    double weight = 0;
                    recyclableCustomPart.GetReportProperty("WEIGHT_NET", ref weight);

                    totalRecyclableWeight += weight;
                }

                return totalRecyclableWeight;
            }

            public double CalculateWeightAllDisposableCustomParts()
            {
                double totalDisposableWeight = 0;
                foreach (var disposableCustomPart in AllDisposable.AllDisposableCustomParts())
                {
                    double weight = 0;
                    disposableCustomPart.GetReportProperty("WEIGHT_NET", ref weight);

                    totalDisposableWeight += weight;
                }

                return totalDisposableWeight;
            }

            public double CalculateWeightAllUnassignedCustomParts()
            {
                double totalUnassignedWeight = 0;
                foreach (var unassignedCustomPart in AllUnassigned.AllUnassignedCustomParts())
                {
                    double weight = 0;
                    unassignedCustomPart.GetReportProperty("WEIGHT_NET", ref weight);

                    totalUnassignedWeight += weight;
                }

                return totalUnassignedWeight;
            }

            //Calculate all steel parts weight
            public double CalculateWeightAllSteelParts()
            {
                double totalWeight = 0;
                foreach (var part in AllSteelObjectsInModel.AllSteelParts())
```

```
                {
                    double weight = 0;
                    part.GetReportProperty("WEIGHT_NET", ref weight);

                    totalWeight += weight;

                }

                return totalWeight;
            }

            //Calculate weight per EOL scenario for parts
            public double CalculateWeightAllReusableParts()
            {
                double totalReusableWeight = 0;
                foreach (var reusablePart in AllReusable.AllReusableParts())
                {
                    double weight = 0;
                    reusablePart.GetReportProperty("WEIGHT_NET", ref weight);

                    totalReusableWeight += weight;
                }

                return totalReusableWeight;
            }

            public double CalculateWeightAllRecyclableParts()
            {
                double totalRecyclableWeight = 0;
                foreach (var recyclablePart in AllRecyclable.AllRecyclableParts())
                {
                    double weight = 0;
                    recyclablePart.GetReportProperty("WEIGHT_NET", ref weight);

                    totalRecyclableWeight += weight;
                }

                return totalRecyclableWeight;
            }

            public double CalculateWeightAllDisposableParts()
            {
                double totalDisposableWeight = 0;
                foreach (var disposablePart in AllDisposable.AllDisposableParts())
                {
                    double weight = 0;
                    disposablePart.GetReportProperty("WEIGHT_NET", ref weight);

                    totalDisposableWeight += weight;
                }

                return totalDisposableWeight;
            }

            public double CalculateWeightAllUnassignedParts()
            {
                double totalUnassignedWeight = 0;
                foreach (var unassignedPart in AllUnassigned.AllUnassignedParts())
                {
                    double weight = 0;
                    unassignedPart.GetReportProperty("WEIGHT_NET", ref weight);

                    totalUnassignedWeight += weight;
                }

                return totalUnassignedWeight;
            }
        }
    }
```

```
********************************************************************************
CreateUDAs.cs
********************************************************************************
using System.Collections.Generic;
using Tekla.Structures;
using Tekla.Structures.Catalogs;
using Tekla.Structures.Model;

namespace WFA_Thesis
{
    public class CreateUDAs
    {
        public void AddBoltGroupCustomProperties(List<BoltGroup> boltGroups)
        {
            //Define list of UDAs to be created for the object type

            var names = new List<string> { "COMMENT", "EOL_SCENARIO", "HAZARDOUS", "RADIOACTIVE" };

            //Create UDAs
            CreateUserPropertyItem(names);

            //Set UDAs default values
            foreach (var boltGroup in boltGroups)
            {
                boltGroup.SetUserProperty("COMMENT", string.Empty);
                boltGroup.SetUserProperty("EOL_SCENARIO", "UNASSIGNED");
                boltGroup.SetUserProperty("HAZARDOUS", "NO");
                boltGroup.SetUserProperty("RADIOACTIVE", "NO");
            }
        }

        public void AddPartCustomProperties(List<Part> parts)
        {

            var names = new List<string> { "COMMENT", "CORROSION_LEVEL", "DEFORMATION", "EOL_SCENARIO", "FIRE EXPOSURE", "HAZARDOUS", "RADIOACTIVE" };

            CreateUserPropertyItem(names);

            foreach (var part in parts)
            {
                part.SetUserProperty("COMMENT", string.Empty);
                part.SetUserProperty("CORROSION_LEVEL", "NEGLIGIBLE");
                part.SetUserProperty("DEFORMATION", "NEGLIGIBLE");
                part.SetUserProperty("EOL_SCENARIO", "UNASSIGNED");
                part.SetUserProperty("FIRE_EXPOSURE", "NO");
                part.SetUserProperty("HAZARDOUS", "NO");
                part.SetUserProperty("RADIOACTIVE", "NO");
            }

        }

        public void AddCustomPartCustomProperties(List<CustomPart> customParts)
        {

            var names = new List<string> { "COMMENT", "CORROSION_LEVEL", "DEFORMATION", "EOL_SCENARIO", "FIRE EXPOSURE", "HAZARDOUS", "RADIOACTIVE" };

            CreateUserPropertyItem(names);

            foreach (var customPart in customParts)
            {
                customPart.SetUserProperty("COMMENT", string.Empty);
                customPart.SetUserProperty("CORROSION_LEVEL", "NEGLIGIBLE");
                customPart.SetUserProperty("DEFORMATION", "NEGLIGIBLE");
                customPart.SetUserProperty("EOL_SCENARIO", "UNASSIGNED");
                customPart.SetUserProperty("FIRE_EXPOSURE", "NO");
                customPart.SetUserProperty("HAZARDOUS", "NO");
                customPart.SetUserProperty("RADIOACTIVE", "NO");
            }
        }

        public void CreateUserPropertyItem(List<string> names)
```

```
            {
                foreach (var name in names)
                {
                    var userProperty = new UserPropertyItem
                    {
                        Name = name,
                        Level = UserPropertyLevelEnum.LEVEL_MODEL,
                        FieldType = UserPropertyFieldTypeEnum.FIELDTYPE_USERDEFINED,
                        Type = PropertyTypeEnum.TYPE_STRING,
                        Visibility = UserPropertyVisibilityEnum.VISIBILITY_NORMAL,
                        Unique = true,
                        AffectsNumbering = true
                    };
                    userProperty.Insert();
                    userProperty.SetLabel(name);

                    //Define object types to assign UDAs
                    userProperty.AddToObjectType(CatalogObjectTypeEnum.STEEL_BEAM);
                    userProperty.AddToObjectType(CatalogObjectTypeEnum.STEEL_COLUMN);
                    userProperty.AddToObjectType(CatalogObjectTypeEnum.STEEL_ORTHOGONAL_BEAM);
                    userProperty.AddToObjectType(CatalogObjectTypeEnum.STEEL_TWIN_PROFILE_BEAM);
                    userProperty.AddToObjectType(CatalogObjectTypeEnum.STEEL_CONTOUR_PLATE);
                    userProperty.AddToObjectType(CatalogObjectTypeEnum.STEEL_FOLDED_PLATE);
                    userProperty.AddToObjectType(CatalogObjectTypeEnum.BOLT);
                    userProperty.AddToObjectType(CatalogObjectTypeEnum.BENT_PLATE);
                    userProperty.AddToObjectType(CatalogObjectTypeEnum.STEEL_BREP_PART);
                    userProperty.AddToObjectType(CatalogObjectTypeEnum.STEEL_SPIRAL_BEAM);
                    userProperty.AddToObjectType(CatalogObjectTypeEnum.STEEL_LOFTED_PLATE);

                }
            }
        }
    }
```

```
********************************************************************************
CreateUDAs.cs
********************************************************************************
using System.Collections;
using System.Collections.Generic;
using Tekla.Structures.Model;

namespace WFA_Thesis
{
    public class ExtractIfcFiles
    {

        public void ExtractIfcPart(List<Part> allReusableParts, string modelPath, string modelName)
        {
            //Generate IFC files for each assembly  with reusable parts
            foreach (var part in allReusableParts)
            {
                var selection = new ArrayList { part };
                var selector = new Tekla.Structures.Model.UI.ModelObjectSelector();
                selector.Select(selection, false);

                IfcSettings.ExportIfc($"{modelPath}\\IFC\\OUT_{modelName}_{part.AssemblyNumber}");

                //IfcSettings.ExportIfc($"{modelPath}\\IFC\\OUT_{modelName}_{part.Name}_{part.Identifier.GUID}");
            }
        }


        public void ExtractIfcCustomPart(List<CustomPart> allReusableCustomParts, string modelPath,
            string modelName)
        {
            //Generate IFC files for each assembly with reusable custom part
            foreach (var customPart in allReusableCustomParts)
            {
                var selection = new ArrayList { customPart };
                var selector = new Tekla.Structures.Model.UI.ModelObjectSelector();
                selector.Select(selection, false);


IfcSettings.ExportIfc($"{modelPath}\\IFC\\OUT_{modelName}_{customPart.Name}_{customPart.Identifier.GUID}");
            }
        }
    }
}
```

```
*********************************************************************************
FilterByEol.cs
*********************************************************************************
namespace WFA_Thesis
{
    public class FilterByEol
    {
        public void SetClass()
        {

            foreach (var reusablePart in AllReusable.AllReusableParts())
            {
                reusablePart.Class = "3";
                reusablePart.Modify();
            }

            foreach (var recyclablePart in AllRecyclable.AllRecyclableParts())
            {
                recyclablePart.Class = "6";
                recyclablePart.Modify();
            }

            foreach (var disposablePart in AllDisposable.AllDisposableParts())
            {
                disposablePart.Class = "9";
                disposablePart.Modify();
            }

            foreach (var unassignedPart in AllUnassigned.AllUnassignedParts())
            {
                unassignedPart.Class = "1";
                unassignedPart.Modify();
            }



        }
    }
}
```

```
*********************************************************************************
IfcSettings.cs
*********************************************************************************
using Tekla.Structures.Geometry3d;
using Tekla.Structures.Model;

namespace WFA_Thesis
{
    class IfcSettings
    {
        public static void ExportIfc(string outputFileName)
        {
            var componentInput = new ComponentInput();
            componentInput.AddOneInputPosition(new Point(0, 0, 0));
            var comp = new Component(componentInput)
            {
                Name = "ExportIFC",
                Number = BaseComponent.PLUGIN_OBJECT_NUMBER
            };

            // Parameters
            comp.SetAttribute("OutputFile", outputFileName);
            comp.SetAttribute("Format", 0);
            comp.SetAttribute("ExportType", 0); //0 for Coordination view 2.0
            comp.SetAttribute("AdditionalPSets", "");
            comp.SetAttribute("CreateAll", 0); // 0 to export only selected objects

            // Advanced

            comp.SetAttribute("Assemblies", 1); //To export the whole assembly containing the reusable part(s)
            comp.SetAttribute("Bolts", 1);
            comp.SetAttribute("Welds", 1);
            comp.SetAttribute("SurfaceTreatments", 1);

            comp.SetAttribute("BaseQuantities", 1);
            comp.SetAttribute("PropertySets", 0);
            comp.SetAttribute("GridExport", 1);
            comp.SetAttribute("ReinforcingBars", 1);
            comp.SetAttribute("PourObjects", 1);

            comp.SetAttribute("LayersNameAsPart", 1);
            comp.SetAttribute("PLprofileToPlate", 0);
            comp.SetAttribute("ExcludeSnglPrtAsmb", 0);

            comp.SetAttribute("LocsFromOrganizer", 0);

            comp.Insert();
        }
    }
}
```

```
********************************************************************************
PrintToExcel.cs
********************************************************************************
using ClosedXML.Excel;
using System;
using System.Collections.Generic;
using System.Diagnostics;
using System.IO;
using System.Windows.Forms;

namespace WFA_Thesis
{
    public class PrintToExcel
    {
        public void PrintToExcelParts()
        {
            //Define weight variables
            var totalWeightAllSteelAssemblies = new CalculateWeight().CalculateWeightAllSteelAssemblies();
            var totalWeightAllBoltGroups = new CalculateWeight().CalculateWeightAllBoltGroups();
            var totalWeightAllCustomParts = new CalculateWeight().CalculateWeightAllSteelCustomParts();
            var totalWeightAllSteelParts = new CalculateWeight().CalculateWeightAllSteelParts();
            var totalWeightAnalyzedObjects = totalWeightAllBoltGroups + totalWeightAllCustomParts + totalWeightAllSteelParts;

            var weightReusableAssemblies = new CalculateWeight().CalculateWeightAllReusableAssemblies();
            var weightReusableCustomParts = new CalculateWeight().CalculateWeightAllReusableCustomParts();
            var weightReusableParts = new CalculateWeight().CalculateWeightAllReusableParts();
            var totalWeightReusableObjects = weightReusableCustomParts + weightReusableParts;

            var weightRecyclableAssemblies = new CalculateWeight().CalculateWeightAllRecyclableAssemblies();
            var weightRecyclableBoltGroups = new CalculateWeight().CalculateWeightAllRecyclableBoltGroups();
            var weightRecyclableCustomParts = new CalculateWeight().CalculateWeightAllRecyclableCustomParts();
            var weightRecyclableParts = new CalculateWeight().CalculateWeightAllRecyclableParts();
            var totalWeightRecyclableObjects =
                weightRecyclableBoltGroups + weightRecyclableCustomParts + weightRecyclableParts;

            var weightDisposableAssemblies = new CalculateWeight().CalculateWeightAllDisposableAssemblies();
            var weightDisposableBoltGroups = new CalculateWeight().CalculateWeightAllDisposableBoltGroups();
            var weightDisposableCustomParts = new CalculateWeight().CalculateWeightAllDisposableCustomParts();
            var weightDisposableParts = new CalculateWeight().CalculateWeightAllDisposableParts();
            var totalWeightDisposableObjects =
```

```
                weightDisposableBoltGroups + weightDisposableCustomParts + weightDisposableParts;



            var weightUnassignedBoltGroups = new CalculateWeight().CalculateWeightAllUnassignedBoltGroups();
            var weightUnassignedCustomParts = new CalculateWeight().CalculateWeightAllUnassignedCustomParts();
            var weightUnassignedParts = new CalculateWeight().CalculateWeightAllUnassignedParts();
            var totalWeightUnassignedObjects =
                weightUnassignedBoltGroups + weightUnassignedCustomParts + weightUnassignedParts;

            var totalConnections = AllSteelObjectsInModel.AllConnections().Count;
            var subtotalReusableConnections = AllReusable.AllReusableConnections().Count;
            var subtotalRecyclableConnections = AllRecyclable.AllRecyclableConnections().Count;
            var subtotalDisposableConnections = AllDisposable.AllDisposableConnections().Count;


            //Define Excel workbook path and name
            var workbook = new XLWorkbook();
            var modelPath = Form1.CurrentModel.GetInfo().ModelPath;
            var modelName = Form1.CurrentModel.GetInfo().ModelName.Split('.')[0];

            //Create worksheets inside the excel file
            var wsSummary = workbook.Worksheets.Add("Summary");
            var allSteelObjects = workbook.Worksheets.Add("AllSteel");
            var wsAllReusableObjects = workbook.Worksheets.Add("Reusable");
            var wsAllRecyclableObjects = workbook.Worksheets.Add("Recyclable");
            var wsAllDisposableObjects = workbook.Worksheets.Add("Disposable");
            var wsAllUnassignedObjects = workbook.Worksheets.Add("Unassigned");

            var AllWorkSheets = new List<IXLWorksheet>
            {
                allSteelObjects,
                wsAllReusableObjects,
                wsAllRecyclableObjects,
                wsAllDisposableObjects,
                wsAllUnassignedObjects,
            };

            //Print summary info
            wsSummary.Cell(1, 1).Value = "Model file name:";
            wsSummary.Cell(1, 2).Value = modelName;
            wsSummary.Cell(2, 1).Value = "File location:";
            wsSummary.Cell(2, 2).Value = modelPath;

            wsSummary.Cell(4, 1).Value = "Total weight of analyzed objects:";
            wsSummary.Cell(4, 2).Value = totalWeightAnalyzedObjects;
            wsSummary.Cell(5, 1).Value = "Reusable weight:";
            wsSummary.Cell(5, 2).Value = totalWeightReusableObjects;
            wsSummary.Cell(6, 1).Value = "Recyclable weight:";
            wsSummary.Cell(6, 2).Value = totalWeightRecyclableObjects;
            wsSummary.Cell(7, 1).Value = "Disposable weight:";
            wsSummary.Cell(7, 2).Value = totalWeightDisposableObjects;
            wsSummary.Cell(8, 1).Value = "Unassigned weight";
            wsSummary.Cell(8, 2).Value = totalWeightUnassignedObjects;

            wsSummary.Cell(10, 1).Value = "Deconstructability score:";

            //Calculate Deconstructabilty score

            var connectionRatio = 0;
            if (totalConnections != 0)
            {
                connectionRatio = subtotalReusableConnections / totalConnections;
            }
            else
```

```
            {
                connectionRatio = 1;
            }

            if (totalWeightAnalyzedObjects != 0)
            {
                var deconsScore = totalWeightReusableObjects / totalWeightAnalyzedObjects;
                wsSummary.Cell(10, 2).Value = deconsScore;
            }

            else
            {
                wsSummary.Cell(10, 2).Value = "Deconstructability score cannot be calculated";
            }


            wsSummary.Cell(12, 2).Value = "Total";
            wsSummary.Cell(12, 3).Value = "Reusable";
            wsSummary.Cell(12, 4).Value = "Recyclable";
            wsSummary.Cell(12, 5).Value = "Disposable";
            wsSummary.Cell(12, 6).Value = "Unassigned";

            wsSummary.Cell(13, 1).Value = "Bolt groups";
            wsSummary.Cell(13, 2).Value = AllSteelObjectsInModel.AllSteelBoltGroups().Count;
            //All bolts are considered as non-reusable
            wsSummary.Cell(13, 4).Value = AllRecyclable.AllRecyclableBoltGroups().Count;
            wsSummary.Cell(13, 5).Value = AllDisposable.AllDisposableBoltGroups().Count;
            wsSummary.Cell(13, 6).Value = AllUnassigned.AllUnassignedBoltGroups().Count;

            wsSummary.Cell(14, 1).Value = "Connections";
            wsSummary.Cell(14, 2).Value = AllSteelObjectsInModel.AllConnections().Count;
            wsSummary.Cell(14, 3).Value = AllReusable.AllReusableConnections().Count;
            wsSummary.Cell(14, 4).Value = AllRecyclable.AllRecyclableConnections().Count;
            wsSummary.Cell(14, 5).Value = AllDisposable.AllDisposableConnections().Count;
            wsSummary.Cell(14, 6).Value = AllUnassigned.AllUnassignedConnections().Count;

            wsSummary.Cell(15, 1).Value = "Custom parts";
            wsSummary.Cell(15, 2).Value = AllSteelObjectsInModel.AllSteelCustomParts().Count;
            wsSummary.Cell(15, 3).Value = AllReusable.AllReusableCustomParts().Count;
            wsSummary.Cell(15, 4).Value = AllRecyclable.AllRecyclableCustomParts().Count;
            wsSummary.Cell(15, 5).Value = AllDisposable.AllDisposableCustomParts().Count;
            wsSummary.Cell(15, 6).Value = AllUnassigned.AllUnassignedCustomParts().Count;

            wsSummary.Cell(16, 1).Value = "Parts";
            wsSummary.Cell(16, 2).Value = AllSteelObjectsInModel.AllSteelParts().Count;
            wsSummary.Cell(16, 3).Value = AllReusable.AllReusableParts().Count;
            wsSummary.Cell(16, 4).Value = AllRecyclable.AllRecyclableParts().Count;
            wsSummary.Cell(16, 5).Value = AllDisposable.AllDisposableParts().Count;
            wsSummary.Cell(16, 6).Value = AllUnassigned.AllUnassignedParts().Count;

            //Format worksheet
            wsSummary.Column(1).Width = 25;
            wsSummary.Column(2).Width = 10;
            wsSummary.Column(3).Width = 10;
            wsSummary.Column(4).Width = 10;
            wsSummary.Column(5).Width = 10;
            wsSummary.Column(6).Width = 10;


            //Print model basic info and column labels in each worksheet
            foreach (var worksheet in AllWorkSheets)
            {
                worksheet.Cell(1, 1).Value = "Model file name:";
                worksheet.Cell(1, 2).Value = modelName;
                worksheet.Cell(2, 1).Value = "File location:";
                worksheet.Cell(2, 2).Value = modelPath;

                //Print column labels
                worksheet.Cell(6, 1).Value = "OBJECT_TYPE";
                worksheet.Cell(6, 2).Value = "GUID";
                worksheet.Cell(6, 3).Value = "OBJECT NAME";
                worksheet.Cell(6, 4).Value = "MATERIAL";
                worksheet.Cell(6, 5).Value = "PROFILE";
                worksheet.Cell(6, 6).Value = "WEIGHT_NET";
```

```
                worksheet.Cell(6, 7).Value = "COMMENT";

                worksheet.Column(1).Width = 25;
                worksheet.Column(2).Width = 40;
                worksheet.Column(3).Width = 25;
                worksheet.Column(4).Width = 25;
                worksheet.Column(5).Width = 25;
                worksheet.Column(6).Width = 25;
                worksheet.Column(7).Width = 25;
                worksheet.Column(8).Width = 25;

            }

            //Print list of all analyzed parts
            //Print EOL scenario assigned to part
            allSteelObjects.Cell(6, 8).Value = "EOL_SCENARIO";


            //Print weight totals
            allSteelObjects.Cell(3, 1).Value = "All steel";
            allSteelObjects.Cell(3, 2).Value = "Reusable";
            allSteelObjects.Cell(3, 3).Value = "Recyclable";
            allSteelObjects.Cell(3, 4).Value = "Disposable";
            allSteelObjects.Cell(3, 5).Value = "Unassigned";
            allSteelObjects.Cell(4, 1).Value = totalWeightAllSteelParts;
            allSteelObjects.Cell(4, 2).Value = weightReusableParts;
            allSteelObjects.Cell(4, 3).Value = weightRecyclableParts;
            allSteelObjects.Cell(4, 4).Value = weightDisposableParts;
            allSteelObjects.Cell(4, 5).Value = weightUnassignedParts;

            //Print all objects in analysis
            var count = 0;

            //Print all bolt groups
            foreach (var boltGroup in AllSteelObjectsInModel.AllSteelBoltGroups())
            {
                var row = count + 7;

                allSteelObjects.Cell(row, 1).Value = "BOLT_GROUP";

                allSteelObjects.Cell(row, 2).Value = boltGroup.Identifier.GUID;

                var name = string.Empty;
                boltGroup.GetReportProperty("NAME", ref name);
                allSteelObjects.Cell(row, 3).Value = name;

                var material = string.Empty;
                boltGroup.GetReportProperty("MATERIAL", ref material);
                allSteelObjects.Cell(row, 4).Value = material;

                double weight = 0;
                boltGroup.GetReportProperty("WEIGHT_NET", ref weight);
                allSteelObjects.Cell(row, 6).Value = weight;

                var comment = string.Empty;
                boltGroup.GetUserProperty("COMMENT", ref comment);
                allSteelObjects.Cell(row, 7).Value = comment;

                var eolScenario = string.Empty;
                boltGroup.GetUserProperty("EOL_SCENARIO", ref eolScenario);
                allSteelObjects.Cell(row, 8).Value = eolScenario;

                count++;

            }

            //Print all connections
            foreach (var connection in AllSteelObjectsInModel.AllConnections())
            {
                var row = count + 9;

                allSteelObjects.Cell(row, 1).Value = "CONNECTION";

                allSteelObjects.Cell(row, 2).Value = connection.Identifier.GUID;
```

```

                    var name = string.Empty;
                    connection.GetReportProperty("NAME", ref name);
                    allSteelObjects.Cell(row, 3).Value = name;

                    var material = string.Empty;
                    connection.GetReportProperty("MATERIAL", ref material);
                    allSteelObjects.Cell(row, 4).Value = material;

                    double weight = 0;
                    connection.GetReportProperty("WEIGHT_NET", ref weight);
                    allSteelObjects.Cell(row, 6).Value = weight;

                    var comment = string.Empty;
                    connection.GetUserProperty("COMMENT", ref comment);
                    allSteelObjects.Cell(row, 7).Value = comment;

                    var eolScenario = string.Empty;
                    connection.GetUserProperty("EOL_SCENARIO", ref eolScenario);
                    allSteelObjects.Cell(row, 8).Value = eolScenario;

                    count++;

                }

                //Print all custom parts
                foreach (var customPart in AllSteelObjectsInModel.AllSteelCustomParts())
                {
                    var row = count + 9;

                    allSteelObjects.Cell(row, 1).Value = "CUSTOM_PART";

                    allSteelObjects.Cell(row, 2).Value = customPart.Identifier.GUID;
                    allSteelObjects.Cell(row, 3).Value = customPart.Name;

                    var material = string.Empty;
                    customPart.GetReportProperty("MATERIAL", ref material);
                    allSteelObjects.Cell(row, 4).Value = material;

                    double weight = 0;
                    customPart.GetReportProperty("WEIGHT_NET", ref weight);
                    allSteelObjects.Cell(row, 6).Value = weight;

                    var commentString = string.Empty;
                    customPart.GetUserProperty("COMMENT", ref commentString);
                    allSteelObjects.Cell(row, 7).Value = commentString;

                    var eolScenario = string.Empty;
                    customPart.GetUserProperty("EOL_SCENARIO", ref eolScenario);
                    allSteelObjects.Cell(row, 8).Value = eolScenario;

                    count++;

                }

                //Print all parts
                foreach (var part in AllSteelObjectsInModel.AllSteelParts())
                {
                    var row = count + 9;

                    allSteelObjects.Cell(row, 1).Value = "PART";
                    allSteelObjects.Cell(row, 2).Value = part.Identifier.GUID;
                    allSteelObjects.Cell(row, 3).Value = part.Name;
                    allSteelObjects.Cell(row, 4).Value = part.Material.MaterialString;
                    allSteelObjects.Cell(row, 5).Value = part.Profile.ProfileString;

                    double weight = 0;
                    part.GetReportProperty("WEIGHT_NET", ref weight);
                    allSteelObjects.Cell(row, 6).Value = weight;

                    var commentString = string.Empty;
                    part.GetUserProperty("COMMENT", ref commentString);
                    allSteelObjects.Cell(row, 7).Value = commentString;

```

```
                    var eolScenario = string.Empty;
                    part.GetUserProperty("EOL_SCENARIO", ref eolScenario);
                    allSteelObjects.Cell(row, 8).Value = eolScenario;

                    count++;
                }

                /////////////
                //Print AllReusableObjects spreadsheet data
                var countReusable = 0;

                //All bolt groups are considered as non reusable

                //Print all reusable connections
                foreach (var reusableConnection in AllReusable.AllReusableConnections())
                {
                    var row = countReusable + 7;

                    wsAllReusableObjects.Cell(row, 1).Value = "CONNECTION";
                    wsAllReusableObjects.Cell(row, 2).Value = reusableConnection.Identifier.GUID;
                    wsAllReusableObjects.Cell(row, 3).Value = reusableConnection.Name;

                    var material = string.Empty;
                    reusableConnection.GetReportProperty("MATERIAL", ref material);
                    wsAllReusableObjects.Cell(row, 4).Value = material;


                    double weight = 0;
                    reusableConnection.GetReportProperty("WEIGHT_NET", ref weight);
                    allSteelObjects.Cell(row, 6).Value = weight;

                    var commentString = string.Empty;
                    reusableConnection.GetUserProperty("COMMENT", ref commentString);
                    allSteelObjects.Cell(row, 7).Value = commentString;

                    countReusable++;

                }

                //Print all reusable custom parts
                foreach (var reusableCustomPart in AllReusable.AllReusableCustomParts())
                {
                    var row = countReusable + 8;

                    wsAllReusableObjects.Cell(row, 1).Value = "CUSTOM_PART";
                    wsAllReusableObjects.Cell(row, 2).Value = reusableCustomPart.Identifier.GUID;
                    wsAllReusableObjects.Cell(row, 3).Value = reusableCustomPart.Name;

                    var material = string.Empty;
                    reusableCustomPart.GetReportProperty("MATERIAL", ref material);
                    wsAllReusableObjects.Cell(row, 4).Value = material;

                    double weight = 0;
                    reusableCustomPart.GetReportProperty("WEIGHT_NET", ref weight);
                    allSteelObjects.Cell(row, 6).Value = weight;

                    var commentString = string.Empty;
                    reusableCustomPart.GetUserProperty("COMMENT", ref commentString);
                    allSteelObjects.Cell(row, 7).Value = commentString;

                    countReusable++;
                }

                //Print all reusable parts
                foreach (var reusablePart in AllReusable.AllReusableParts())
                {
                    var row = countReusable + 9;

                    wsAllReusableObjects.Cell(row, 1).Value = "PART";
                    wsAllReusableObjects.Cell(row, 2).Value = reusablePart.Identifier.GUID;
                    wsAllReusableObjects.Cell(row, 3).Value = reusablePart.Name;
                    wsAllReusableObjects.Cell(row, 4).Value = reusablePart.Material.MaterialString;
                    wsAllReusableObjects.Cell(row, 5).Value = reusablePart.Profile.ProfileString;

```

```
                        double weight = 0;
                        reusablePart.GetReportProperty("WEIGHT_NET", ref weight);
                        wsAllReusableObjects.Cell(row, 6).Value = weight;

                        var commentString = string.Empty;
                        reusablePart.GetUserProperty("COMMENT", ref commentString);
                        wsAllReusableObjects.Cell(row, 7).Value = commentString;

                        countReusable++;
                    }

                    /////////////
                    //Print AllRecyclableObjects spreadsheet data
                    var countRecyclable = 0;

                    //Print all recyclable bolt groups
                    foreach (var recyclableBoltGroup in AllRecyclable.AllRecyclableBoltGroups())
                    {
                        var row = countRecyclable + 7;

                        wsAllRecyclableObjects.Cell(row, 1).Value = "BOLT_GROUP";

                        wsAllRecyclableObjects.Cell(row, 2).Value = recyclableBoltGroup.Identifier.GUID
;
                        wsAllRecyclableObjects.Cell(row, 3).Value = recyclableBoltGroup.BoltType;

                        var material = string.Empty;
                        recyclableBoltGroup.GetReportProperty("MATERIAL", ref material);
                        wsAllRecyclableObjects.Cell(row, 4).Value = material;

                        double weight = 0;
                        recyclableBoltGroup.GetReportProperty("WEIGHT_NET", ref weight);
                        wsAllRecyclableObjects.Cell(row, 6).Value = weight;

                        var commentString = string.Empty;
                        recyclableBoltGroup.GetUserProperty("COMMENT", ref commentString);
                        wsAllRecyclableObjects.Cell(row, 7).Value = commentString;

                        countRecyclable++;
                    }


                    //Print all recyclable connections
                    foreach (var recyclableConnection in AllRecyclable.AllRecyclableConnections())
                    {
                        var row = countRecyclable + 8;

                        wsAllRecyclableObjects.Cell(row, 1).Value = "CONNECTION";

                        wsAllRecyclableObjects.Cell(row, 2).Value = recyclableConnection.Identifier.GUI
D;
                        wsAllRecyclableObjects.Cell(row, 3).Value = recyclableConnection.Name;

                        var material = string.Empty;
                        recyclableConnection.GetReportProperty("MATERIAL", ref material);
                        wsAllRecyclableObjects.Cell(row, 4).Value = material;

                        double weight = 0;
                        recyclableConnection.GetReportProperty("WEIGHT_NET", ref weight);
                        wsAllRecyclableObjects.Cell(row, 6).Value = weight;

                        var commentString = string.Empty;
                        recyclableConnection.GetUserProperty("COMMENT", ref commentString);
                        wsAllRecyclableObjects.Cell(row, 7).Value = commentString;

                        countRecyclable++;
                    }

                    //Print all recyclable custom parts
                    foreach (var recyclableCustomPart in AllRecyclable.AllRecyclableCustomParts())
                    {
                        var row = countRecyclable + 9;

                        wsAllDisposableObjects.Cell(row, 1).Value = "CUSTOM_PART";
```

```
                    wsAllRecyclableObjects.Cell(row, 2).Value = recyclableCustomPart.Identifier.GUID;
                    wsAllRecyclableObjects.Cell(row, 3).Value = recyclableCustomPart.Name;

                    var material = string.Empty;
                    recyclableCustomPart.GetReportProperty("MATERIAL", ref material);
                    wsAllRecyclableObjects.Cell(row, 4).Value = material;

                    double weight = 0;
                    recyclableCustomPart.GetReportProperty("WEIGHT_NET", ref weight);
                    wsAllRecyclableObjects.Cell(row, 6).Value = weight;

                    var commentString = string.Empty;
                    recyclableCustomPart.GetUserProperty("COMMENT", ref commentString);
                    wsAllRecyclableObjects.Cell(row, 7).Value = commentString;

                    countRecyclable++;
                }


                //Print all recyclable parts

                foreach (var recyclablePart in AllRecyclable.AllRecyclableParts())
                {
                    var row = countRecyclable + 10;

                    wsAllRecyclableObjects.Cell(row, 1).Value = "PART";
                    wsAllRecyclableObjects.Cell(row, 2).Value = recyclablePart.Identifier.GUID;
                    wsAllRecyclableObjects.Cell(row, 3).Value = recyclablePart.Name;
                    wsAllRecyclableObjects.Cell(row, 4).Value = recyclablePart.Material.MaterialString;
                    wsAllRecyclableObjects.Cell(row, 5).Value = recyclablePart.Profile.ProfileString;

                    double weight = 0;
                    recyclablePart.GetReportProperty("WEIGHT_NET", ref weight);
                    wsAllRecyclableObjects.Cell(row, 6).Value = weight;

                    var commentString = string.Empty;
                    recyclablePart.GetUserProperty("COMMENT", ref commentString);
                    wsAllRecyclableObjects.Cell(row, 7).Value = commentString;

                    countRecyclable++;
                }

                /////////////
                //Print all disposable parts

                var countDisposable = 0;

                //Print all disposable bolt groups
                foreach (var disposableBoltGroup in AllDisposable.AllDisposableBoltGroups())
                {
                    var row = countDisposable + 7;

                    wsAllDisposableObjects.Cell(row, 1).Value = "BOLT_GROUP";
                    wsAllDisposableObjects.Cell(row, 2).Value = disposableBoltGroup.Identifier.GUID;
                    wsAllDisposableObjects.Cell(row, 3).Value = disposableBoltGroup.BoltType;

                    var material = string.Empty;
                    disposableBoltGroup.GetReportProperty("MATERIAL", ref material);
                    wsAllDisposableObjects.Cell(row, 4).Value = material;

                    double weight = 0;
                    disposableBoltGroup.GetReportProperty("WEIGHT_NET", ref weight);
                    wsAllDisposableObjects.Cell(row, 6).Value = weight;

                    var commentString = string.Empty;
                    disposableBoltGroup.GetUserProperty("COMMENT", ref commentString);
```

```
                    wsAllDisposableObjects.Cell(row, 7).Value = commentString;

                    countDisposable++;
                }

                //Print all disposable connections
                foreach (var disposableConnection in AllDisposable.AllDisposableConnections())
                {
                    var row = countDisposable + 8;

                    wsAllDisposableObjects.Cell(row, 1).Value = "CONNECTION";

                    wsAllDisposableObjects.Cell(row, 2).Value = disposableConnection.Identifier.GUID;
                    wsAllDisposableObjects.Cell(row, 3).Value = disposableConnection.Name;

                    var material = string.Empty;
                    disposableConnection.GetReportProperty("MATERIAL", ref material);
                    wsAllDisposableObjects.Cell(row, 4).Value = material;

                    double weight = 0;
                    disposableConnection.GetReportProperty("WEIGHT_NET", ref weight);
                    wsAllDisposableObjects.Cell(row, 6).Value = weight;

                    var commentString = string.Empty;
                    disposableConnection.GetUserProperty("COMMENT", ref commentString);
                    wsAllDisposableObjects.Cell(row, 7).Value = commentString;

                    countDisposable++;

                }

                //Print all disposable custom parts
                foreach (var disposableCustomPart in AllDisposable.AllDisposableCustomParts())
                {
                    var row = countDisposable + 9;

                    wsAllDisposableObjects.Cell(row, 1).Value = "CUSTOM_PART";

                    wsAllDisposableObjects.Cell(row, 2).Value = disposableCustomPart.Identifier.GUID;
                    wsAllDisposableObjects.Cell(row, 3).Value = disposableCustomPart.Name;

                    var material = string.Empty;
                    disposableCustomPart.GetReportProperty("MATERIAL", ref material);
                    wsAllDisposableObjects.Cell(row, 4).Value = material;

                    double weight = 0;
                    disposableCustomPart.GetReportProperty("WEIGHT_NET", ref weight);
                    wsAllDisposableObjects.Cell(row, 6).Value = weight;

                    var commentString = string.Empty;
                    disposableCustomPart.GetUserProperty("COMMENT", ref commentString);
                    wsAllDisposableObjects.Cell(row, 7).Value = commentString;

                    countDisposable++;
                }

                //Print all disposable parts

                foreach (var disposablePart in AllDisposable.AllDisposableParts())
                {
                    var row = countDisposable + 10;

                    wsAllDisposableObjects.Cell(row, 1).Value = "PART";
                    wsAllDisposableObjects.Cell(row, 2).Value = disposablePart.Identifier.GUID;
                    wsAllDisposableObjects.Cell(row, 3).Value = disposablePart.Name;

                    wsAllDisposableObjects.Cell(row, 4).Value = disposablePart.Material.MaterialString;

                    wsAllDisposableObjects.Cell(row, 5).Value = disposablePart.Profile.ProfileString;

```

```
                double weight = 0;
                disposablePart.GetReportProperty("WEIGHT_NET", ref weight);
                wsAllDisposableObjects.Cell(row, 6).Value = weight;

                var commentString = string.Empty;
                disposablePart.GetUserProperty("COMMENT", ref commentString);
                wsAllDisposableObjects.Cell(row, 7).Value = commentString;

                countDisposable++;
            }

            /////////////
            //Print all unassigned objects
            var countUnassigned = 0;

            //Print all unassigned bolt groups
            foreach (var unassignedBoltGroup in AllUnassigned.AllUnassignedBoltGroups())
            {
                var row = countUnassigned + 7;

                wsAllUnassignedObjects.Cell(row, 1).Value = "BOLT_GROUP";

                wsAllUnassignedObjects.Cell(row, 2).Value = unassignedBoltGroup.Identifier.GUID
;

                var material = string.Empty;
                unassignedBoltGroup.GetReportProperty("MATERIAL", ref material);
                wsAllUnassignedObjects.Cell(row, 4).Value = material;

                double weight = 0;
                unassignedBoltGroup.GetReportProperty("WEIGHT_NET", ref weight);
                wsAllUnassignedObjects.Cell(row, 6).Value = weight;

                var commentString = string.Empty;
                unassignedBoltGroup.GetUserProperty("COMMENT", ref commentString);
                wsAllUnassignedObjects.Cell(row, 7).Value = commentString;

                countUnassigned++;
            }

            //Print all unassigned connections
            foreach (var unassignedConnection in AllUnassigned.AllUnassignedConnections())
            {
                var row = countUnassigned + 8;

                wsAllUnassignedObjects.Cell(row, 1).Value = "CONNECTION";

                wsAllUnassignedObjects.Cell(row, 2).Value = unassignedConnection.Identifier.GUI
D;

                double weight = 0;
                unassignedConnection.GetReportProperty("WEIGHT_NET", ref weight);
                wsAllUnassignedObjects.Cell(row, 6).Value = weight;

                var commentString = string.Empty;
                unassignedConnection.GetUserProperty("COMMENT", ref commentString);
                wsAllUnassignedObjects.Cell(row, 7).Value = commentString;

                countUnassigned++;

            }

            //Print all unassigned custom parts
            foreach (var unassignedCustomPart in AllUnassigned.AllUnassignedCustomParts())
            {
                var row = countUnassigned + 9;

                wsAllUnassignedObjects.Cell(row, 1).Value = "CUSTOM_PART";

                wsAllUnassignedObjects.Cell(row, 2).Value = unassignedCustomPart.Identifier.GUI
D;

                var material = string.Empty;
                unassignedCustomPart.GetReportProperty("MATERIAL", ref material);
```

```
                    wsAllUnassignedObjects.Cell(row, 4).Value = material;

                    double weight = 0;
                    unassignedCustomPart.GetReportProperty("WEIGHT_NET", ref weight);
                    wsAllUnassignedObjects.Cell(row, 6).Value = weight;

                    var commentString = string.Empty;
                    unassignedCustomPart.GetUserProperty("COMMENT", ref commentString);
                    wsAllUnassignedObjects.Cell(row, 7).Value = commentString;

                    countUnassigned++;
                }


                //Print all unassigned parts

                foreach (var unassignedPart in AllUnassigned.AllUnassignedParts())
                {
                    var row = countUnassigned + 10;

                    wsAllUnassignedObjects.Cell(row, 1).Value = "PART";
                    wsAllUnassignedObjects.Cell(row, 2).Value = unassignedPart.Identifier.GUID;
                    wsAllUnassignedObjects.Cell(row, 3).Value = unassignedPart.Name;
                    wsAllUnassignedObjects.Cell(row, 4).Value = unassignedPart.Material.MaterialString;
                    wsAllUnassignedObjects.Cell(row, 5).Value = unassignedPart.Profile.ProfileString;

                    double weight = 0;
                    unassignedPart.GetReportProperty("WEIGHT_NET", ref weight);
                    wsAllUnassignedObjects.Cell(row, 6).Value = weight;

                    var commentString = string.Empty;
                    unassignedPart.GetUserProperty("COMMENT", ref commentString);
                    wsAllUnassignedObjects.Cell(row, 7).Value = commentString;

                    countUnassigned++;
                }


                //Generate directory and save excel file

                try
                {
                    if (Directory.Exists(Path.Combine(modelPath + @"\ReuseReport")))
                    {
                        workbook.SaveAs(Path.Combine(modelPath + @"\ReuseReport\" + modelName + ".xlsx"));
                    }
                    else
                    {
                        Directory.CreateDirectory(Path.Combine(modelPath + @"\ReuseReport"));
                        workbook.SaveAs(Path.Combine(modelPath + @"\ReuseReport\" + modelName + ".xlsx"));
                    }

                    if (File.Exists(modelPath + @"\ReuseReport\" + modelName + ".xlsx"))
                    {
                        Process.Start("explorer.exe", modelPath + @"\ReuseReport\" + modelName + ".xlsx");
                    }

                    MessageBox.Show(@"Report successfully generated");

                }
                catch (Exception)
                {
```

```
                    MessageBox.Show(@"Failed to generate report in Excel. Check the file is not open");
                    Environment.Exit(-1);
                }
            }
        }
    }
```

```
*********************************************************************************
TeklaExtensionMethods.cs
*********************************************************************************
using System.Collections;
using System.Collections.Generic;
using Tekla.Structures.Model;
using Connection = Tekla.Structures.Model.Connection;

namespace WFA_Thesis
{
    public static class TeklaExtensionMethods
    {
        //Define method for assembly selection
        public static List<Assembly> GetAllAssemblies(this Model model)
        {
            return model.GetModelObjectSelector()
                .GetAllObjectsWithType(ModelObject.ModelObjectEnum.ASSEMBLY)
                .ToNewList<Assembly>();
        }

        //Define methods for bolt selection
        public static List<BoltArray> GetAllBoltArrays(this Model model)
        {
            return model.GetModelObjectSelector()
                .GetAllObjectsWithType(ModelObject.ModelObjectEnum.BOLT_ARRAY)
                .ToNewList<BoltArray>();
        }

        public static List<BoltXYList> GetAllBoltXyLists(this Model model)
        {
            return model.GetModelObjectSelector()
                .GetAllObjectsWithType(ModelObject.ModelObjectEnum.BOLT_XYLIST)
                .ToNewList<BoltXYList>();
        }

        public static List<BoltCircle> GetAllBoltCircles(this Model model)
        {
            return model.GetModelObjectSelector()
                .GetAllObjectsWithType(ModelObject.ModelObjectEnum.BOLT_CIRCLE)
                .ToNewList<BoltCircle>();
        }

        //Define method for connection selection
        public static List<Connection> GetAllConnections(this Model model)
        {
            return model.GetModelObjectSelector()
                .GetAllObjectsWithType(ModelObject.ModelObjectEnum.CONNECTION)
                .ToNewList<Connection>();
        }

        //Define methods for parts selection
        public static List<Beam> GetAllBeams(this Model model)
        {
            return model.GetModelObjectSelector()
                .GetAllObjectsWithType(ModelObject.ModelObjectEnum.BEAM)
                .ToNewList<Beam>();
        }

        public static List<SpiralBeam> GetAllSpiralBeams(this Model model)
        {
            return model.GetModelObjectSelector()
                .GetAllObjectsWithType(ModelObject.ModelObjectEnum.SPIRAL_BEAM)
                .ToNewList<SpiralBeam>();
        }

        public static List<ContourPlate> GetAllContourPlates(this Model model)
        {
            return model.GetModelObjectSelector()
                .GetAllObjectsWithType(ModelObject.ModelObjectEnum.CONTOURPLATE)
                .ToNewList<ContourPlate>();
        }

        public static List<LoftedPlate> GetAllLoftedPlates(this Model model)
        {
```

```
                return model.GetModelObjectSelector()
                    .GetAllObjectsWithType(ModelObject.ModelObjectEnum.LOFTED_PLATE)
                    .ToNewList<LoftedPlate>();
            }

            public static List<BentPlate> GetAllBentPlates(this Model model)
            {
                return model.GetModelObjectSelector()
                    .GetAllObjectsWithType(ModelObject.ModelObjectEnum.BENT_PLATE)
                    .ToNewList<BentPlate>();
            }

            //Define method for custom parts selection
            public static List<CustomPart> GetAllCustomParts(this Model model)
            {
                return model.GetModelObjectSelector()
                    .GetAllObjectsWithType(ModelObject.ModelObjectEnum.CUSTOM_PART)
                    .ToNewList<CustomPart>();
            }


            //Define method for List creation
            public static List<T> ToNewList<T>(this IEnumerator enumerator)
            {
                var list = new List<T>();
                while (enumerator.MoveNext())
                {
                    var current = (T)enumerator.Current;
                    if (current != null)
                        list.Add(current);
                }

                return list;
            }

        }
    }
```

APPENDIX 3: USER DEFINED ATTRIBUTES FILE CONTENT

```
/**************************************************************************/
/* Part attributes  */
/**************************************************************************/
part(0,"Part")
{
        /* User defined tab page */
        tab_page("Steel Deconstruction")
        {
                /* User defined attribute */
                unique_attribute("CORROSION_LEVEL", "Corrosion_Level", string,"%s", no, none, "0.0", "0.0")
                {
                        value("", 0)
                }
                unique_attribute("DEFORMATION", "Deformation", string,"%s", no, none, "0.0", "0.0")
                {
                        value("", 0)
                }
                unique_attribute("EOL_SCENARIO", "EOL_Scenario", string,"%s", no, none, "0.0", "0.0")
                {
                        value("UNASSIGNED", 2)
                }
                unique_attribute("FIRE_EXPOSURE", "Fire_Exposure", string,"%s", no, none, "0.0", "0.0")
                {
                        value("", 0)
                }
                unique_attribute("HAZARDOUS", "Hazardous", string,"%s", no, none, "0.0", "0.0")

                {
                        value("", 0)
                }
                unique_attribute("RADIOACTIVE", "Radioactive", string,"%s", no, none, "0.0", "0.0")
                {
                        value("", 0)
                }
                attribute("FIRE_RATING", "j_Fire_rating", string, "%s", yes, none, "0.0", "0.0")

                {
                        value("", 0)
                }
                unique_attribute("COMPRESIVE_STRENGHT", "Compresive_Strenght", string,"%s", no, none, "0.0", "0.0")
                {
                        value("", 0)
                }
                unique_attribute("YIELD_STRENGHT", "Yield_Strenght", string,"%s", no, none, "0.0", "0.0")
                {
                        value("", 0)
                }
                unique_attribute("ULTIMATE_STRENGHT", "Ultimate_Strenght", string,"%s", no, none, "0.0", "0.0")
```

```
		{
			value("", 0)
		}
		unique_attribute("ULTIMATE_STRAIN", "Ultimate_Strain", string,"%s", no, none, "0.0", "0.0")
		{
			value("", 0)
		}
		unique_attribute("MODULUS_OF_ELASTICITY", "Modulus_of_Elasticity", string,"%s", no, none, "0.0", "0.0")
		{
			value("", 0)
		}
		attribute("LOAD_BEARING", "j_Load_bearing", option, "%s", no, none, "0.0", "0.0")
		{
			value("j_No", 0)
			value("j_Bearing", 0)
			value("j_Shear", 0)
			value("j_Structural_combined", 0)
			value("j_Unset", 2)
		}
		unique_attribute("EXPECTED_LIFETIME", "Expected_Lifetime", string,"%s", no, none, "0.0", "0.0")
		{
			value("", 0)
		}
		unique_attribute("CEV", "CEV", string,"%s", no, none, "0.0", "0.0")
		{
			value("", 0)
		}
		unique_attribute("RECOMMENDED_PRICE", "Recommended_Retail_Price", string,"%s", no, none, "0.0", "0.0")
		{
			value("", 0)
		}
		unique_attribute("RFID_TAG", "RFID_Tag", string,"%s", no, none, "0.0", "0.0")

		{
			value("", 0)
		}
		unique_attribute("HANDLING_DOCUMENTATION", "Handling_Documentation", string,"%s", no, none, "0.0", "0.0")
		{
			value("", 0)
		}
		unique_attribute("MANUFACTURER", "Manufacturer", string,"%s", no, none, "0.0", "0.0")
		{
			value("", 0)
		}
		unique_attribute("MANUFACTURER_ARTICLE_NUMBER", "Manufacturer_Article_Number", string,"%s", no, none, "0.0", "0.0")
		{
			value("", 0)
		}
		attribute("PRODUCT_CODE", "j_Product_code", string, "%s", no, none, "0.0", "0.0")
		{
			value("", 0)
```

```
                }
                attribute("PRODUCT_DESCR", "j_Product_description", string, "%s", no, none, "0.0", "0.0")
                {
                        value("", 0)
                }


        }
                tab_page("Steel Deconstruction", "Steel Deconstruction", 19)
                modify (1)
}


/***************************************************************************/
/* Beam attributes  */
/***************************************************************************/
beam(0,"j_beam")
{
        /* Reference to the user defined tab page that is defined above in */
        /* the part() section: */
                tab_page("Steel Deconstruction", "Steel Deconstruction", 19)
        modify (1)
}
/***************************************************************************/
/* Spiral beam attributes  */
/***************************************************************************/
spiral_beam(0,"j_spiral_beam")
{
                tab_page("Steel Deconstruction", "Steel Deconstruction", 19)
        modify (1)
}
/***************************************************************************/
/* Column attributes  */
/***************************************************************************/
column(0,"j_column")
{
                tab_page("Steel Deconstruction", "Steel Deconstruction", 19)
        modify (1)
}
/***************************************************************************/
/* Beam/Orthogonal attributes  */
/***************************************************************************/
beamortho(0,"Beam/orthogonal")
{
                tab_page("Steel Deconstruction", "Steel Deconstruction", 19)
        modify (1)
}
/***************************************************************************/
/* Twin profile attributes  */
/***************************************************************************/
beamortho(0,"Beam/orthogonal")
{
                tab_page("Steel Deconstruction", "Steel Deconstruction", 19)
        modify (1)
}
/***************************************************************************/
/* Contour plate attributes  */
/***************************************************************************/
```

```
contourplate(0,"j_contour_plate")
{
                tab_page("Steel Deconstruction", "Steel Deconstruction", 19)
        modify (1)
}
/***************************************************************************/
/* Bent plate attributes  */
/***************************************************************************/
bentplate(0,"j_bent_plate")
{
                tab_page("Steel Deconstruction", "Steel Deconstruction", 19)
        modify (1)
}
/***************************************************************************/
/* Folded plate attributes  */
/***************************************************************************/
foldedplate(0,"j_folded_plate")
{
                tab_page("Steel Deconstruction", "Steel Deconstruction", 19)
        modify (1)
}
/***************************************************************************/
/* welding attributes */
/***************************************************************************/
welding(0,"j_welding")
{

}
/***************************************************************************/
/* Bolt attributes */
/***************************************************************************/
bolt(0,"j_bolt")
{
                tab_page("Steel Deconstruction", "Steel Deconstruction", 19)
        modify (1)
}
/***************************************************************************/
/* Project attributes */
/***************************************************************************/
project(0,"j_Project")
{

}
/***************************************************************************/
/* Phase attributes */
/***************************************************************************/
phase(0,"j_Phase")
{

}
/***************************************************************************/
/* Reference object attributes                                              */
/***************************************************************************/
reference_part(0,"j_Reference_object")
{

}
/***************************************************************************/
/* Assembly attributes */
/***************************************************************************/
```

```
steelassembly(0, "jd_SteelAssembly")
{
                tab_page(" Deconstruction", "Steel Deconstruction", 19)
        modify (1)
}
```

APPENDIX 4: SAMPLES FROM THE REPORT GENERATED BY THE APPLICATION

Spreadsheet: Summary

Model file name:	BY0089			
File location:	C:\Users\...\BY0089			
Total weight of analysed objects:	250,536.02	kg		
Reusable weight:	191,193.79	kg	**Reusable steel ratio:**	0.76
Recyclable weight:	59,033.71	kg	**Recyclable steel ratio:**	0.24
Disposable weight:	308.51	kg	**Disposable steel ratio:**	0.00
Unassigned weight	-	kg		

Deconstructability score: **0.76**

	Total	Reusable	Recyclable	Disposable	Unassigned
Bolt groups	2089	NA	0	0	2089
Connections	0	0	0	0	0
Custom parts	0	0	0	0	0
Parts	14233	2762	11451	4	16
Total	**16322**	**2762**	**11451**	**4**	**2105**

Spreadsheet: AllSteel

(Note: this a sample of the reported data containing a list of the analyzed model objects and classified by their EOL_SCENARIO value)

Model file name:	BY0089
File location:	C:\Users\...\BY0089

OBJECT_TYPE	**GUID**	**OBJECT NAME**	**MATERIAL_GRADE**	**PROFILE**	**WEIGHT_NET**	**COMMENT**	**EOL_SCENARIO**
PART	5c52ca48-0000-2233-3135-343932393538	VIGA PRS14	S355JR EN10025	PL30	128.3239025		DISPOSABLE
PART	5c52ca48-0000-6d0a-3135-343935363638	VIGA PRS14	S355JR EN10025	PL10	56.74911695		DISPOSABLE
PART	5c52ca48-0000-6cf1-3135-343935363635	VIGA PRS14	S355JR EN10025	PL250*15	65.52416986		DISPOSABLE
PART	5c0e47ef-0000-0157-3135-343434343036	VIGA PRS20	S355JR EN10025	PL10	57.91686737		DISPOSABLE
PART	5c46dcab-0000-15b1-3135-343832353236	TRELIÇA	S355JR EN10025	PL40	418.9264665		RECYCLABLE
PART	5c46dcab-0000-13cd-3135-343832343131	TRELIÇA	S355JR EN10025	PL40	418.4009597		RECYCLABLE
PART	5c52ca48-0000-022b-3135-343839343635	PILAR PRS P6	S355JR EN10025	PL35	406.5039648		RECYCLABLE
PART	5c52ca48-0000-00e5-3135-343839333632	PILAR PRS P6	S355JR EN10025	PL35	401.9096149		RECYCLABLE
PART	5c52ca48-0000-4bb9-3135-343934363133	TRELIÇA	S355JR EN10025	PL30	337.0757324		RECYCLABLE
PART	5c52ca48-0000-4b8c-3135-343934353734	TRELIÇA	S355JR EN10025	PL30	333.4052702		RECYCLABLE
PART	5c52ca48-0000-1588-3135-343932373937	TRELIÇA	S355JR EN10025	PL20	326.0534619		RECYCLABLE
PART	5c52ca48-0000-1496-3135-343932373539	TRELIÇA	S355JR EN10025	PL20	326.0533639		RECYCLABLE
PART	5c52ca48-0000-072b-3135-343839353932	TRELIÇA	S355JR EN10025	PL30	280.4223496		RECYCLABLE
PART	5c52ca48-0000-0734-3135-343839353934	TRELIÇA	S355JR EN10025	PL30	280.4223483		RECYCLABLE
PART	5c52ca48-0000-0245-3135-343839343734	PILAR PRS P6	S355JR EN10025	PL30	276.7815197		RECYCLABLE
PART	5c52ca48-0000-0242-3135-343839343639	PILAR PRS P6	S355JR EN10025	PL30	276.7560742		RECYCLABLE
PART	5c52ca48-0000-004c-3135-343839333238	PILAR PRS P6	S355JR EN10025	PL30	272.4963737		RECYCLABLE
PART	5c52ca48-0000-023b-3135-343839343636	PILAR PRS P6	S355JR EN10025	PL30	272.4963323		RECYCLABLE
PART	5c46dcab-0000-1585-3135-343832343733	TRELIÇA	S355JR EN10025	PL20	244.4522991		RECYCLABLE
PART	5c46dcab-0000-15b6-3135-343832353237	TRELIÇA	S355JR EN10025	PL20	244.4522537		RECYCLABLE
PART	5c331a40-0001-acdf-3135-343732323930	TRELIÇA	S355JR EN10025	PL20	187.6829907		RECYCLABLE
PART	5c3da4e2-0000-12cf-3135-343736353230	TRELIÇA	S355JR EN10025	PL20	187.6829797		RECYCLABLE
PART	5c2fa5fb-0000-5040-3135-343735343731	TRELIÇA	S355JR EN10025	PL20	183.8693634		RECYCLABLE
PART	5c331a40-0001-ad45-3135-343732333136	TRELIÇA	S355JR EN10025	PL20	183.8693477		RECYCLABLE
PART	5c2fa5fb-0000-3f7c-3135-343734353638	TRELIÇA	S355JR EN10025	PL20	180.0248682		RECYCLABLE
PART	5c2fa5fb-0000-439c-3135-343734373736	TRELIÇA	S355JR EN10025	PL20	180.0247833		RECYCLABLE
PART	5c0e9ab9-0000-00a3-3135-343434363333	PILAR PRS P6	S355JR EN10025	PL400*30	168.6116991		RECYCLABLE
PART	5c0e9ab9-0000-00a7-3135-343434363333	PILAR PRS P6	S355JR EN10025	PL400*30	168.6116855		RECYCLABLE
PART	5c9b60ad-0000-0574-3135-353337303131	Chapa Colaborante	S275JR EN10025	ARCELOR_PPC_COFRASTRA_70_75	63.59777126		RECYCLABLE

Model file name: BY0089
File location: C:\Users\...\BY0089

OBJECT_TYPE	GUID	OBJECT NAME	MATERIAL_GRADE	PROFILE	WEIGHT_NET	COMMENT	EOL_SCENARIO
PART	5c9b60ad-0000-0588-3135-353337303132	Chapa Colaborante	S275JR EN10025	ARCELOR_PPC_COFRASTRA_70_75	63.59777126		RECYCLABLE
PART	5c9b60ad-0000-0570-3135-353337303131	Chapa Colaborante	S275JR EN10025	ARCELOR_PPC_COFRASTRA_70_75	63.59777126		RECYCLABLE
PART	5c23c0f9-0000-0afa-3135-343539333239	Chapa Colaborante	S275JR EN10025	ARCELOR_PPC_COFRASTRA_70_75	40.08309571		RECYCLABLE
PART	5c1d0808-0000-1426-3135-343534313333	PILAR	S355J0H EN10219	SHS300*12	670.9106584		REUSABLE
PART	5c1d0808-0000-1455-3135-343534313433	PILAR	S355J0H EN10219	SHS300*12	670.2270767		REUSABLE
PART	5c52ca48-0000-d0d6-3135-353032353739	PILAR	S355J0H EN10219	SHS300*12	669.04798		REUSABLE
PART	5c263156-0000-0265-3135-343630313430	PILAR	S355J0H EN10219	SHS300*12	667.2329474		REUSABLE
PART	5c52ca48-0000-8cab-3135-343938383635	PILAR PRS P25	S355JR EN10025	PL45	651.3119905		REUSABLE
PART	5c52ca48-0000-8cd8-3135-343938383730	PILAR PRS P25	S355JR EN10025	PL45	651.2118731		REUSABLE
PART	5c52ca48-0000-d0e5-3135-353032353839	PILAR	S355J0H EN10219	SHS300*12	650.5238049		REUSABLE
PART	5caef568-0000-13ef-3135-353530303130	PILAR	S355J0H EN10219	SHS300*8	650.0006134		REUSABLE
PART	5c0e9ab9-0000-0080-3135-343434363235	PILAR	S355J0H EN10219	SHS300*12	649.9194921		REUSABLE
PART	5c1a6a06-0000-0214-3135-343533303332	VIGA	S275JR EN10025	HEA300	563.6091252		REUSABLE
PART	5c8a2ae7-0000-25dd-3135-353236363632	VIGA	S275JR EN10025	HEA300	563.5713789		REUSABLE
PART	5c6af4fc-0000-ba89-3135-353134353433	VIGA	S275JR EN10025	HEA300	563.5713787		REUSABLE
PART	5c8a2ae7-0000-c45d-3135-353330373335	VIGA	S275JR EN10025	HEA300	563.5713783		REUSABLE
PART	5c1a6a06-0000-0461-3135-343533323136	VIGA	S275JR EN10025	HEA300	563.5712207		REUSABLE
PART	5c76cd26-0000-bda6-3135-353133363830	VIGA	S275JR EN10025	HEA300	563.5712207		REUSABLE
PART	5c1d0808-0000-1422-3135-343534313333	PILAR	S355J0H EN10219	SHS300*10	563.4036918		REUSABLE
PART	5c6af4fc-0000-4468-3135-353131303732	PILAR	S355J0H EN10219	SHS300*10	563.3723907		REUSABLE
PART	5c8a2ae7-0000-0884-3135-353236343830	PILAR	S355J0H EN10219	SHS300*10	563.2815802		REUSABLE
PART	5c6af4fc-0000-4491-3135-353131303733	PILAR	S355J0H EN10219	SHS300*10	562.967776		REUSABLE
PART	5c1d0808-0000-1416-3135-343534313333	PILAR	S355J0H EN10219	SHS300*10	562.9495168		REUSABLE
PART	5c488c14-0000-1310-3135-343833353834	TRELIÇA	S355JR EN10025	PL40	397.0445954		REUSABLE

Model file name: BY0089
File location: C:\Users\...\BY0089

OBJECT_TYPE	GUID	OBJECT NAME	MATERIAL_GRADE	PROFILE	WEIGHT_NET	COMMENT	EOL_SCENARIO
PART	5c488c14-0000-12aa-3135-343833353733	TRELIÇA	S355JR EN10025	PL40	395.6735527		REUSABLE
PART	5c52ca48-0000-36cb-3135-343933363638	PILAR PRS P6	S355JR EN10025	PL40	383.6051366		REUSABLE
PART	5c52ca48-0000-36f7-3135-343933363733	PILAR PRS P6	S355JR EN10025	PL40	381.4195759		REUSABLE
PART	5ca373d7-0000-00d5-3135-353432323034	VIGA	S275JR EN10025	HEA300	373.2382858		REUSABLE
PART	5ca373d7-0000-015e-3135-353432323335	VIGA PRS PT13	S355JR EN10025	PL15	372.6779381		REUSABLE
PART	5c25f157-0000-23e1-3135-343630313433	VIGA PRS PT13	S355JR EN10025	PL15	370.4425346		REUSABLE
PART	5c458770-0000-865f-3135-343833323938	CHAPA	S355JR EN10025	PL40	366.1497147		REUSABLE
PART	5c458770-0000-8669-3135-343833333131	CHAPA	S355JR EN10025	PL40	364.3233418		REUSABLE
PART	5c52ca48-0000-7a77-3135-343936323731	PILAR PRS P4	S355JR EN10025	PL20	361.5617359		REUSABLE
PART	5c52ca48-0000-7a7a-3135-343936323731	PILAR PRS P4	S355JR EN10025	PL20	361.5519295		REUSABLE
PART	5c2fa5fb-0000-4fe0-3135-343735343639	PILAR PRS P2	S355JR EN10025	PL20	340.0717307		REUSABLE
PART	5c2fa5fb-0000-3dd9-3135-343732323736	PILAR PRS P2	S355JR EN10025	PL20	340.0666683		REUSABLE
PART	5ca373d7-0000-00db-3135-353432323037	VIGA	S275JR EN10025	HEA300	337.1229939		REUSABLE
PART	5c46dcab-0000-2a3c-3135-343834313433	PILAR PRS P2	S355JR EN10025	PL15	182.765649		REUSABLE
PART	5c46dcab-0000-28ea-3135-343834303839	PILAR PRS P2	S355JR EN10025	PL15	182.765649		REUSABLE
PART	5c8a2ae7-0001-0c5e-3135-353331363935	VIGA	S275JR EN10025	IPE300	182.0515702		REUSABLE
PART	5c8a2ae7-0000-6194-3135-353239313831	VIGA	S275JR EN10025	IPE300	182.0515702		REUSABLE
PART	5c6af4fc-0001-0470-3135-353137323233	VIGA	S275JR EN10025	IPE300	182.0510749		REUSABLE
PART	5c78f416-0000-21d4-3135-353134343334	VIGA	S275JR EN10025	IPE300	182.0510749		REUSABLE
PART	5c1a6a06-0000-0967-3135-343533393230	VIGA	S275JR EN10025	IPE300	182.0510749		REUSABLE
PART	5c1a6a06-0000-012c-3135-343532343037	VIGA	S275JR EN10025	IPE300	182.0509793		REUSABLE

Spreadsheet: Reusable

(Note: this a sample of the reported data, containing the list of reusable objects)

Model file name: BY0089

File location: C:\Users\...\BY0089

OBJECT_TYPE	GUID	OBJECT NAME	MATERIAL	PROFILE	WEIGHT_NET	COMMENT
PART	5c59681f-0000-4f48-3135-343935363431	PILAR P25	S355JR EN10025	PL45	2041.195158	
PART	5c59681f-0000-56db-3135-343936323438	PILAR P25	S355JR EN10025	PL45	2036.504935	
PART	5c3da4e2-0000-16b3-3135-343736353636	PILAR PRS P7	S355JR EN10025	PL40	1328.959681	
PART	5c46dcab-0000-03f7-3135-343831363130	PILAR PRS P7	S355JR EN10025	PL40	1326.647822	
PART	5c0e9ab9-0000-0070-3135-343434363234	PILAR	S355J0H EN10219	SHS300*12	1266.259533	
PART	5c9e5ca3-0000-5178-3135-353434373531	VIGA PRS31	S275JR EN10025	PL630*20	1246.827217	
PART	5c52ca48-0000-b898-3135-353031343536	PILAR	S355J0H EN10219	SHS300*10	1090.059233	
PART	5c8a2ae7-0000-0740-3135-353236343433	PILAR	S355J0H EN10219	SHS300*10	1089.188185	
PART	5c9e5ca3-0001-6bff-3135-353530363331	PILAR	S355J0H EN10219	SHS300*10	1089.100033	
PART	5c9e5ca3-0000-5170-3135-353434373438	VIGA PRS31	S275JR EN10025	PL280*35	969.8094523	
PART	5c2fa5fb-0000-3909-3135-343731343234	PILAR PRS P6	S355JR EN10025	PL30	961.5277167	
PART	5c9e5ca3-0000-5173-3135-353434373530	VIGA PRS31	S275JR EN10025	PL280*35	960.1090758	
PART	5c2fa5fb-0000-4571-3135-343734383035	PILAR PRS P6	S355JR EN10025	PL30	959.367987	
PART	5c52ca48-0000-d0bf-3135-353032353735	PILAR	S355J0H EN10219	SHS300*16	854.5175904	
PART	5c1d0808-0000-13dd-3135-343534313232	PILAR	S355J0H EN10219	SHS300*16	854.3674084	
PART	5c1d0808-0000-141e-3135-343534313333	PILAR	S355J0H EN10219	SHS300*16	854.3025891	
PART	5c0e9ab9-0000-0078-3135-343434363235	PILAR	S355J0H EN10219	SHS300*16	853.6288692	
PART	5c1d0808-0000-13e5-3135-343534313232	PILAR	S355J0H EN10219	SHS300*16	835.2972063	
PART	5c52ca48-0000-cfbf-3135-353032353338	PILAR	S355J0H EN10219	SHS300*16	791.3135804	
PART	5c52ca48-0000-6511-3135-343935343932	PILAR PRS P4	S355JR EN10025	PL20	752.8560077	
PART	5c52ca48-0000-650b-3135-343935343432	PILAR PRS P4	S355JR EN10025	PL20	750.6215545	
PART	5c52ca48-0000-c7f7-3135-353032343135	PILAR	S355J0H EN10219	SHS300*16	722.2543001	
PART	5c52ca48-0000-b4f6-3135-353031333730	PILAR	S355J0H EN10219	SHS300*12	684.6180633	
PART	5c52ca48-0000-b539-3135-353031333732	PILAR	S355J0H EN10219	SHS300*12	684.2715444	
PART	5c263156-0000-028b-3135-343630313639	PILAR	S355J0H EN10219	SHS300*12	684.2136565	
PART	5c52ca48-0000-d0c7-3135-353032353736	PILAR	S355J0H EN10219	SHS300*12	683.7206011	

Spreadsheet: Recyclable
(Note: this a sample of the reported data, containing the list of recyclable objects)

Model file name: BY0089
File location: C:\Users\...\BY0089

OBJECT_TYPE	GUID	OBJECT NAME	MATERIAL	PROFILE	WEIGHT_NET	COMMENT
PART	5c46dcab-0000-15b1-3135-343832353236	TRELIÇA	S355JR EN10025	PL40	418.9264665	
PART	5c46dcab-0000-13cd-3135-343832343131	TRELIÇA	S355JR EN10025	PL40	418.4009597	
PART	5c52ca48-0000-022b-3135-343839343635	PILAR PRS P6	S355JR EN10025	PL35	406.5039648	
PART	5c52ca48-0000-00e5-3135-343839333632	PILAR PRS P6	S355JR EN10025	PL35	401.9096149	
PART	5c52ca48-0000-4bb9-3135-343934363133	TRELIÇA	S355JR EN10025	PL30	337.0757324	
PART	5c52ca48-0000-4b8c-3135-343934353734	TRELIÇA	S355JR EN10025	PL30	333.4052702	
PART	5c52ca48-0000-1588-3135-343932373937	TRELIÇA	S355JR EN10025	PL20	326.0534619	
PART	5c52ca48-0000-1496-3135-343932373539	TRELIÇA	S355JR EN10025	PL20	326.0533639	
PART	5c52ca48-0000-072b-3135-343839353932	TRELIÇA	S355JR EN10025	PL30	280.4223496	
PART	5c52ca48-0000-0734-3135-343839353934	TRELIÇA	S355JR EN10025	PL30	280.4223483	
PART	5c52ca48-0000-0245-3135-343839343734	PILAR PRS P6	S355JR EN10025	PL30	276.7815197	
PART	5c52ca48-0000-0242-3135-343839343639	PILAR PRS P6	S355JR EN10025	PL30	276.7560742	
PART	5c52ca48-0000-004c-3135-343839333238	PILAR PRS P6	S355JR EN10025	PL30	272.4963737	
PART	5c52ca48-0000-023b-3135-343839343636	PILAR PRS P6	S355JR EN10025	PL30	272.4963323	
PART	5c46dcab-0000-1585-3135-343832343733	TRELIÇA	S355JR EN10025	PL20	244.4522991	
PART	5c46dcab-0000-15b6-3135-343832353237	TRELIÇA	S355JR EN10025	PL20	244.4522537	
PART	5c2fa5fb-0000-4617-3135-343734383039	VIGA PRS14	S355JR EN10025	PL20	196.3259973	
PART	5c2fa5fb-0000-3fc2-3135-343734353832	VIGA PRS14	S355JR EN10025	PL20	196.0084522	
PART	5c331a40-0001-acdf-3135-343732323930	TRELIÇA	S355JR EN10025	PL20	187.6829907	
PART	5c3da4e2-0000-12cf-3135-343736353230	TRELIÇA	S355JR EN10025	PL20	187.6829797	
PART	5c2fa5fb-0000-5040-3135-343735343731	TRELIÇA	S355JR EN10025	PL20	183.8693634	
PART	5c331a40-0001-ad45-3135-343732333136	TRELIÇA	S355JR EN10025	PL20	183.8693477	
PART	5c2fa5fb-0000-3f7c-3135-343734353638	TRELIÇA	S355JR EN10025	PL20	180.0248682	

Spreadsheet: Disposable
(Note: this a sample of the reported data, containing the list of disposable objects)

Model file name: BY0089
File location: C:\Users\...\BY0089

OBJECT_TYPE	GUID	OBJECT NAME	MATERIAL	PROFILE	WEIGHT_NET	COMMENT
PART	5c52ca48-0000-6cf1-3135-343935363635	VIGA PRS14	S355JR EN10025	PL250*15	65.52416986	
PART	5c52ca48-0000-6d0a-3135-343935363638	VIGA PRS14	S355JR EN10025	PL10	56.74911695	
PART	5c52ca48-0000-2233-3135-343932393538	VIGA PRS14	S355JR EN10025	PL30	128.3239025	
PART	5c0e47ef-0000-0157-3135-343434343036	VIGA PRS20	S355JR EN10025	PL10	57.91686737	

Spreadsheet: Unassigned

(Note: this a sample of the reported data, containing the list of objects without an EOL_SCENARIO value assigned)

Model file name:	BY0089
File location:	C:\Users\...\BY0089

OBJECT_TYPE	GUID	OBJECT NAME	MATERIAL	PROFILE	WEIGHT_NET	COMMENT
PART	5c9e5ca3-0000-27ae-3135-353432393034	VIGA	S275JR EN10025	HEB650	0	
PART	5c8a2ae7-0000-e01b-3135-353330383234	VIGA	S275JR EN10025	HEB650	0	
PART	5c8a2ae7-0000-74c3-3135-353239323334	VIGA	S275JR EN10025	HEB650	0	
PART	5c6af4fc-0000-cacc-3135-353134353939	VIGA	S275JR EN10025	HEB650	0	
PART	5c6af4fc-0000-66c7-3135-353132373131	VIGA	S275JR EN10025	HEB650	0	
PART	5c1a6a06-0000-0144-3135-343532343133	VIGA	S275JR EN10025	HEB650	0	
PART	5c099fa8-0000-04fe-3135-343431333736	VIGA	S275JR EN10025	HEB650	0	
PART	5c6d4a8a-0000-2604-3135-353037353831	VIGA	S275JR EN10025	HEB650	0	
PART	5c6d4a8a-0000-82ba-3135-353038333634	VIGA	S275JR EN10025	HEB650	0	
PART	5c73bb10-0000-003a-3135-353131303234	VIGA	S275JR EN10025	HEB650	0	
PART	5c76cd26-0000-a165-3135-353133353738	VIGA	S275JR EN10025	HEB650	0	
PART	5c78f416-0000-0b1a-3135-353134333237	VIGA	S275JR EN10025	HEB650	0	
PART	5c6af4fc-0001-13cd-3135-353137323432	VIGA	S275JR EN10025	HEB650	0	
PART	5c8a2ae7-0000-325d-3135-353236363932	VIGA	S275JR EN10025	HEB650	0	
PART	5c8a2ae7-0001-209d-3135-353331373839	VIGA	S275JR EN10025	HEB650	0	
PART	5c9e5ca3-0000-9af4-3135-353437323239	VIGA	S275JR EN10025	HEB650	0	
BOLT_GROUP	5cb84a9d-0000-0f54-3135-353630303934	931-8.8			0	
BOLT_GROUP	5cb45ab9-0000-37db-3135-353535373536	931-8.8			0	
BOLT_GROUP	5cb458bc-0000-0449-3135-353535313238	931-8.8			0	
BOLT_GROUP	5cb458bc-0000-0458-3135-353535313330	931-8.8			0	
BOLT_GROUP	5cb45bb9-0000-3bdb-3135-353534393833	931-8.8			0	
BOLT_GROUP	5cb45bb9-0000-3ca4-3135-353534393838	931-8.8			0	