Computational modelling tools for the promotion of

DESIGN FOR DECONSTRUCTION

Master thesis
Anastasios Kokkos

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Computational modelling tools for the promotion of

"Design for Deconstruction"

Msc Graduation Thesis

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PREFACE

The current report is the result of a research that was concluded as a partial requirement for the completion of my post-graduate studies in Civil Engineering at TUDelft. The aim of the research was to promote the concept of Design for Deconstruction within the construction industry through the development of a parametric and associative toolbox. The development of the toolbox required at first the development and later on the implementation of a strategy that would expose the environmental and financial impacts of the concept of Design for Deconstruction.

The research was carried out under the aegis of the BEMNext Laboratory of the Faculty of Civil Engineering and Geosciences of TUDelft. BEMNext Laboratory is focused on the development of software tools and platforms for the support of design and engineering processes including fields like Building Information Modelling, advanced geometry and design systems, optimization algorithms, data management, sustainability and others for the next generation of the Built Environmental Modelling (BEM). (http://bemnext.org)

During my research I had the lack to be supported by people who showed trust in me and encouraged me in every step I needed to take both in academic and moral level. I need to thank specifically the head of my committee Prof. Dr. Ir. E M Haas for his support and useful insight on the main topics of the research. Also special thanks to Dr. Ir. J Coenders and Ir. A Rolvink who were my daily supervisors and the reason I decided to step into the field of software development and parametric and associative tools whose insight, knowledge and guidance allowed me to complete this research. Also I need to thank Ir. J P Hollander who provided me with information and instructions that became a drive for the completion of this research and for his special interest on my progress. Finally I would like to thank Dr. E Durmisevic from the University of Twente, who accepted to be in my committee and provided me with a valuable insight on the topic of Design for Deconstruction and guidance through out the process that added a significant value to the final product.

I also need to thank my friends and classmates, Veronica, Alex, Dion and the rest of the BEMNext Laboratory team who walked on the same path with me and made every part of this process look easier.

Also all of my friends and each one of them seperately, whose presence in my life and support make every step I take possible.

Most important I need to thank my family whose unconditional love and support through my life brought me here and whose values and ethos made me the person I am. Nothing would be the same without each one of them in my life.

Last, a special thanks to Achilleas who was my mentor and supporter in the unknown for me path of development.

Delft, March 2014

Anastasios Kokkos

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MOTIVATION

During my research in order to end up with a thesis topic that would cover my personal interests both in structural and building engineering and definitely including aspects of sustainable development, Design for Deconstruction came up as a unique field to focus on.

The potential environmental benefits that the concept of deconstruction and reuse can bring along with the fact that it is a topic that seems to be on the limelight for many years, fluctuating from low to high importance depending on the period and the place, made it specifically interesting as there are no indications that it has ever been fully deployed by the construction industry. Despite the fact that within the same industry one can meet perfectionism in many theories and especially those focused on technical details and lately on technics that enhance the efforts for a sustainable industry, DfD seems to be constantly ignored. There are some bright examples popping out like the centre Pomidu in France where Deconstruction was the main axis of interest and was achieved to high level. But also these example were not aiming to just achieve this goal but to become examples and starting points for a shift of approach in the whole industry regarding what a structure is, why it is built for and how one can build for deconstruction.

As time proven so far though the utter goal of those involved in these projects was never achieved despite the fact that they managed to prove the benefits of their action not only in financial terms that could on its own be a robust reason for a shift, but in every level of influence that a structure can have.

The main question in a personal level was how can we as engineers overcome these obstacles and take actions in order to promote DfD and benefit from its positive effects. As the technical difficulties never seemed to be an obstacle in any engineering challenge so far the question becomes what should be addressed in order to convince people to design and most important live in structures designed to be deconstructed.

The main motive behind this research project is the fact that if we aim for a sustainable world we have to be able to give up all these habits that brought us to this position, but for a good reason. So if there is a need to deploy a strategy that will form a better world for tomorrow then there is a need to quantify the benefits of this strategy in an understandable form and provide the right tools to those involved in order to put it into practice.

The benefits so far are measurable as there is an extensive and multilevel on going research but there is not a formed approach that will not only sum up the benefits but will also quantify and expose them in a way that will convince the designers to make a step and deploy those technics required to apply DfD and make it part of the basic requirements of any structure.

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SUMMARY

Design for Deconstruction (DfD) is "**the design of buildings to facilitate future change and the eventual dismantlement (in part or whole) for recovery of systems, components and materials. This design process includes developing the assemblies, components, materials, construction techniques, and information and management systems to accomplish this goal.**" (B. Guy et al., 2006).

Introduction

This Master's thesis is focused on the ambiguous topic concept of Designing for Deconstruction and its application within the construction industry. The aim of the research is to investigate the feasibility of the concept by pointing out the main topics of interest that could influence its overall performance and propose a strategy that will assess the environmental and financial performance of the concept when applied on a new design. The strategy will also propose a scheme for utilization of the concept for managerial purposes. Furthermore, the main objective is to implement the proposed strategy into a computational modelling toolbox based on the principals of parametric and associative design. The toolbox will provide assessment of the various factors which could affect the early design stage of a project, aligning with the main requirement of Designing for Deconstruction that is to be applied in this preliminary stage of a design process.

Problem definition

The concept of Design for Deconstruction (DfD) has several, diverse benefits if applied on a building level. Despite these potential benefits and even though the construction industry is constantly trying to reduce its environmental impact, DfD is ignored with the exception of very few cases. Although DfD is technically feasible, the diversity of the designs, the multiple parameters that can influence the efficiency of the concept and its low-paste nature discourage the industry from deploying it. This lack of deployment is accompanied by a lack of standardise procedures which could assist the assessment of the impacts DfD could bring. The lack of infrastructure and the scarcity of software tools (for simulating & calculating purposes), which could support it on a managerial level and for purposes of supply chain improvement also makes it harder for deployment.

However, the implementation of a structured strategy that would allow the quantification of the potential benefits of DfD, through a computational modelling tool during the early design stage of a project, could provide the motives to the construction industry to deploy DfD. Finally, the use of such a tool could provide better understanding of the parameters that influence the efficiency improvements which result from the concept and could prompt the efforts of the designers to utilize this methodology.

Research methodology

The research was driven by two main objectives and was carried out in two respective phases:

- During the first phase the research focused on the formation of a strategy that could quantify the environmental and financial impacts of the application of the concept of DfD for building design and could support it on a management level.

- The second phase of the research is focused on the practical implementation of the proposed strategy through the development of a computational modelling tool for the early design stage of a project, based on the principals of parametric and associative design.

Results

The proposed strategy follows a set of steps that aim to highlight the potential benefits of DfD. The strategy is constituted of four main steps:

1. The conduction of a life cycle analysis (LCA) in form of Environmental Product Declaration (EPD) for the initial design.

2. The conduction of EPDs for two scenarios: (i) the initial building is demolished, recycled and replaced by a new identical one and (ii) the initial building is deconstructed and replaced by a new building constructed by the reclaimed components.

3. The financial assessment of these two scenarios is then evaluated.

4. The results and design related information are exported to spreadsheets in support of the creation of a management system for the facilitation of the concept based on the scheme proposed by Fujita (Fujita et al., 2008) described in Section 3.1.6.

The implemented strategy is currently focused on the structural frame of steel buildings as a proof of concept but it can be applied to any construction material in the future.

The DesignforDeconstruction toolbox is developed in the form of a plug-in for Grasshopper3D, a graphical algorithm editor integrated into Rhino3D's modelling platform. It is able to provide real time feedback on the design choices of the user and the variation of the parameters that influence the efficiency of the concept of DfD on the design under assessment.

Conclusions

The strategy developed in the current research provides a framework for the assessment of the impacts of DfD following a process that encapsulates all the different parameters that may influence the efficiency improvements that the concept yields on the applied design. The implementation of the strategy into a toolbox allows the users to apply the strategy directly on their designs, exempting them from the task of researching and forming a methodology themselves for every new project which is usually one of the main reasons that DfD is not taken into consideration.

The implementation of the proposed strategy in a toolbox for the early design stage of a project allows the users to assess their design options and decide if the implementation of the concept is beneficial for their project at a stage where DfD can be applied without significant impacts on the time schedule and budget of the project.

The parametric and associative nature of the toolbox offers the possibility to simultaneously model and get feedback on the design options, exempting the engineers from the process of assembling labour intensive models and manually performing repetitive calculations. The translation of the parameters that influence the concept of DfD to input factors through the toolbox allows the users to understand their gravitation within the concept and to make informed choices based on this fact. Finally, the assessment of the financial impacts and the exportation of the results and relative design details to spreadsheets, creates a platform for a management system that can support the concept of DfD on a supply chain level and can provide an incentive for the stakeholders involved in the project. As of today, the lack of such infrastructure seems to be a discouraging factor for investment on the concept.

The application of the strategy on a case study proved that the environmental gains of DfD are significant for every indicator related to the environmental impacts of a design. The same results were noted also regarding the financial impacts that the concept of DfD although these results can differ depending on the market conditions.

The developed toolbox can be considered as a prototype and a proof-of-concept as the implemented strategy is subject to further research. It can be enhanced with more detailed information regarding the environmental and financial impacts of the demolition and deconstruction process while the export of the results to a central database will provide a more solid approach for the creation of the proposed management scheme. The strategy though aims to produce results based on the comparison of two scenarios and as such, the results can be considered suitable for the conceptual design stage while the proposed export to Excel spreadsheets can be considered a starting point for further development. Finally, the modular set up of the toolbox offers the foundation for further extension and enhancement of its functionality based on specific design requirements.

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‘since products are essentially carriers of services, the trick is to find ways of delivering the service without wasting the material carrier’

(Ayers 1999)

1 Introduction

This chapter is an introduction to the main topics of this Master's thesis that will form the basis for the upcoming research. These topics will be part of the definition of the research's objectives and questions and as such will be referred back to in the following chapters of the report.

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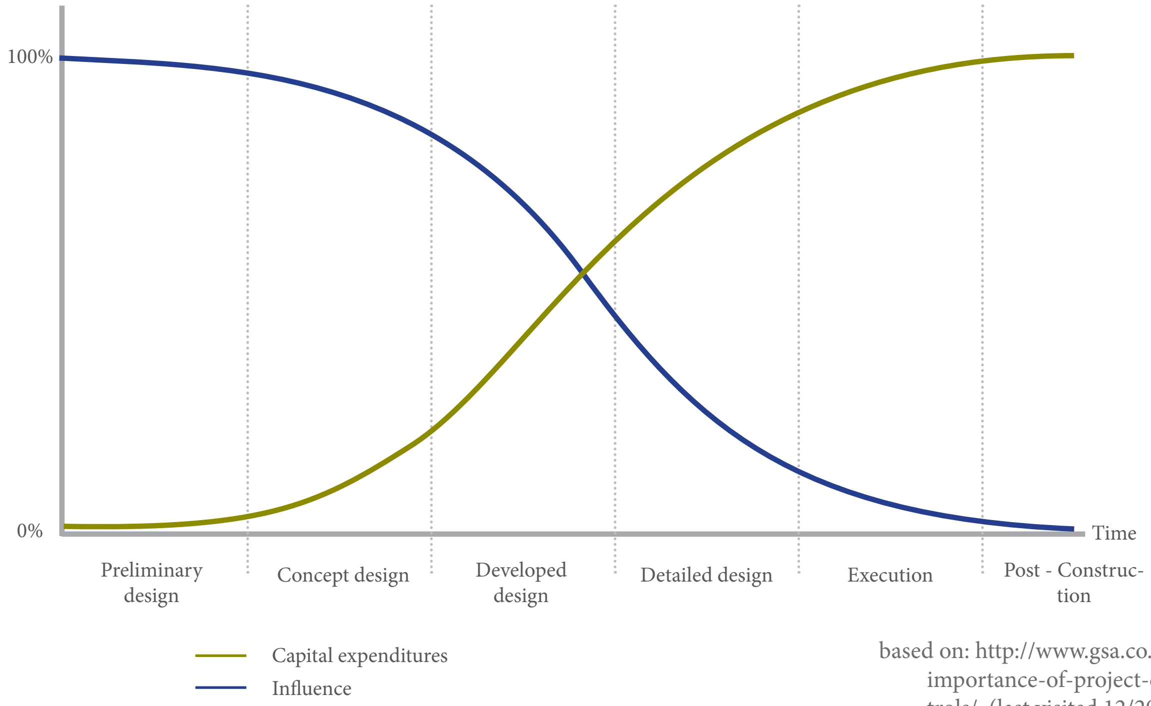
1.1. The importance of early design stage

Every construction project is being developed under a specific sequence that is guided through specific stages. Each stage has specific requirements concluded in tasks, updates, and key considerations and are formed as follows:

1. Preliminary design stage
2. Concept Design stage
3. Developed design stage
4. Detailed design stage
5. Execution and Construction stage
6. Post Construction stage

In each of these stages there are different parties of the construction industry involved that influence the project from a different perspective. The involvement and influence to the final product though changes gradually as the project progresses. The degree of influence and the impacts of changes caused expressed in capital expenditures are directly connected and progress through the project stages with an opposite rate as shown in Figure 1.1.



based on: http://www.gsa.co.uk/importance-of-project-controls/ (last visited 12/2013)

Figure 1.1. Influence and cost expenditure relation through a project's realization stages

The early design stage of a project includes the preliminary and the concept design stage. During the preliminary design stage the conceptual outline of the project is being developed. The requirements of the client are starting to get in shape through different conceptual models that are being revised through a dynamic process of collaboration among architects and engineers of different disciplines. This process results to continuous adaptation of the initial design through a repetitive cycle till the requirements are optimally met.

The concept design stage is following the guides provided by the first stage. Though the designer still posses a significant amount of freedom and design choices the information available that could get these choices in line with the final requirements is missing. The relation between the available information and the design freedom through this stage is shown in Figure 1.2.

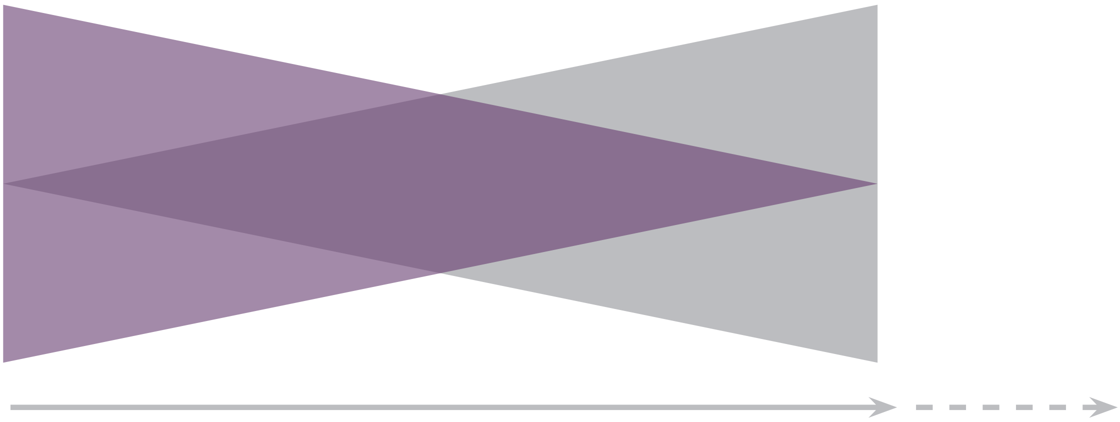


Figure 1.2. Design freedom in relation to amount of information available (Coenders, 2011)

Despite the lack of information though the final concept design will have a high impact on the design and in return on the execution phase of a project. For these reasons it is crucial for the total performance of the project that the decisions made at this stage are viable in the extend that is currently possible. Though the quantification of the impacts of different design option at the early design stage might not be efficient or possible the understanding of the relations between different design parameters and their impact on the later stages of the project is crucial as the adaption of changes after the completion of the early design process is much more expensive and sometimes prohibitive.

1.2. Environmental Product Declaration (EPD)

Environmental Product Declaration referred as EPD (NEN-ISO-14025) is as particular type of Life Cycle assessment developed to provide analysis results from LCAs in a common and understandable format. EPDs are based on Products Category Rules (PCR) that help ensure the transparency and robustness of the provided results. PCRs for construction products are developed from countries like UK, Germany, Australia and Scandinavia amongst others.

The conduction of Life Cycle analysis and in return the implementation of the results into EPD formats is an optional process for the construction industry and is usually adapted by manufacturers of products that want to expose the environmental impacts of their products preferably as a marketing tool. EPDs though are gaining more and more grounds within the industry as they can reveal the impacts of a construction through its whole life cycle including the end-of-life scenarios that introduce the potential benefits that can derive from recycling or reusing the product/building under assessment. They are conducted though through a difficult process that need analytical description of the followed steps and of the boundaries of the system under assessment, that is usually difficult to define as every product has developed relations with multiple systems around it.

An EPD offers the chance even to a no LCA expert to understand the impacts of a product/system. EPDs though are developed after the design phase of a project has been developed examining in essence the impacts of the design choices and not the product itself. The development of a preliminary form of EPD during the early design stage of a building can bring significant input to the designers regarding the impacts of their designs and can play a definitive role in the final design choices resulting to more environmental friendly outcomes.

1.3. Parametric and associative design

Parametric design is the setting of models, constituted of objects that are defined by a series of items based on variable parameters. These objects are related through a series of associations that are subject to change and can be adjusted any time in the design process. Working with parametric models in software tools will allow the user to define, adjust and evaluate design alternatives in order to understand the impacts of different design choices.

SInce parametric design was introduced to the engineering world the main CAD platforms have turned their interest in this direction. As a result of this shift there are many programs offering the possibility of parametric design through their interface. One of them is Grasshopper3d, a plug in for the 3D modelling tool Rhino developed by McNeel. Grasshopper3d is an interface for the use of a set of algorithms connected with diverse relations defined by the user in order to define a parametric model. The model in return is graphically represented in Rhino's environment allowing the users to exploit the benefits of parametric modelling and the power of generative algorithms without the need of having the knowledge of a developer. The algorithms are represented through components and the relations are built by connecting the output of a component to the input of the next one. The representation of the outcome geometry is shown instantly in Rhino's interface along and the user can experiment with different forms and ideas by only changing the values of each parameter after the relations have been defined.

1.4. Shadow prices

Shadow prices are "*constructed prices for goods or production factors that are not traded in markets*" such as environmental quality. (Shadow Prices Handbook, 2010).As such shadow prices indicate the value of a good to society. They can be assigned to emissions, environmental quality, toxicity and other impacts and are used in various applications such as cost-benefits analyses or comparison of the magnitude of different environmental impacts. Shadow prices can be used as weighing factors to translate the results of life cycle analyses into uniform figures. The concept of Shadow prices was developed by CE Delft and are used in an official manner by government and industry.

1.5. Computational Modelling and SustainabilityOpen framework

Computer-aided design (CAD) is the use of computer systems to assist in the creation, modification, analysis, or optimization of a design. CAD software is used to increase the productivity of the designer, improve the quality of design, improve communications through documentation, and to create a database for manufacturing. (http://en.wikipedia.org/)

Especially though during the last years there is a shift from Computer Aided Design (CAD) to Computational Design. Computational Design is the simulation instead of representation of objects where crafting is being supported by computational processes created by the designer-developer. Lately it has been widely developed as more and more power is shifting from the software companies to developers. This shift is mainly caused due to the fact that there are several software platforms that can be enhanced and support development from individuals using widely used programming languages such as C#, Python etc.

Driven by this mentality and in an effort to explore the future of Building Information Modelling (BIM) that will potentially be transform to Building Environmental Modelling (BEM) in the engineering world, BEMNext laboratory (http://www.bemnext.org) of the Civil Engineering and Geosciences department of Delft University of Technology is providing an open-source framework under the incentive of "sustainability - open" (http://www.sustainability-open.com) for students and any interested third party to develop their own tools in order to promote any idea related with sustainability in the built environment.

In Figure 1.3 one can see the general framework of SustainabilityOpen incentive where designers can input their components - plug-ins mainly developed for Grasshopper3d using the programming language C# within Microsoft Visual Studio.

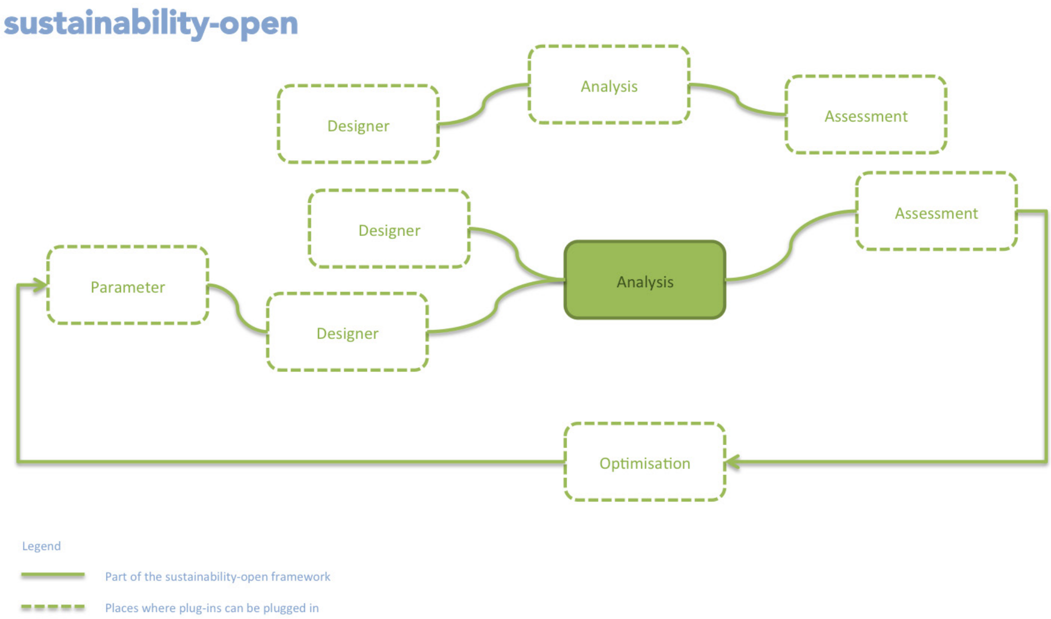


Figure 1.3. Sustainability-open framework (http://www.sustainability-open.com)

The framework consists of a number of abstract classes called components, which need to be overridden in order to do something. There are three types:

Designers: Designers produce a 'design' on which the analysis and assessment components can work.

Analysis components: the analysis components take in a number of design components that aggregated contain the design and perform one or more analyses on the design. The analysis components produce an output for assessment components to use. An example could be an analysis that adds up all materials into their total quantities.

Assessment components: The assessment components take a number of analysis outputs in and perform one or more assessments to produce an assessment result. An example could be an assessment that calculates the total embodied energy in the design from the material quantities. (http://www.sustainability-open.com)

2

Problem definition and Research objectives

This chapter is an introduction to the research that will be presented. A general description of the problem is given along with the different parameters that influence the research and form its boundaries. The main and sub-questions that will drive the research are formulated followed by the definition of the scope. Finally the approach and development of the research methodology is presented.

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2.1. General Problem description

The buildings' legacy of the 20th century has been one of waste and toxicity. The construction industry as we know it is one of the most unsustainable industries due to its contribution to climate problems (B. Guy et al, 2003). Construction of buildings plays a significant role in land and raw material consumption plus generates a great amount of waste before during and after its completion. According to data from the Worldwatch Institute, the construction of buildings consumes 40% of the stone, sand and gravel, 25% of the timber and 16% of the water used annually in the world. (Arena and de Rosa, 2003). Considering these numbers and the fact that for example in European Union only construction, use and demolition of buildings contribute almost 50% to the total CO_2 emissions released in the atmosphere every year, one can conclude that there is an urgent need for action. (Dimoudi and Tompa, 2008).

This urgent need, that is already on the top of the priority list of every stakeholder's agenda for diverse purposes is to build "green". Building "green" though is focusing mainly on lowering operational energy demands or improve indoor quality and in return often material selection is playing a secondary role. Materials' sciences on the other hand are pushing through more sustainable solutions producing more environmental friendly products made from materials such as bamboo, recycled glass, wood etc. The Building industry deploys progressively these new material as their low environmental impact reflect directly to the total impact of any project. This deployment though seems to follow the traditional approach of linear consumption and fit for purpose idea where every material is produce to serve one purpose and after its use is disposed regardless if it reached the end of its technical life-cycle. A shift though from linear to circular consumption, where the products instead of disposed would be reclaimed and reused either for the same or for a different purpose would result to a better outcome concerning the total environmental impact of a project and in return of the construction industry as a whole.

This shift can be facilitated by the concept of Design for Deconstruction (DfD) and is a process that needs to be addressed in an early design stage and not decided after the end of life of a structure. Components or assemblies that are not designed for this purpose are most of the times mounted in a way that cannot be reclaimed intact or might contain hazardous materials that state it dangerous for the health of those involved in the reclamation process.

Re-use of building components means that there is no demand for new resources nor energy for the production of new elements or demolishing and recycling/disposing the existing ones stating DfD as one of the most efficient processes in terms of sustainability.

2.2. Problem Formulation

Re-use of components, despite the benefits that it may arise, is constantly ignored by the construction industry. Reclamation of components in a state that they can be reused to serve another purpose during their technical life-cycle needs to be addressed in the early design stage of a project as there are certain design strategies that need to be followed for the composition of materials, components and systems that will form the final construction. Despite the fact though that these design strategies are already known and in certain cases applied with success designers are discouraged to take them into account in any stage of the design phase as they will need to invest time and energy and even re-configure the initial design in order to form a deconstructable structure.

Besides that, reclamation and re fabrication industry is still suffering from lack of infrastructure and missing economies of scale (Geyer et al. 2002). To add to this problem, lack of standardization and building legislation for re-used construction components along with the mistrust of users regarding the integrity and safety of the reclaimed material are not encouraging designers to steer their efforts into Design for Deconstruction strategies.

Finally the lack of perspective for potential future uses of a structure or of its components creates a big disadvantage for any designer that will try to integrate DfD in a design. This mainly rises from the fact that buildings are constructed to serve a purpose for a specific time-frame and there is no scenarios for potential reuse after the end of their functional life-cycle. So after use, material and components end up to landfills, wasting this way a significant part of their technical life-cycle as in most cases exceeds the functional life-cycle of the structure they were used on.

So one can conclude that despite the established benefits of Design for Deconstruction and re-use, designers are lacking of incentives in order to start taking DfD into account as a standard requirement in their designs in the early stage of a project. In one hand the lack of knowledge and infrastructure to support an easy implementation and on the other hand the lack of direct and comparable results between conventional design and DfD regarding environmental and financial criteria which would give incentives to the designers to adapt DfD strategies, is forcing construction industry to ignore probably the most effective solution in order to become sustainable and eliminate its impact on resources exploitation.

Product	% Reused	% Recycled	% Lost
Heavy structural sections/tubes[1]	7	93	0
Rebar (in concrete superstructures)	0	98	2
Rebar (in concrete sub-structure or foundations)	2	95	2
Steel piles (sheet and bearing)	15	71	14
Light structural steel	5	93	2
Profile steel cladding (roof/facade)	10	89	1
Internal light steel (e.g. plaster profiles, door frames)	0	94	6
Other (e.g. stainless steel)	4	95	1
Average (across all products)	**5**	**91**	**4**

Figure 2.1. Reuse, Recycle and Losses rates of steel products in construction industry[http://www.steelconstruction.info/]

In Figure 2.1 one can see the reuse, recycle and losses rates of steel products in construction industry where it is obvious that recycling is the ruling process among any other placing steel as one of the most sustainable materials among the industry but still reuse will have a much more efficient outcome if deployed in equivalent rates.

Once designers and involved parties decide to take DfD into consideration and apply it as a requirement in any project with predefined life-cycle the industry will be forced to adapt to this new market in order to meet the new needs that will be created. In order though for this to happen, part from a targeted education that is needed to create a solid knowledge base where designers will be able to rely on for technical knowledge and will provide a basis for trust regarding re-use of existing elements, there is a need that DfD strategies are following the constantly developing Computational Modelling and software industry and vice versa. This follow up is needed as despite the fact that CAD industry has developed very powerful engineering design and analysis software for every field along with multi- disciplinary platforms like Building Information Modelling (BIM) that facilitate the design of all the technical aspects of a project, including the data that follow them, not much are being done so far for the field of deconstruction and how it can be implemented in this modelling process.

Before reaching the detailed modelling levels that other aspects of engineering have reached with the aid of CAD tools it is important to demonstrate the benefits of deconstruction to convince engineers and involved parties to proceed to a detailed design for this purpose. In order to do so there is a need to provide designers with tools that will indicate them in an early design stage, through an easy and understandable way, overcoming the existing hectic processes that they need to apply in order to quantify and understand the impacts of such an action on their design. It is also important at the same time to demonstrate the ease of building a structured management system that can facilitate the process from the early design stage till the end-of-life and deconstruction of the structure as only in this case the concept of deconstruction will be promoted not only from the designers but also from the involved stakeholders who need to be sure that such concept can be facilitated by a structured market in order to promote it.

Summarizing, the problem can be defined as follows:

Despite the benefits that the concept of designing for deconstruction can bring it is constantly ignored by the construction industry. The lack of application brings along a lack of simulation tools that could address the concept of deconstruction in any extend as the lack of market demotivates development in this direction stating the quantification of the benefits of such a process and the formation of a basis of a management system that could support it and force the industry to deploy it almost impossible.

2.3. Research objectives

Currently the market is lacking of tools that can support the concept of Design for Deconstruction stating the process difficult to understand and quantify. Before moving into detailed designs and strategies it is important to promote the benefits of deconstruction in an early design stage as it is a concept that needs to be addressed from the very beginning of a project in order to be realized as the design freedom and the high costs of changes during a later stage are restrictive. It is also important for the involved parties to understand that a formation of a structured scheme for the management of the information that follow the process is not a complicated issue and can be solved if DfD is decided to be deployed.

As such the research objective of this research can be formed as follows:

"To develop a strategy that will demonstrate the benefits of designing for deconstruction in comparison to a conventional design in an early design stage and to form a basis for the formation of a management system that will support the concept in a wider sense by exploiting the potentials of parametric and associative design"

In order to demonstrate these benefits and provide a basic framework to facilitate the process of design for deconstruction from the early design stage of a process the aim of the research is to incorporate the demonstration of these benefits and the means to build the missing management system into a design tool that will be easy to handle and will provide results easy to understand and exploit. So the main research objective is becoming:

"Develop a software tool for the early design stage that will assess the benefits of Design for deconstruction regarding its environmental impacts and costs and will support the formation of a management system that will facilitate the process."

The tool will primarily focus on the assessment of environmental and financial benefits of steel structures as they provide multiple benefits that can ease the process of deconstruction as it will be explained further on this chapter. The scope of the tool can thus be expanded to any kind of structure promoting DfD in a wider sense if the outcome of the assessment shows that is actually beneficial to do so.

2.4. Research Questions

This research is focused on the development of a strategy that will state possible to assess the benefits of the concept of deconstruction and will provide incentives to the construction industry to deploy this concept through the implementation of the strategy in a software tool based on parametric and associative design. The broader aim is to extend the functional life-cycle of structural components rather than disposing or recycling them saving this way valuable energy and resources and contributing to a more sustainable outcome for the construction industry. In order to develop a sound strategy it is important to identify the setbacks that keep deconstruction from flourishing and provide results that will actually act as incentives to this direction. In order to do so the research will be driven from a range of questions that will lead to the desirable results and give a better insight to the reader regarding the initial drive of this research. These basic questions are formed as followed:

Background research

- Which are the main setbacks that are discouraging construction industry to deploy Design for Deconstruction despite its benefits?
- What are the benefits of steel structures in the concept of designing for deconstruction?
- What are the existing assessment methods for recycling and reuse of structural components?
- Which are the benefits of DfD in comparison to the recycling model that is developed in an extended manner within steel construction industry?

Assessment of design options

- What is an Environmental Product Declaration and how can a deconstruction and reuse scenario be implemented in this concept?
- What is Embodied Energy and Embodied Carbon and how are they interpreted as indicators of environmental impacts?
- What are shadow costs and how can they be used in the content of design for deconstruction

End product

- How can the impacts of the design alternatives provided by the user be quantified and presented encapsulating the concept of Design for Deconstruction?
- How can the benefits of deconstruction in comparison to conventional building routes be assessed?
- How can the concept of Deconstruction be supported in a management and supply chain level that will state it feasible in extended manner?

2.5. Scope

Design for Deconstruction is a process that involves many parties in multiple levels of a project and through its whole life cycle, including of course the end of the functional life of a project that might happen after 20 or more years. In these terms it was a challenge from the very beginning to narrow down and target specific parties as history so far has proven that in order to create a feasible strategy for the deployment of DfD one needs to ensure that all the involved parties will be motivated enough to collaborate for this wide and long term goal. To add to this complexity DfD is arising special requirements, benefits and approaches depending also on the construction materials that are used each time. So the scope of this thesis had to be defined from two diverse factors. The parties involved and the construction materials that will be referring to.

Regarding the target group, as already mentioned, it would not be wise to explicitly refer to one or two involved parties as for example if architects and engineers are convinced for the benefits of DfD and the stakeholders are still not willing to get involved then DfD will still remain a 'plan to be realised'. This fact forced the scope of the research to be wide enough to meet every involved party's interest. In brief these are:

- Stakeholders
- Contractors
- Designers
- Civil engineers
- Supply chain

During the literature study of the next chapter there will be a detailed explanation of how this research's final product will address all these incentives required to convince each of the above mentioned parties to a certain extent in order to promote DfD by communicating its benefits in every level.

In order to narrow down and define the limits of the research the choice of a construction material suitable for deconstruction was necessary. Prefabricated concrete elements, timber and steel structures are the most suitable for deconstruction as by definition all three are results of preformed elements fixed together in a specific sequence. The technical details though are widely diverse making each material unique and of special treatment in terms of deconstruction technics. Steel structures, as will be analysed further in the next chapter, are chosen as showcase due to the potentials of steel for reuse and its particular interest as it is considered as the most sustainable in the market due to the fact that almost 95% of the existing steel components are subject to recycle after the end of its functional life cycle. The challenge is to explore the benefits of reusing instead of recycling the material as recycle is also an energy demanding process and the technical life-cycle of steel components are usually much longer than the functional life-cycle; a fact that states steel as a very suitable material for reuse. Far from that, steel structures are usually following a specific construction sequence with connections that are modular and easily reached. In addition steel is used as construction material for industrial and commercial building that are subject to frequent change in terms of function and DfD could be applied and result in a very efficient technique to facilitate these changes.

So steel is the selected material to focus on for further analysis but the aim is to showcase the approach and understand the benefits of DfD so to be able in the future to apply it to more material and broaden the scope of the tool.

2.6. Research Methodology

2.6.1 Research process

The general layout is consisted of three parts that will be distributed within three stages during the research. The three parts are:

- Background research
- Technical study
- Tool development

Each of these parts will be conducted of sub-chapters where the general idea, the results of the literature study and the way these results are taken into account for the strategy and tool development will be explained in detail.

The development will be realized in three stages as described above:

In Stage 1 a background research will be conducted in order for the researcher to understand and analyse the existing situation. During this stage the existing approaches regarding DfD will be analysed and an effort will be made to understand the reasons that prevent construction industry to adapt DfD despite its benefits. There will also be a focus and analysis of projects that have been realized under this purpose to identify the benefits and setbacks of DfD. Finally the research will focus on the analysis and registration of existing elements, components and connection of steel structures that best fit the purpose of DfD in order to provide the users with an insight that will improve the performance of their design.

During Stage 2 of the research the findings from the first stage will be connected in order to form a sound strategy for the assessment of the benefits that the concept of deconstruction can bring. During this stage there will also be a focus on current environmental impact assessment methods in order to identify and implement the most suitable one in the developed strategy. The suitability of the process will be weighted not only regarding its efficiency but also regarding the directness of the provided results and their reflection to different stages of a building's life cycle. Finally there will be an analysis of existing management schemes for the overall facilitation of the concept of DfD and the ways these management schemes could be support by the developed strategy.

Finally Stage 3 will be devoted to the development of a parametric and associative tool that will implement the developed strategy and will provide the intended users with a tool that will state the assessment of the process feasible in the early design stage of the project.

The research will be concluded with the validation of the developed tool using a case study of a design by assessing and demonstrating the results.

The research and report sequence is presented in Figure 2.2.

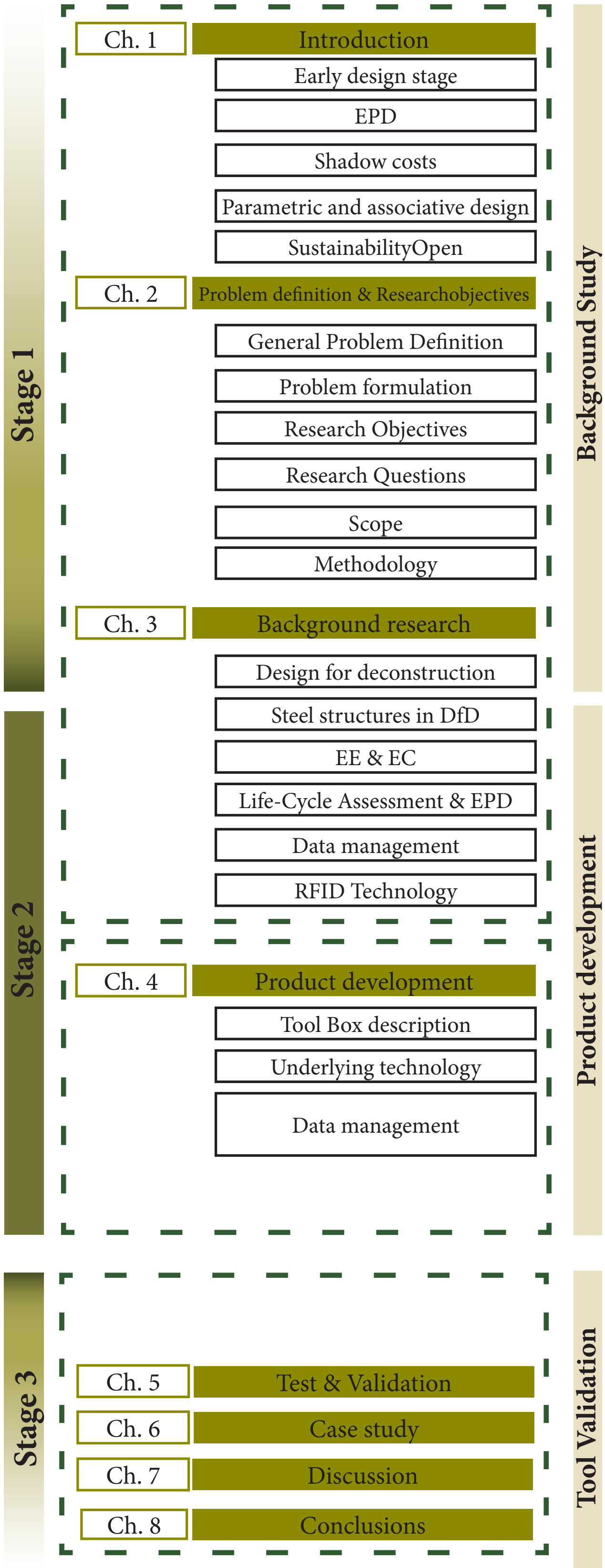
2.6.2 General approach

This research is being conducted in order to carry out results that will be used as an input to develop a product that will support the discussed topic. The research deals with a concept that has undergone deep investigation but lacks of implementation in the design cycle. So the question is not anymore focused on what is Design for Deconstruction or why is not implemented but how one can provide those motives needed in order all the involved parties to understand its benefits, quantify their profits and be convinced in return to get involved so DfD is fully deployed.

In these terms the research will relay on existing scientific research and practices and the effort will be mainly put on defining methodologies for the assessment of the environmental impacts and benefits that deconstruction can bring and implement them into a software tool that will be used in the early design stage of any project.

2.6.3 Report structure

The report will be consisted of 7 chapters. The chapters will be developed as described in section 1.9 and will follow the structure shown in Figure 1.5.



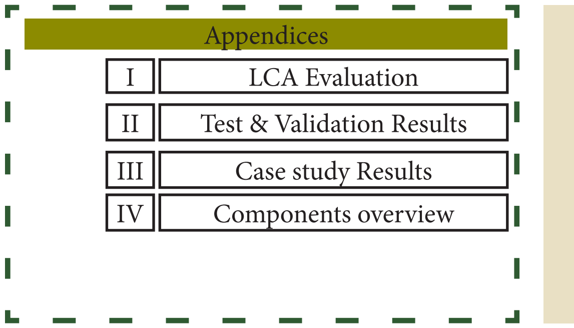


Figure 2.2. Research methodology and report layout

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3

Background Research

The next chapter will give an overview of the background research. An analysis of the aspects of deconstruction and how it is applied within construction industry is presented, followed by an insight to the potentials of steel structures in the content of DfD with a synopsis of the most recommended technics that can facilitate it. Far from these two areas of focus an overview of Life-Cycle analyses approaches regarding recycle and reuse along with a description of embodied energy and carbon assessment methods for constructions and how these are implemented in the strategy under development

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3.1. Design for Deconstruction (DfD)

3.1.1 Deconstruction and sustainability objectives

Design for Deconstruction (DfD) is "*the design of buildings to facilitate future change and the eventual dismantlement (in part or whole) for recovery of systems, components and materials. This design process includes developing the assemblies, components, materials, construction techniques, and information and management systems to accomplish this goal.*" (B. Guy et al., 2006).

DfD borrows principals from the fields of design for disassembly, reuse, remanufacturing and recycling from the consumer products industries as they have adapted this philosophy in an extended manner and in different products beginning from printers and ending up in automotive manufacturers. And although a building is not considered typically a "product" it is composed from materials, connections and components and is created through collaboration of people from various disciplines. The end products of this collaboration are residential or civil buildings of significant value for society providing shelter and comfort to humans to accommodate their needs as a craftsman product would, respectively. Due to this importance to society and enormous effect to resources utilization all the parties involved in making construction industry sustainable to the extend of resources exploitation must consider their sustainable management flow during the entire life-cycle of constructions from extraction, to manufacture, to construction, to use, to re-use till the end of their technical life-cycle. In order though to reach the technical end of life-cycle there is a need to shift to DfD as in most cases, like for example the structural components of a building are reaching the end of their functional life-cycle and are disposed as waste where in fact the resources included in the components haven't lost their initial properties and could be reused for the same or another purpose.

Designing a building to be deconstructable is a feature that can enhance the efforts for a sustainable future. The buildings are currently perceived as permanent and fixed structures but shifting to a perception of buildings as something transformable, temporary and open will turn them into resource banks for future use allowing this way the elimination of resource exploitation.(Durmisevic, 2006) At the same time there will be a significant reduction of CO_2 emissions as the deconstruction processes demand significantly less energy than recycling or demolition and re-manufacture of new components as will be discussed in detail in Chapter 4.

3.1.2 DfD and the theory of 3R's

In May 2008, during a G8 meeting in Kobe the initiative of 3R's (Reduce, Recycle, Reuse) was adopted as the main objective of the meeting related to climate change. The plan 3R's has three main goals that are constituted by many different associated actions all related to the final goal of resource efficiency. The three main Goals and main actions related to resource efficiency as described in Kobe's 3R action plan are:

1) Prioritize 3R's policies and Improve Resource Productivity

2) Establishment of an International Sound Material-Cycle Society

3) Collaborate for 3Rs Capacity Development in Developing Countries

(Kobe 3R Action Plan, 2008)

As derived by this directive Design for Deconstruction is one of the main strategies that needs to be introduced in order to help construction industry comply with it. The main 3R's initiative is to take action in order to prevent waste production. Once waste reduction was at the top of the waste hierarchy but gradually it has been overlooked as waste prevention has come first in both resource efficiency support and governmental policy sustainability agendas. In these terms DfD fits the purpose of waste prevention as the reclaimed components/material/resources are not perceived as waste but as resources that enter back in the cycle of construction preventing in the most efficient way the waste production.

In Figure 3.1 one can see the waste hierarchy in accordance to levels of sustainability achieved as described in CIBE's guide "Waste Reduction around the World" (CIBE publication 364, 2011).

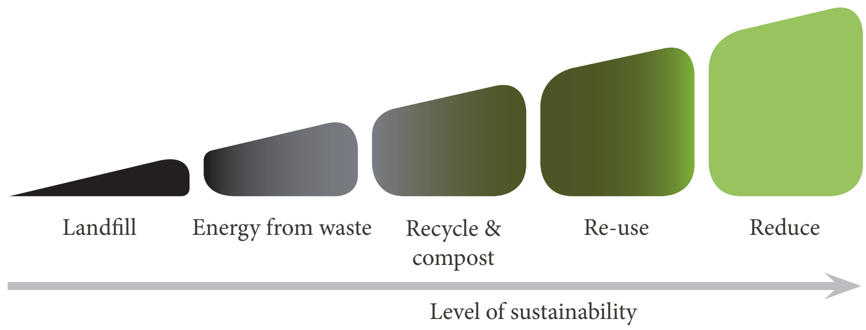


Figure 3.1. Waste hierarchy (source: CIBE, 2011)

3.1.3 Deconstruction methodologies

There are several researches focused on identifying these basic steps that would state DfD more sound and easily approached and applied. The diversity of constructions in terms of materials, typologies and use though makes it really difficult to form generalized guidelines.

According to Rose, et al, two of the most critical factors in predicting the end-of- life path of products are wear-out life and technology cycle (Rose, 1998). According to Billatos and Basaly, the main criteria for examining a product for increasing its assembly efficiency is to reduce the number of parts and to reduce the amount of time required for assembly (Billatos and Basaly, 1997) According to Otto and Wood, critical factors in design for disassembly are the number of tasks, number of tools, and the time or degree of difficulty of the tasks (Otto and Wood, 2001). Each of these factors also has relevance for building disassembly.

A common place though is that Design for Deconstruction is preferable to be applied in the early design stage where all the necessary actions need to be taken into account. According to Guy, B. et al (Guy et al., 2003) there are a number of basic steps that can lead to a sound deconstruction strategy and are described as follows:

- **Design for Prefabrication and modular construction** in order to deconstruct in the same sequence followed during construction. Prefabricated elements can be beneficial during deconstruction. Repetitive and easily stackable units can be dismantled in large sections and transported reducing deconstruction time improving this way transportation costs and scheduling.

- **Simplify and standardize connection details.** Simple connections can enhance both assembly and disassembly process. Deploying standard connections preferably of the same type within a project will lower construction costs will allow the reclamation of intact components in comparison to complicated connection details that may cause difficulties to the deconstruction process, leading in many cases to undesired deformation of the elements that can state them unsuitable for reuse.

- **Simplify and separate building systems.** Considering the separation of building systems in a way that can afterwards be reclaimed individually can improve significantly both the assembly and the disassembly process but can also allow for selective deconstruction. The simplification and consolidation of these systems improve deconstruction time reducing significantly the first costs of the process.

- **Consider worker safety.** One of the main concerns that arise considering DfD is the safety issued that may occur during deconstruction process. There are specific techniques that can ensure the safety of the workers but the designer and engineers involved in the design process have to make sure to reduce these hazards by designing in detail the deconstruction process by eliminating the use of hazardous material, avoiding the use of dangerous activities such as scaffoldings, fall protection and respiratory protection. Simplified mounting systems, built-in tie-offs and connection points for machinery are some examples of simple strategies that can ensure the required safety during deconstruction process.

- **Minimize building components and materials.** Following the examples of other industries like the automotive manufactures that design and prefabricate their components to fit exactly to purpose In combination with design strategies such as open-bay design that reduces the amount of partition walls and grid layouts that follow those of the structure can result in significant reduction of material during construction. At the same time these strategies can expedite future deconstruction processes as the development of the structure is exposed and factors such as manual fittings are eliminated.

- **Select fittings, fasteners, adhesives and sealants that allow for quicker disassembly and facilitate the removal of reusable materials.** The reuse of components require that they have been reclaimed intact. Especially under the unknown factor of structural integrity for safe reuse it is crucial that components are assembled in a way that can be taken apart without critical deformation. This can be ensured only if components are connected with mechanical fasteners and releasable adhesives. Chemical sealants and adhesives are raising special attention during deconstruction process both for the proper reclamation of the components and for ensuring the health safety of the workers involved resulting in more time consuming processes that reflect also to the total cost of the project.

- **Design to accommodate deconstruction logistics.** A major cost driver during deconstruction is the waste removal and the handling of reclaimed components. Simple measures like lift-shafts can facilitate the waste removal during the process while identification of components and a careful design for the storage and transport of the components can improve the total time needed for the deconstruction to be completed and can ease the management of the re-use process.

- **Reduce building complexity.** Complex structural elements like post-tension beams or pre-stressed elements are more difficult to deconstruct. Using simple components and transparent assembly sequence can simplify the deconstruction process. At the same time the preference of structural grids that are commonly used can facilitate the easier re-use of the components that is also one of the main objectives of DfD.

- **Design to reusable materials.** The selection of material that can withstand during time and are adaptable for reuse is also necessary in the scope of DfD as they can be recycled or reused increasing this way the materials' life cycle. Recycling and reuse are significantly less energy demanding processes in comparison to harvesting new materials. Especially use of materials like steel that can be recycle infinite times and do not loose their structural capacity under normal loading, can result to immense energy savings.

- **Design for flexibility and adaptability.** Considering DfD in the early design stage of a project can play a crucial role to the level of deconstruct ability that can be achieved. It can also save significant time and reduce risks of safety as described above. During the life-cycle of the project though the needs for change in function and the level of flexibility achieved during design and construction can extend the initial life-cycle saving energy and deconstruction costs. Designing for open layout and elimination of partition walls can contribute to this direction.

Design for Deconstruction, following any common design process involves many different parties of the construction sector and on top of that requires a long term commitment to a low-pace and complex process. The chain of parties involved are the client, the architects, the engineer, general contractors, subcontractors, manufacturers and suppliers. In Figure 3.2 there is a matching matrix regarding the steps mentioned above and these involved parties, presenting their level of relevance to each step.

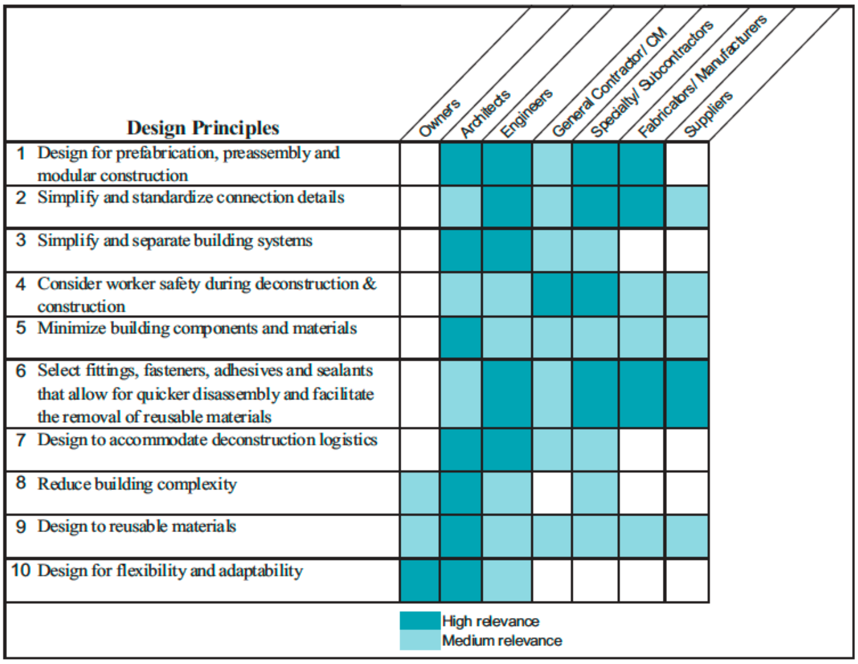


Figure 3.2. Design principles and involved parties relevance diagram (CIBE, 2011)

3.1.4 Adapting Design Strategies

Besides these general principles that should be followed in case design for deconstruction is decided to be implemented in a project, the involved parties are encouraged to follow specific design strategies that will facilitate the purpose of deconstruction and reuse. A design might represent the specific form that the building - project will have by the end of the construction period but implementing design strategies implies that the construction of a building does not end at the initial construction phase but follows it in a dynamic form through its whole life cycle. Adapting design strategies will engage the involved parties to determine how the building will be operated, maintained, repaired and eventually how it will meet the end-of-its life cycle in order to become a resource bank for the next buildings. These design strategies that are recommended in order to introduce deconstruction scenarios in a building's life cycle propose that:

- the lead designer should provide a DfD brief to all the members of the team in order to understand their roles within the team and within their speciality

- The optimum DfD approach should be evaluated through life - cycle environmental impact and cost analysis based on the initial use of the building and with a perspective use of 50 years or more depending on the typology

- The designers should take into account site conditions, building functions and lifespan, project budget and potential construction and delivery methods as main factors that will define the goals and expectation of the DfD strategy

- Involve as much as possible all the disciplines involved in the engineering part of the project in the early design stage as DfD is focusing in both mechanical and structural systems. For the first a "passive system" is preferable than active control systems as it minimizes the required equipment and complexity of the design. In addition those systems should be facilitated by accessible and adaptable technics such as raised floor systems in order to be easily maintained or replaced. For the structural part; detailed structural connections that are accessible and multifunctional are required to facilitate deconstruction and reuse without compromising functionality and flexibility.

- Target specific components for material recovery and reuse and form scenarios for potential reuse functions for the deconstruction plan in order to help the designers of the future projects in design decisions.

- Run detailed cost - benefit analysis of low-cost design - for - reuse options for the existing components of the DfD design

- Use three dimensional drawings to facilitate the both the construction but also the potential deconstruction process either partially (for maintenance or replacement of elements) or for full deconstruction.

- Design a deconstruction plan early in the design process that will help both the designers of the current building to understand the feasibility of the deconstruction process and adapt their design accordingly but also the future involved parties in the deconstruction process in order to maintain the components intact by avoiding any collisions through the process.

- Take into account the extra time needed for the process of DfD to be taken into account during the design stage.

- there should be an effort from the lead of the design team to communicate the idea of deconstruction to all the involved parties and mainly to the client and the team from the very early design phase.

- before the concept of deconstruction is implemented the designers and contractors should ensure the initial briefing and training that DfD requires in management level but also in the levels of workers and available networks

- Add all alternations to drawings and specification to provide a complete set of 'as built' drawings for maintenance and deconstruction purposes (adapted from Guy et al, 2006)

3.1.5 Setbacks of Deconstruction and Reuse

In order Design for Deconstruction to be implemented in the current design practices there are three different parties that are involved and need to address changes individually but in the same time in close collaboration in order to ensure that they focus on the same direction. The parties involved are:

- **the public sector:** government, local authorities, educational institutions and organizations
- **the private sector:** contractors, constructors, supply chain and stakeholders
- **Society**: the existing and potential users of buildings facilitating or realized within the concept of DfD

Those parties are the ones who at the moment raise the setbacks that does not promote DfD. Those setbacks are subject to discussion and affected by many different factors that can diverse depending on the location, the time and the political and cultural aspects of each region and can be categorized briefly as follow:

- **Existing perception towards reused materials:** People's perception of re-used materials is quite circumspect; even more when these material are about to become part of the buildings that will facilitate their needs. The main reason for this mistrust, as stated by Gorgolewski (Gorgolewski, 2006) , is the lack of clear information and guidance regarding the safety of reusing structural components as the main perception is that such entities are already exposed to boundary conditions of loading and might have lost part of their capacity which though as will be discussed in the next chapter is most of the times not the case.

- **Lack of legislation:** no legislation exists that requires client or contractors to consider deconstruction at the design stage. At the same time the lack of proper information regarding the advantages of reused elements might convince insurance companies to reduce their premiums that are the moment are high enough to result to prices that are discouraging the use of reclaimed material.

- **Human barrier:** People are used to perceive buildings as property of high value; so is a real shift in our mentality to design one as temporary. It needs time and consistent effort to shift to an era where buildings will be perceived as service providers facilitating (housing or commercial) functions rather than properties as is today.

- **Procurement and contractual responsibilities:** The existing procurement and contractual methods take as a prerequisite the use of new components for the completion of any project. There is no clear framework that covers the issues of responsibility distribution regarding the use of reclaimed elements; discouraging contractors of getting involved in such an undefined situation.

- **Technical barrier:** Existing jointing systems, for example between precast concrete elements, are usually stronger than the element itself and are very difficult to take apart especially if one aims to do so for a future use and needs to reclaim them intact.

- **Economic barrier:** The cost of DfD is usually initially higher than that of a normal design. Both in terms of construction price due to special requirement but also in terms of construction/ deconstruction time that again reflects on the total cost of the process. In these terms a client will be very difficult to be convinced to invest more for a value whose benefits will not reflect directly as a turnover to his investment.

- **Dimensional barrier:** As a result of the mentality described above; structural units (beams, columns, etc) are for one-off bespoke structures with unique dimensions.

- **Physical barriers:** pre- and post-tensioned beam/ floors, jointing systems, natural ageing of concrete, reinforcement corrosion or presence of coatings results to components that may not be ready to reuse or require an in deep assessment process to ensure their integrity.

- **Re-certification of materials for reuse:** Currently there is very poor approach to re-certification of used elements. There is no official way to ensure the integrity of the element subject to reuse and results as a significant barrier for deconstruction as many grading companies will not re-grade structural elements in order not to be held responsible for any future failure. In return the scope of deconstruction is in doubt if the reclaimed components cannot officially be assessed and certified.

- **Contamination and aesthetics of components issues:** contamination with pollutants (petrol, grease, grime or adhesives) may result to components that are either difficult to clean and reform or sometimes completely defected. This kind of components may also be hazardous for the workers during deconstruction raising issues of safety that are not present in a normal demolition process.

- **Lack of structured supply/demand chain:** The lack of a potential market for reclaimed materials result to a poor supply chain for this purpose. The reclamation and possession of material from the contractors requires the creation of inventories on site in order to keep track of the salvaged material, an efficient storage space for further storage and the responsibilty of selling back their stock or otherwise recycling it. In these terms very few contractors are willing to do so especially considering the fact of lack of a constant demand for reused elements and a structured supply chain that would support their effort. This lack of infrastructure in many cases results in raising the total cost of reused elements as there is a need to transfer and store in remote locations which at the same time adds to their total environmental impact.

3.1.6 Deconstruction and Reuse management

Since deconstruction and reuse are not widely used in the construction industry there are some main infrastructure problems that are not yet addressed. The main problem seems to be the lack of sound management systems that could facilitate a market of reused product and act as a base on top of which the industry could built a solid management process. The literature research showed that there are some efforts focusing on that with the main contributors to be Grogolewski and Fujita. Gorgolewski mainly focuses on steel reuse while Fujita, despite his focus on deconstruction processes and reuse of steel structures, has developed a management system that could be generally applied to any construction system for this purposes.

The existence of a management system is important as the lack of knowledge regarding the existing stock of reusable members, along with the lack of information regarding the structural integrity of these elements and the poor network of manufacturers and storage spaces that can store and provide them are being the major reasons preventing construction industry of adapting design for deconstruction .

Fujita et al (Fujita et al, 2008) proposed through their scientific research a basic model for the flow of the reused elements as shown in Figure 3.3

This model proposes a cyclic flow of reusable members that is facilitated through a database. The dotted lines represent the information flow while the green continuous lines represent the flow of the reusable elements.

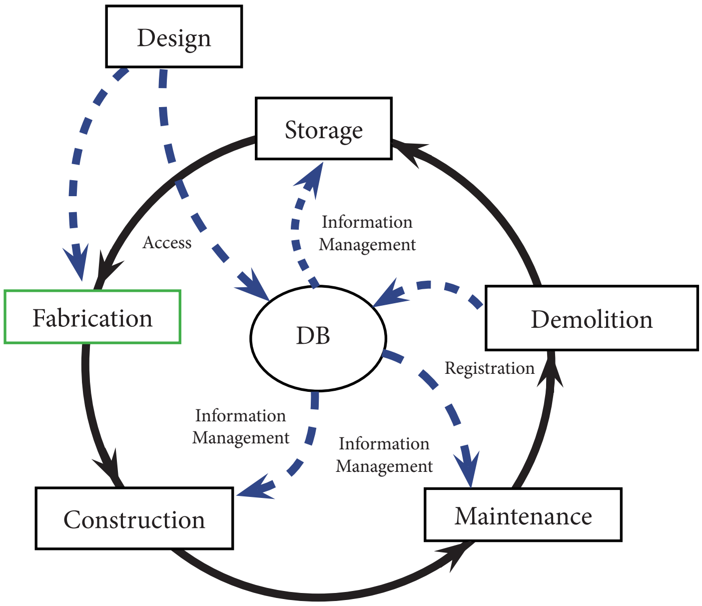


Figure 3.3. Reuse flow (based on image from Fujita et al, 2008)

During design phase designers access the database to get informed about the availability of structural elements and take decisions ideally based on this factor. The database can include members that are stored and ready to be reused but also members of existing building that are registered for this purpose or are close to the end of their life cycle. During construction phase the constructor will order the proposed structural elements, that will be modified either on site or on the manufacturer's site, to meet the requirements of the new design. In case the demand is not covered by the current availability new elements are also being manufactured and used in combination with the reused. For this reason it is important that during design stage structural engineers and architects work tightly in collaboration to eliminate the need for new elements taking into account the existing stock. Regarding the maintenance phase the if any damage is observed - caused by fire or earthquakes or the exposure to the local environmental conditions - or if the building's use is about to be altered the involved parties are called to decide either to repair the building or demolish it. In the second case all the eligible structural elements are registered back to the database to become available for further reuse. This process is also covered by a proposed diagram showing the construction and maintenance flow that should be followed as shown in Figure 3.4.

During demolition phase the owner is the one to decide the potential future of the elements. Since the owner decides to make the elements available for reuse an assessment regarding the structural integrity should follow. If the elements are found to be safe for reuse (without any critical damage) they must be registered to the database in order to be available for the next cycle of use. This process is demonstrated in Figure 3.5.

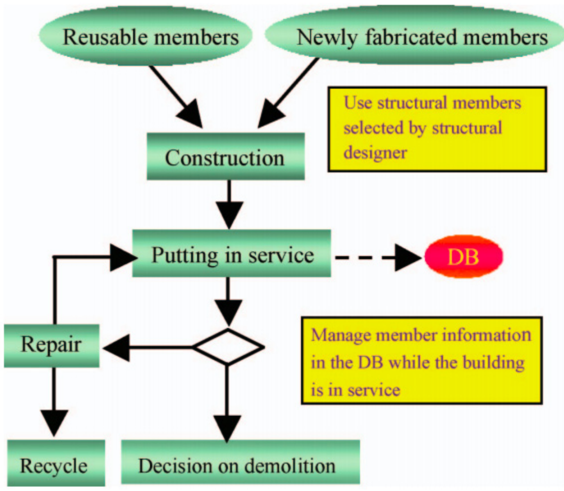


Figure 3.4. Construction and maintenance flow (Image courtesy: Fujita et al, 2008)

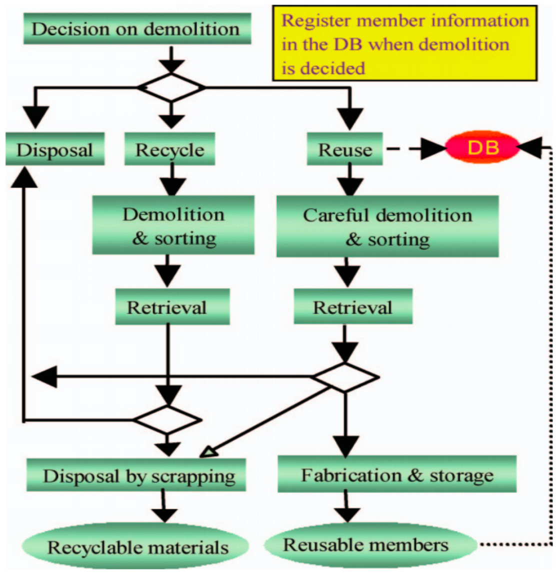


Figure 3.5. Demolition flow (Image courtesy: Fujita et al, 2008)

In order to take into account the economic feasibility of the deconstruction process, a factor that seems to be the main concern of the involved parties that must collaborate in order for the concept to develop further, Fujita et al propose a model consisted of three basic fields: management, design and stock. The scheme of this model is shown in Figure 3.6.

The management field include the Business management that is responsible for the coordination of the reuse process along with the control of the Information technology (IT) engineering and fabrication process of reusable members. The IT is responsible for the set up and control of the database (DB) along with the set up of a quality control system for the information regarding the reusable members. At the same time IT must make sure that the DB is accessible from an unlimited amount of engineers and designers. The fabricators are responsible for the quality of the reusable members and the maintenance and adjustment according to the requirements.

The design field includes the architect that will translate the requirements of a client into feasible designs and the structural designer who evaluates the designs and select the proper structural elements to bring it to life. If the structural engineer decides to use reused elements he/she access the database in order to select the suitable ones from the current stock. The constructor is responsible to order the elements (reused or new) from the manufacturer who in return is responsible to supply them.

Finally demolition and storing of the reused elements should be handled with great care in order to ensure that the components will remain intact. An inspection of the elements must take place prior to their storage and all the eligible components should be registered back to the IT database.

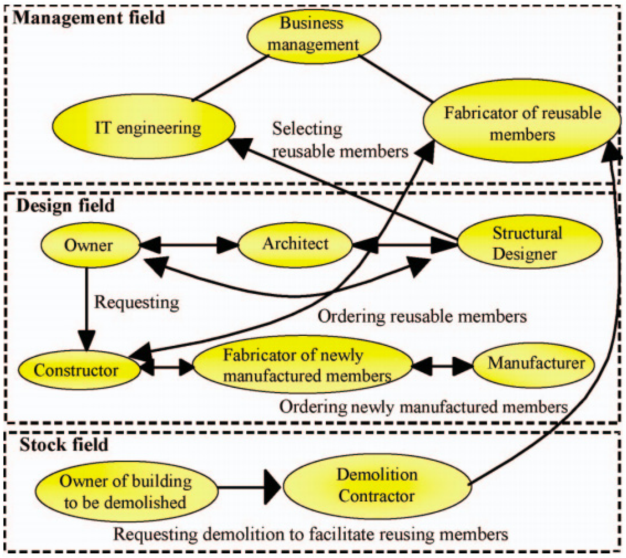


Figure 3.6. Reuse management model (Image courtesy: Fujita et al, 2008)

According to Fujita et al if the basic management is addressed and develop in the proposed way the construction industry will be able to overcome basic problems that does not allow the implementation of deconstruction as a standard during the design process. The creation of stock components, the proper set up of a database that will facilitate the process, a deconstruction process designed in detailed and carried out carefully and a standardization of fabrication procedures for the adjustment of reusable elements will significantly promote the concept under the coordination of a sound management system and the missing financial incentives.

Implementation in the toolbox

One of the main goals of the toolbox is to provide a basic setup in the form of data sheets that will store all the necessary for future use. The idea is that after the assessment of the design options and the choice of the most suitable one according to the design criteria and to the environmental impacts of the design the user will be able to export all the data related with the elements of the building including the results of the environmental impact assessment and the information regarding the properties of the structural components that are necessary for a future use.

The aim is to demonstrate that, even with tools for the early design stages of a project, the creation of a database that can support the concept of deconstruction on a management level is feasible.

The way the toolbox is applied in the management scheme shown in Figure 3.3 is schematically shown in Figure 3.7.

The green coloured boxes show the areas where the use and results of the toolbox are directly applied. The green dashed lines show the direct information flow that are produced from the toolbox's components and are supporting the creation of a database and the fabrication process while the blue dashed lines show the indirect influence of the toolbox's strategy by the use of the produced database.

More specifically the application of the toolbox in the early design stage influence the design results as the user can decide if the concept of deconstruction will be taken into account. If so the fabrication process is also influenced, indirectly, as the design details will be adapted for this purpose. In case the concept is applied the produced information from the toolbox will be exported to spreadsheets for the creation of a database that will support the concept of deconstruction in a wider extend as described earlier in this chapter. As such the database is also directly influenced. In case the management scheme is utilized the rest of the stages of this proposed scheme will also be influenced indirectly as they will be supported and based on the created database as also described earlier in this chapter.

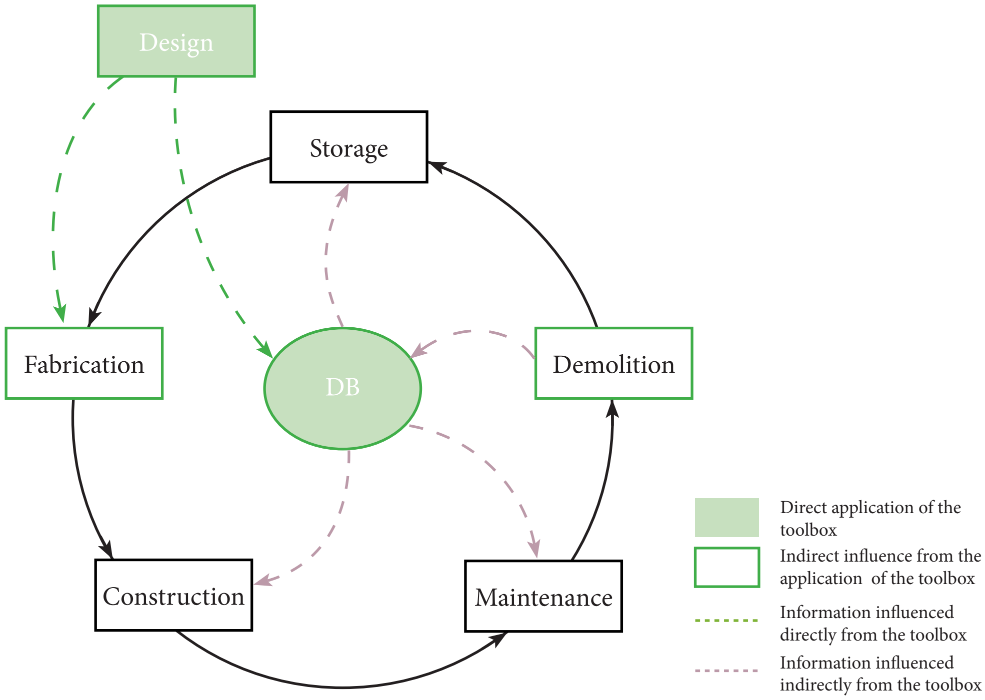


Figure 3.7. Implementation of the management scheme into the toolbox strategy

3.2. Steel structures in DfD concept

This section will focus on steel structures and the potentials they offer for reuse. Steel structures were chosen as a showcase for the tool as the main structural systems they follow in residential and commercial buildings are formed by prefabricated components and in most cases follow a direct construction sequence that can be reversed in order to achieve deconstruction. In these terms there will be a focus on the main structural systems that are suitable for deconstruction and their connection and component types that can facilitate ease of deconstruction and reuse processes. An overview and comparison of reuse vs. recycle scenarios regarding the environmental impacts and benefits they can bring and finally an overview of successful examples and lessons learned from failures of structures designed in this content.

3.2.1 Introduction

Globally, over 1.3 billion tons of steel are manufactured and used every year and it is predicted there will be continuing strong growth in the volume of steel produced. It is claimed that *'this continued growth prevents the demand for steel being met by means of recycling of end-of-life steel products alone, hence, making it necessary to continue converting virgin iron ore into steel'* (World Steel, 2012) despite the fact that steel is at the moment one of the most recyclable products as it is 100% recyclable due to it's ability to preserve it's properties or performance after the process.
Steel making, recycling and similar processes though are energy demanding resulting in high levels of greenhouse emissions. According to Worldsteel association an average of 1.9 tonnes of CO_2 are emitted for every steel tonne produced while the iron and steel industry accounts for approximately 4-5 % of total word CO_2 emissions.

A big contributor to these production rates and results is the construction industry, occupying almost 51% of the total steel production. (Basson, 2012)
Both industries put a constant effort to become more sustainable in terms of CO_2 emissions and resources exploitation but despite the fact that for every tonne of steel produced nowadays the amount of energy needed is 50% less in comparison with 1980s there is not any margin for dramatic developments with the existing technologies. (World Steel, 2012)

On the other hand construction industry, besides its bad performance in terms of energy use and resources exploitation, has created a big reservoir of structures that have reached the end of their life-cycle and stay unused or being disposed carrying a very big amount of materials and components that could be reused serving a new purpose. Instead construction industry is creating new structures to serve most of the time similar purposes from new or recycled products that are highly energy intensive contributing this way to the inability of steel industry to cover the market's needs in new products by recycled or reused steel.

There is a need for both industries though, in order to become more sustainable, to focus on reuse of steel as it offers the most potential among the 3R's of sustainability (Reduce, Reuse and Recycle) in terms of resource efficiency as described by Stahel (1982). Recycling is by now an efficiently performing market with the recycling rates of structural steel reaching almost 95% but still an energy intensive process that requires the reprocessing of already existing components as will be described later in this chapter.

On the other hand re-use requires not more than the energy used for deconstruction and transportation of the components to a new location for storage or direct reuse. Re-use is also the only process that does not require any new input of raw material providing this way a solution to resource scarcity, one of the most important problems that we will be called to face in the next decades.

Despite those advantages though re-use is not yet a common practice in the construction industry even if the technical knowledge and technology is already in hand of the involved parties and the experience of other industries like car manufactures who has deployed reclamation and reuse of components from their products for over 20 years now can contribute significantly to the implementation of the process in an efficient way.

3.2.2 Why steel

Steel buildings are in principal designed and built from prefabricated components following a specific construction sequence and they are suitable to facilitate design for disassembly by following a reverse sequence for the deconstruction process at the end of their life cycle. In practice steel sections are bolted together in a vertical (columns) and horizontal(beams) sequence to form steel frames and are not degraded in use except from cases when they suffer severe damage by external factors such as fire, earthquakes or corrosion while in such cases deformations are usually easily detected by observation and testing if needed. Far from that steel sections come in standard dimensions so geometries of at least the last 40 years are still specified today and even though steel strength has improved dramatically during this period the stiffness of steel components which appears to be one of the most important factors that states a component suitable for use, remains unchanged. If a steel section is reclaimed intact and sent to the fabricator then there is no difference between the process followed for a new component and for the one that has been reclaimed in order to be reused till both reach the new construction site.

Currently though most steel buildings are dismantled using thermal lances or shear stating them unusable in their original form while at the same time there is a lack of standards for testing and verifying their structural integrity stating the re-use of steel components not feasible in a large scale. These barriers though can be addressed and resolved by adapting new connection techniques and establishing assessment methods if only the industry is convinced for the benefits that can arise from reuse strategies. If so adapting the concept of future deconstruction in steel buildings will only require some extra attention on standardizing dimensions and adapting connections that will allow the deconstruction of a building with the components remaining intact saving at the same time significant amounts of energy and raw material that would other wise be required for the recycling and production of new steel products.

For these reasons steel was selected to be the material that this research will focus on as it is a material that offers already the ground to adapt those strategies and make steel even more efficient than already is.

It is important though to quantify these benefits so the next section of this chapter will focus on the steelmaking process and the benefits that can come up by reusing steel components and avoiding it.

3.2.3 Steel making processes

In order to understand the differences between manufacturing and recycling and the potential benefits of reuse of steel products it is important to have an overview of the processes and their impacts. For this purpose in this section there will be a review of the basic steel making routes as deployed today by the steel industry.

The process of steel products production is consisted of a primary and in many cases a secondary process. The primary process has two basic routes that can be followed, the Blast Furnace route and the Electric Arc Furnace route while during the secondary process the products of the primary process are being treated to produce high grade steel components if necessary.

The Blast Furnace route (BF)

During the blast furnace route pig iron pellets are primarily produced from iron ore using coke in a blast furnace. The by-products of this process including gas and slag are reused for diverse purposes like energy generation and civil engineering applications while the produced iron is processed into a blast oxygen furnace where with the use of high pressure oxygen is turned into steel. During this last phase of the process scrap steel is also added in a percentage of 20-30 depending on the production plant mainly for temperature regulation.

The raw materials used in the blast furnace route in order to produce a tonne of crude steel include iron ore, coal, limestone and recycled steel and the necessary quantities are on average, 14000 kg of iron ore, 770kg of coal, 150kg of limestone and 120kg of steel scrap. (Wordsteel assosciation, 2011)

The Electric Arc Furnace route (EAF)

On the other hand the electric arc furnace process is using 100% scrap steel for the production of steel without the use of primary raw materials. The scrap is being melted in an electric arc furnace while during the process oxygen and lime are added to bind impurities. The process usually starts with the use of molten steel from a previous process and gas burners to help the melt down process. The by-products of this process like zinc and gasses are also reused for the production of new zinc and electricity accordingly.

The raw materials used in the electric arc furnace route are primarily scrap steel and occasionally direct reduced iron and electricity. For the production of a tonne of steel EAF will use 880kg of recycled steel, 150kg of coal and 43kg of limestone stating this process much more efficient in the use of raw material in comparison to the BF route. (Wordsteel assosciation, 2011)

The **secondary steel making process** is performed mainly in ladles and includes de-oxidation, vacuum degassing, alloy addition, inclusion removal, inclusion chemistry modification, de-sulphurisation and homogenization (http://en.wikipedia.org/wiki/Steelmaking). It is usually performed in electric arc heated ladles and is mainly associated though with the production of high steel grades of steel as it offers the possibility for precise control of the chemical content of the mixture.

In theory all steel can be produced using the EAF route, and despite the fact that over 500 million tonnes of steel are recovered and recycled annually worldwide the current stock of steel scrap though is not enough to cover the total demands of the industry. For this purpose, in Europe, almost half of the annual steel production is taking place in EAF and the rest in BF. This amount varies regarding the products and the location as for example in the Netherlands steel products such as structural sections and pipes are being produced exclusively using the EAF route.

In Figure 3.8 the scheme of the two basic routes is presented.

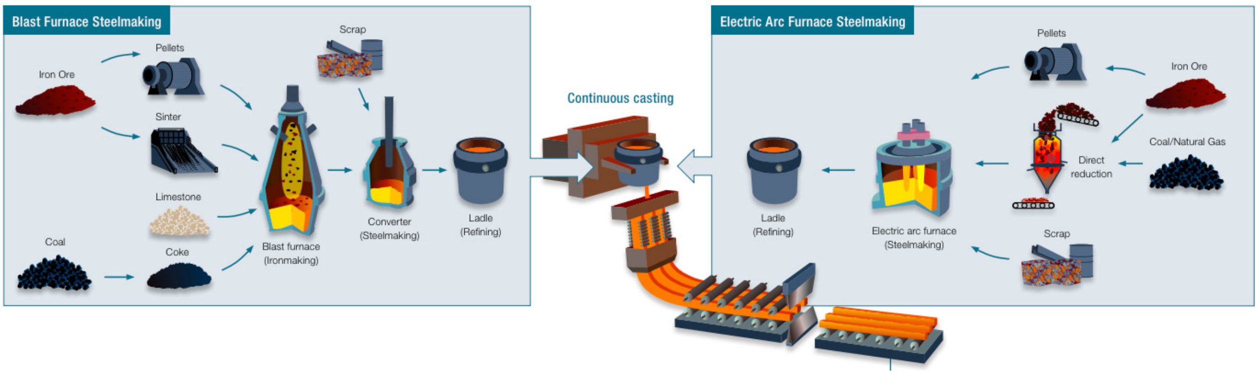


Figure 3.8. Basic routes for the steelmaking process (image courtesy: WorldSteel association, source: http://www.worldsteel.org/dms/internetDocumentList/bookshop/Steelmaking-poster/document/Overview%20of%20the%20steelmaking%20process.pdf)

Energy use in steel making

Steel making is a process that requires significant amounts of energy from the early beginning till its completion. The energy consumption varies among steelmaking facilities depending on the production route, steel products mix and the facility's efficiency in material and operation technology and contributes in an average of 20-40% to the final price of the products. It is mainly coming in form of solid fuel (mainly coal) accounting up to 95% of a facilities's energy input, gas fuels reaching a 3-4% and liquid fuels for the rest 1-2%. At the same time energy consumption is required for the mining and transportation of raw materials including also the scrap steel that is used during the process.

The last decades though steel production has become more efficient due to emerging technologies that allow more precise control of the process and the reuse of the by-products that are used or produced during the process for different reasons such as direct use or energy production from gases produced from the blast and basic oxygen furnace that contribute up to 40% of the total energy demand. The development of the energy efficiency is illustrated in Figure 3.9 where the average energy consumption per tonne of crude steel produced in North America, EU and Japan from 1975 to 2004 is shown.

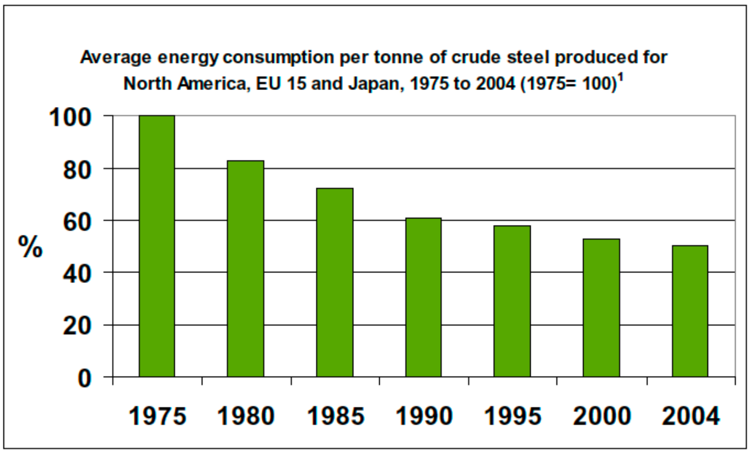


Figure 3.9. Average energy consumption per tonne of crude steel (WorldSteel association, Steel and energy factsheet / image courtesy: WorldSteel association)

It is important to mention though that the last years another emerging technology is being developed and in some cases deployed for steel making. It is called **Hlsarna** and is a variation of the basic oxygen steelmaking process. The basic difference is that during Hlsarna the step of creating pig iron pellets that are used in the blast furnace is no longer necessary as the production of pig iron is taking place directly in a Cyclone Converter Furnace (CCF). This difference states this new process much more energy efficient while reducing its total carbon footprint. The first production units are already set in place and the first data show a potential CO_2 reduction of 20% without capture and an 80% when the produced CO_2 during the process is being captured. (Peeters, 2013). Hlsarna is a process under testing and development but the results so far show that in the future it will contribute significantly to the efforts of steel for a more environmental friendly production process.

3.2.4 Steel buildings suitable for deconstruction

Steel structures facilitate high potentials for demountability and partial or holistic reuse. This fact is already proven in practice if one considers the number of temporary systems where steel products are used. Temporary systems like form works, sheet piles, piping or scaffoldings are all formed by steel components and have established steel as one of the most reliable materials for reuse. In these terms every steel building if designed with future deconstruction in mind could serve this purpose adequately. The reuse of steel components is already taking place in sectors like agriculture where components or whole buildings are reused as warehouses as technical barriers such as reassessment of components are` not required. At the same time there are numerous examples of temporary structures that serve specific cause where the concept of deconstruction has been implemented successfully.

The most characteristic, on a building level, is that of expo pavilions where by definition the structures are designed for a short period of time and serve a specific cause that after the end of the expo is no longer valid. For this purposes deconstruction is a need and not an extra feature but still the number of pavilions built as such are limited. A characteristic examples are the British Pavilion for the Seville Expo in 1992. The pavilion besides its unique vernacular architecture and integration of sustainable system for climate control was designed to be deconstructed after the end of the expo and its components to be reused. As such the steel structure of the building was fabricated in Britain and transported to the site while the joints were designed as simple pins to minimise site work and the steel was designed to be unbolted easily. The building was aimed to be transported elsewhere after the expo although its components were recycled.

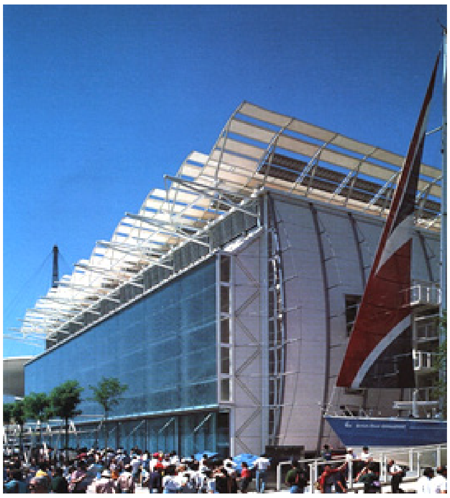


Figure 3.10. British Pavilion for the Seville expo in 1992 (http://www.steelconstruction.info/Recycling_and_reuse, last visited January 2014)

Another example that facilitates the concept of design for deconstruction is the Institute for Research and Coordination in Acoustics and Music (IRCAM) in Paris is an autonomous department of the Centre George Pompidou. The studio is designed as a kit construction that creates a system formed by standard parts that allow the re configuration of the space or the installation of extra components in order to create extra volumes if necessary. The Pompidou centre along with the IRCAM studio though are still in place serving their initial purpose.

Figure 3.11. Center George Pompidou in Paris(http://people.engr.ncsu.edu/dzbaron/pics/2007/2007paris.html, last visited: January 2014)

At the same time there are several examples of buildings that are built from reclaimed structural elements stating that reuse is not only a theoretical concept but can really take place if planned and executed carefully. Dr. Mark Gorgolewski is one of the main contributors in research and development of designing for deconstruction and has published several papers examining buildings that are constructed from reclaimed steel components. Some of the major examples we find in his research are The BedZED complex in South London where despite the fact that the main structural system used is a load bearing masonry structure over 100 tonnes of structural steel were also required. As the concept of the project demanded the complex should be constructed with the minimum possible energy consumption and as such 95% of the steel required came from reclaimed sources. The reclaimed steel was found in salvage yards within a 50 km radius of the site and examined before use to ensure its structural integrity. Far from that the connection details were designed to accommodate a wide range of sizes and despite what expected the initial architectural design was only slightly affected to fir this purpose.

Figure 3.12. The BedZED multipurpose complex in South London (http://en.wikipedia.org/wiki/BedZED, last visited: January 2014)

Finally another characteristic example where reclaimed steel components were used for the rebuilding a school building is The Roy Stibbs School in West Coquitlam of British Columbia. This time the reuse of elements did not only serve environmental purposes but contributed to the faster execution of the project. The school building was destroyed by fire and it had to be reboiled in a short period of time in order to serve the community. For this reason the new building was designed to facilitate the reuse of the structural elements of another school in Northern Columbia that was no longer needed and dismantled recently while the reclaimed components were stored instead of recycled. After some minor modification 466 open web steel joist were reused. To add to the complexity of the project the new school had to be designed for a seismic zone 4 while the old school where the reclaimed components came from was designed for a seismic zone 3. This problem was solved with some adaptation on the structural system proving that reuse of steel components is feasible not only after downgrading its use but also in projects with higher demands.

Figure 3.13. The Roy Stibbs school in British Columbia (http://www.taskcm.com/education-roy-stibbs-school, last visited: January 2014)

As seen from the examples above design for deconstruction and reuse of reclaimed elements can fit various projects and can be serve different purposes. Far from structures that are by definition temporary reuse of steel components can be addressed for environmental purposes but also for faster completion of projects. The only requirement from an engineering point of view is to take it into consideration in the design stage of the project and be able to give up some of the architectural requirements in order to facilitate the process.

Another fast developing sector that is also by definition using the principals of design for deconstruction is the modular structures. Modular constructions are applying design for deconstruction but in a larger scale. Instead of aiming on an component level modular structures preserve whole modules in favour of simplicity and ease of assembly and disassembly process. And although the design freedom is usually lost the mass customizing still applies to modular designs. During the last years Modular construction industry is rising its market shares within the construction industry as shown in the Figure 3.14 as it offers many benefits both in a financial and an environmental extent.

In Brief the financial benefits arising from modular construction are multilevel as it offers the potential of shorter construction times, predefined labour pool, fewer space for mistakes due to up-front designed and detailing and less construction waste with an estimated reduction from 15% to 5% compared to traditional construction eliminating this way material and waste disposal costs. (AMA Research, 2007)

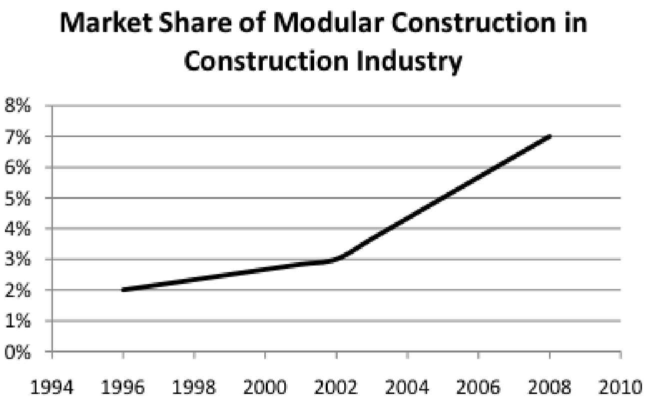


Figure 3.14. Market share of modular construction (Olson, 2010)

Regarding sustainability, part from the waste reduction that modular construction can bring, the concept of design for deconstruction is being used by principal taking advantage of all the benefits that can arise from it. Steel modular units are constructed using the stud and track connection method, where sections are joined together with self-drill fasteners, rivets and bolts. As a result at the end of life of the structure these units are easy to dismantle and reuse in another location forming the same or a similar structure to serve a different purpose. The reconstruction only requires the disassembly and transportation of the components to the new site eliminating any additional energy demands that would add to the embodied energy of the new structure and the waste produced is even further reduced as the components are ready to be reused without any further modifications. At the same time a total 70% less transports of material is required to the construction site as all the material are transported and assembled to the factory where the capacity is much larger than that on site. Finally noise production on construction site is significantly reduced in comparison with conventional building processes. It is worth mentioning though that although a modular structure saves natural resources due to its reuse potentials there is an estimate that an amount of 10-25% more structural material are required to be realised in comparison with an identical conventional building. (Velamati, 2012)

3.2.5 Connections suitable for deconstruction

One of the most important aspects of design for deconstruction is the connections between elements. The chosen connection type will state if the design is successful or not in this content. In general terms and as developed by Durmisevic and Brouwer can be classified in three main types based on possible ways of connection between elements. The integral, the filled and the accessory connections (Durmisevic and Brouwer, 2002) and their subdivisions as shown in Figure 3.15.

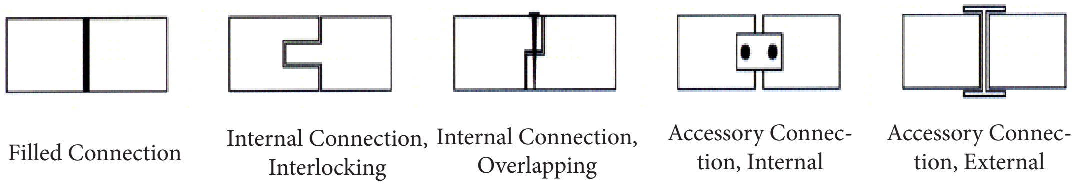


Figure 3.15. Connections Schematics (Durmisevic and Brouwer, 2002)

Integral connections are formed by interfaces that are being held together in shear by the geometry of the two elements. The formation can be an interlocking or an overlapping type where in first case no extra accessories are required as the elements have a male and female part that combined create a strong bond while in the second case each element laps onto the next requiring an extra part such as bolts to complete the connection. Even though interlocking connections are suiting perfectly the concept of repeated reuse the required tolerances and the risk of failure that this may bring in a building scale aren't making them suitable to serve this purpose. On the other hand the extra required element of the overlapping connection is the one that will make the connection suitable or not depending on the damage caused to the element during removal.

The filled connections are usually applied on site forming chemical bonds to connect the elements. the most common are glued or welded connections that make the disconnection of the elements almost impossible. In order to do so special tools are required that usually damage the adjacent elements near the area of connection.

The accessory connections are interfaces between two elements that holds them together. These are interfaces are easily assembled and disassembled parts that undertake connection forces through bearing. They are subdivided in two categories, the internal and the external type connection. The internal type are formed by parts directly connected to the elements and usually bolted together while external type do not connect directly to the element but use other means like increased frictional forces to create bearing capacity. The disadvantage of the first is that they cause local damage to the element in case of modification and require high precision to fit the bolts that will connect them while the second type is not causing any damage but is rarely use due to their low capacities.

The basic principals that will state a connection suitable for deconstruction are:

- the connection to be easily reachable and removable
- formed with preferably mechanical joints like bolts and avoid chemical bonding
- simple in terms of geometry and tools required to be mounted on site
- enable components to be independent and exchangeable
- connection types to be consistent within a project
- cause the least possible damage during disassembly
- ensure safety during disassembly process
- form grids dense enough to state the handling and transfer of components feasible during deconstruction process.

Conventional connections

Steel structures have already some well established connection techniques that are used depending on the type of elements and the type of loads that need to undertaken by the connection itself. Taking into account the above mentioned typologies and requirements each of the conventional typologies have some subcategories that are suitable for the concept of deconstruction. The basic categories are simple shear-resistant connections and moment-resistant connection. The common practice and the least expensive one is to use accessory type connections to accomplish any of them, in form of plates and angles, so the means that these connections use to be mounted such as welds, bolts or high-strength friction grip bolts is of specific interest.

Beginning from there and assuming that all properly designed connections can provide the same strength capacity bolts can be considered more suitable for deconstruction as they follow a specific failure routine in comparison to welded connections that may fail suddenly without prior notification. This is a crucial factor especially for the deconstruction process as a sudden failure can cause fatal accidents. Part from that welds are more difficult to accomplish and need specialized workers to do so but bolt holes can state a component non reusable and most of the times need to be filled for this purpose. If welds need to be used though fillet welds are preferred to but welds as they are difficult to remove and requiring coping of the element they connect to causing as such local damages that may state the component non reusable.

Regarding shear connections (known also as simple connections) they are framed into a column web or a column flange depending mainly on the orientation of the column and are always formed as accessory connections using intermediate plates and angles between the connected elements. The three main shear connections are the fin- plates, flexible end plates and double-angle cleats as shown in Figure 3.16.

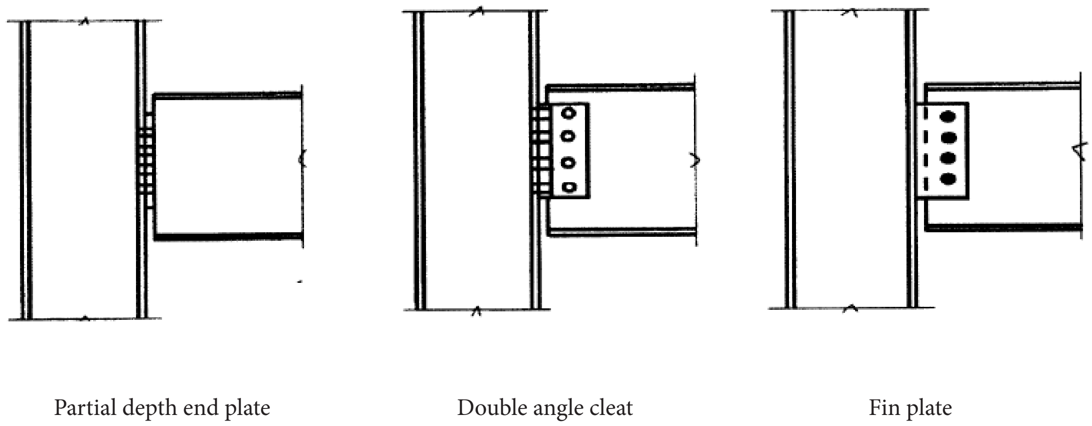
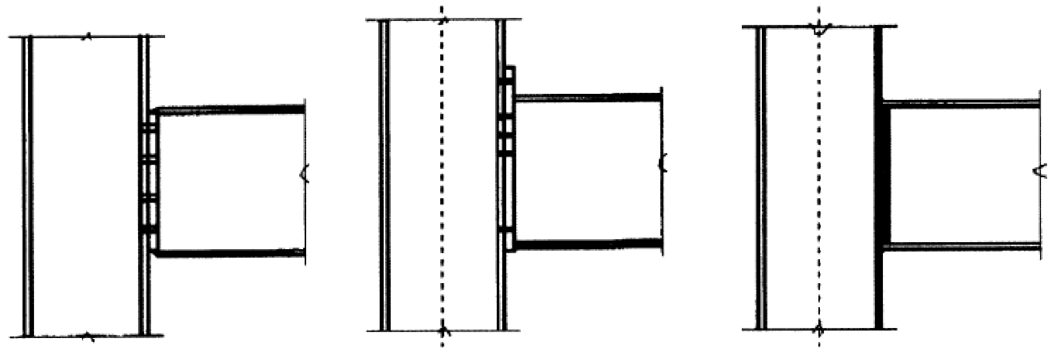


Figure 3.16. Basic Shear Connections (Davison and Owens, 2002)

Fin plate and Flexible end plate connections are both requiring welding and as such create problems during deconstruction while double angle cleats use double angle and bolts to connect beams to columns. As such they are more expensive but state the connection more suitable for the concept of deconstruction.

Regarding moment connections there are also three main types widely used. The flush end plates, the extended end plates and the fully welded connections as shown in Figure 3.17



Fluah end plates   Extended end plates   Fully welded

Figure 3.17. Basic Moment Connections (Davison and Owens, 2002)

Following the same principals flush end plate connections and fully welded connections use welding as part of their connection sequence and as such they should be avoided. On the other hand extended end plates can be formed only with the use of bolts. Moment connection usually require stiffeners that are welded at the level of the beam's flanges. These stiffeners are usually not causing affecting the components' integrity for reuse and can be removed after the frame is dismantled. They can also be avoided though if the connection is designed carefully with the use of an appropriately sized beam framing into the column's flange stating an extended end plate connection perfectly suitable for the concept of deconstruction.

Connection Innovations

Despite the fact that deconstruction is not widely used there are several companies that are focusing on innovative technologies that can ease the process. These technologies are already applied in projects and are certified and ready to use. Some of the most important ones that are also meeting the efficiency in capacity of the conventional connection routines are:

The **Quicon** connection system developed by the Steel Construction Institute in United Kingdom. This system is composed from T-brackets and shoulder bolts. The brackets have a series of keyhole shaped holes where the shoulder bolts are fitted in by sliding. The brackets and bolts can be fitted in place off site and simply be mounted together during on site construction offering a very fast assembly system and the possibility of disassembling the components without any effort and reusing them elsewhere. At the same time there is no requirement for welding at any point of the connection.

Figure 3.18. Quicon connection applied on an IKEA building (source: http://www.newsteelconstruction.com/wp/quicon-wins-contract-at-ikea/, last visited January 2014)

Another example is **ConXtech** connection system. Established in 2000 by ConXtech Space Frame Systems in California it is applicable for seismic load design and has been used in several projects already. It is formed by a shop-welded, field-bolted self-guided system where the machined collar plates are shop-welded on beams and are self-located into place on site where the machined surfaces on the beams and columns are interlocking. (WellMet2050, 2010). It has been calculated that ConX system can reduce the mass of steel by 30% and erection time by 50% (based on an analysis of a construction of a hospital in California) (ConXTech, 2010). Part from these benefits the self-aided and self-supported connections are suitable for deconstruction and reuse purposes but mainly for cases where the geometries of the new structure are identical to the initial one.

Figure 3.19. Left: ConX beam with shop-welded collar plates Right: Column with shop-welded collar plate (source: http://www.conxtech.com/, last visited: January 2014)

Another connection system suitable for deconstruction is the **Girder Clamps**. These type of connections do not require any drilling of the structural components and are based on friction resistance. Girder clamps as shown in Figure 3.20 rely on a gravity shear connection and friction between the connection components and the steel work (WellMet2050, 2010). The nature of the connection provides ease for the adjustment of the steel work while in case of reuse there is no need for any modifications before reuse.

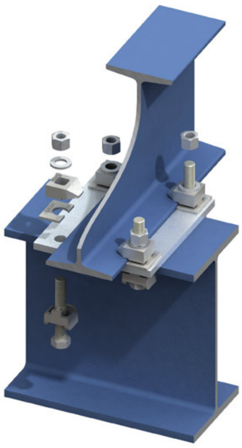


Figure 3.20. Girder-clamp connection (source: http://rebar.ecn.purdue.edu/ect/links/technologies/civil/ibeamclamps.aspx, last visited: January 2014)

There are more innovative connection systems such as ATLSS Connections or post-tension moment Connections that have been in the market for years but were not adapted in a wide extent from the industry for different reasons. Below there is a comparative diagram showing the relation of shear to moment capacity of traditional and innovative connection systems as formed by Cambridge University.

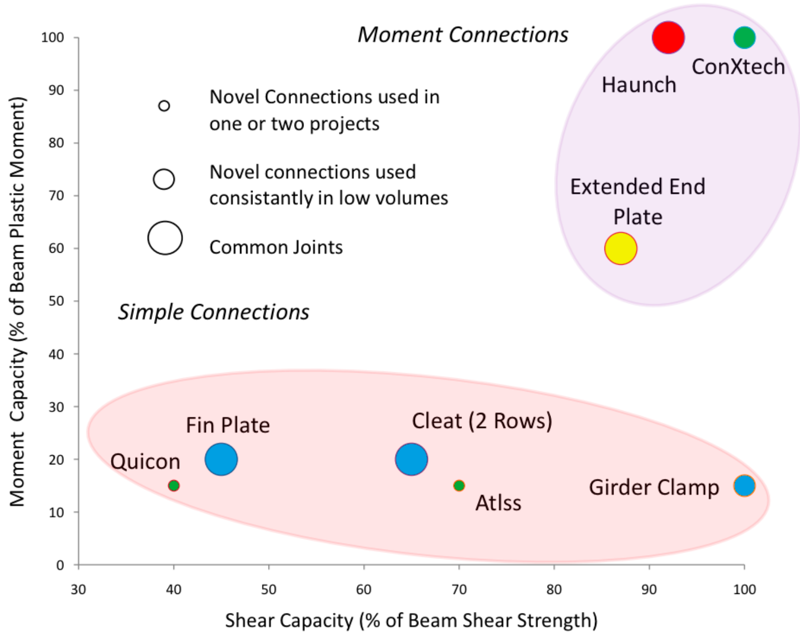


Figure 3.21. Shear - moment capacity of typical and innovative connections (WellMet2050, 2010)

Although the connections are probably the most effective technical aspect for the efficient deployment of the concept of deconstruction, in the current strategy they are not taken into account. The reason is that the aim of the strategy is to expose the benefits of deconstruction in order to convince designers and the involved parties to apply it. As such for the assessment of these benefits the most crucial factor is the amount of material used in the design under study. In these terms connections are consisting only a very small amount of the total weight of a building and are not taken into account for the proposed assessment.

3.2.6 Assessment and regrading of components

A major issue that arises in the case of reusing steel sections is that of safety regarding the structural integrity of the elements that are going to be reused. Assuming that the deconstruction is taken into account from the early design stage and the deconstruction process of a building has been completed successfully, the reclaimed steel sections should be considered ready to be reused following the route that new identical sections would follow. At the moment though this is not the case and the reason is the lack of certifications that will guarantee the integrity of the components. For newly produced sections the certification is a requirement that is supplied by the manufacturer to the contractor and guarantees for the properties of the component. As such in case of failure the contractor can transfer the responsibility back to the supplier. The certification is based on the quality of the manufacturing process starting from the liquid phase of steel and reaching the final product which is tested with statistical sampling verifying that each components meets the demanded requirements.

Fatigue is the only phenomenon that could effect the structural integrity os a steel component and is not detected by visual inspection but although as stated in EN 1993-1-1 :2005 Section 4 “For building structures no fatigue assessment is normally required” insurance industry does not accept the fact that used steel components retain their initial properties independent of the time is being used in a building. For this reason further testing of the reclaimed elements must take place including taking test samples from every individual element and testing under tension to measure its strength. A process that is time consuming and expensive and is currently one of the main setback for the reuse of structural steel components. For this purpose M. Fujita conducted an analysis of the structural performance of reusable steel elements (Fujita, 2012). In his paper Fujita is assessing reusable elements for their performance in comparison to equivalent newly manufactured members. The properties under evaluation is the yield and tensile strengths along with the elongations of the reusable members. The tests are in form of tensile test as described above and chemical analysis. The components used were obtained from a low-storied structure completed in 1976. The test results showed that tensile strengths, yield strengths and elongations are all nearly equal to newly manufactured members. Along with the mechanical properties Fujita tested the sections on a beam-column experimental set up under cyclic loading. The test results showed that yield bending stresses both in tensile and compressive zone are similar for new and reusable members while both elements suffer local buckling within plastic range as shown in Figure 3.22 Finally strain distribution is also similar among them as shown in Figure 3.23.

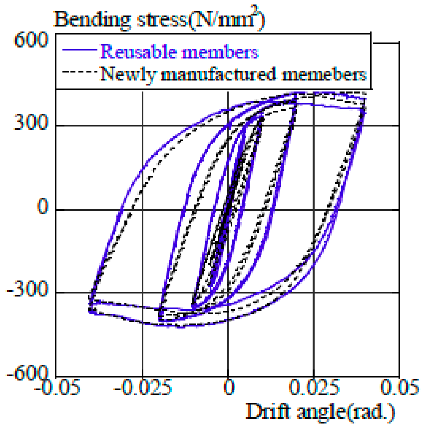


Figure 3.22. Bending stress and drift angle diagram of new and reusable members under testing (Fujita, 2012)

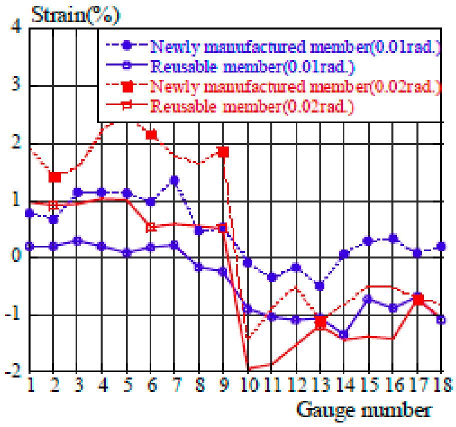


Figure 3.23. Strain between reusable and newly manufactured members (Fujita, 2012)

Concluding this research Fujita is stating that the performances of reusable and newly manufactures members are similar in every tested property, a fact that can be considered as a strong base in the effort to convince insurance and construction industry for the safety of reusing structural steel components and promote the idea of design for deconstruction.

3.2.7 Recycle vs Reuse

Steel is unique among others construction materials mainly because as described above it always contains a percentage of recycled materials. Apart from that steel is 100% recyclable that means that at the end of its life cycle the resources used for its production can be infinitely reused to reproduce new steel products without loosing any of their initial properties. The newly produced steel products are durable with their expected life-cycle, when referring to structural components, meeting always the design life of the buildings designed for as proposed in ISO 15686-1:2011 (Annex B - paragraph B.8.1) and proved in practice, except from cases when they suffer severe damage by external factors such as fire, earthquakes or corrosion. This durability though along with the global economic expansion and growth of steel construction industry's market share creates a constant demand that cannot be met by the available scrap stock. In order to meet this demand, steel industry is forced to produced new steel from primary raw materials. It is considered at the same time that the well established scrap steel collection and distribution infrastructure has reached its maximum capacity expressed as the recycling ratio between the actual quantity of scrap salvaged and recycled and the total quantity of scrap arising, a ratio that has reached the value of 80% in a global scale stating that the use of recycled steel has no further possibilities for development (Wordwide LCI database, 1998). These recycling rates are mainly achieved due to the fact that steel is one of the few metals with magnetic properties and can be easily recollected from demolition debris. Besides that big structural steel components can be easily recollected after the demolition of a building without the need of extra attention as their state is irrelevant for the completion of the recycling process. In practice the current status of recycling rates declares that steel can be considered as not eventually owned during the life cycle of a structure but leased for the according time and returned to steel manufacturing cycle.

Despite though the high recyclability rates that steel construction industry has achieved, steel offers high potentials for reuse as discussed in the previous sections. Exploiting these potentials can bring significant environmental benefits as the components can be re-used in future buildings avoiding the need of recycling whose benefits are proven to be limited in long term application. In order though to achieve a shift from recycling to reuse mentality there is a need to convince the industry for the benefits of such an action. The current section will focus on the comparison between reusing and recycling steel structural elements in environmental and financial terms.

Environmental and financial comparison

Financial aspects

In case a building has reached the end of life stage the current practice is to be demolished and disposed to waste landfills. The steel structural components of the structure are being collected and send to recycle but as they are about to be melted, their state during reclamation is irrelevant giving the opportunity to the demolition contractors to proceed to demolition with heavy machinery. The demolition process is done in a fast pace as from the time the building is left empty and the contracts for the new structure that will replace it have been set in place the existence of the unoccupied building adds to the total cost of the contract. On the other hand if a building is decided to be deconstructed in order to reclaim its structural components for reuse the demolition process will last longer as the components must remain intact, so the operation will be handled with extra attention and a pre-designed accurate sequence as such it is expected to cost more due to the labour and machinery involved.

The collection of data for the involved machinery and the time required for the demolition and deconstruction of a steel structure can differ significantly regarding the location and conditions of the project but a survey conducted by the Cambridge University related to British prices showed that the price of deconstruction is on an average 100 British pounds per tonne of steel more expensive than demolition. If we add on top of that an extra cost for the clean up and modification, if needed, of the reclaimed components then we have the final cost for the reclamation of a tonne of steel. At the same time there is a gap between the price of steel scrap sections sent to recycling and the price of new steel sections. If on the price of scrap the total price of deconstruction and modification is added then the gap between the outcome and the price of new steel sections is the margin for profit from reusing steel sections, so if:

A: price of deconstruction per tonne of steel
B: price of clean up and modification per tonne of steel
C: price of steel scrap per tonne of steel
D: price of new steel per tonne of steel

then the profit margin equals: $PM = D - C + A + B$

If the PM has a positive value then deconstruction is profitable and if PM is negative then the use of new steel is preferable. Figure 3.24 shows schematically the above mentioned approach based on potential market values for a given period showing a how positive profit margin can be created. This figure is based on the logic followed in the Cambridge University's study where a collection and representation of respective data has been undertaken for the British market for the period between 2006 and 2009. In this margin the potential costs for certification as described in Section 2.2.6 may be covered providing a strong incentive to the industry for adapting the concept of deconstruction.

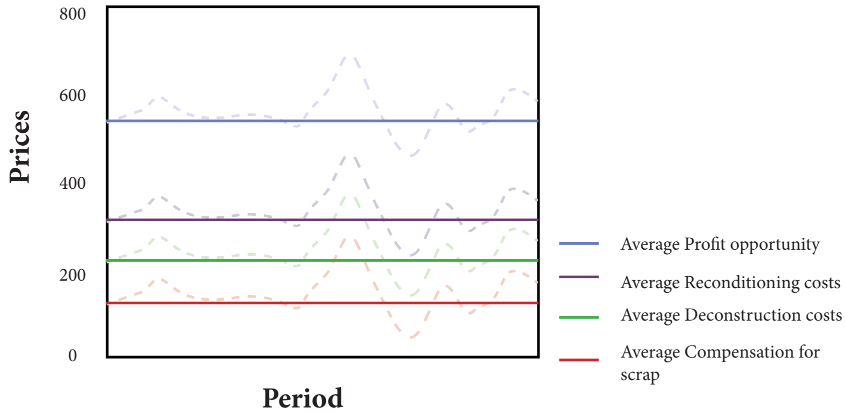


Figure 3.24. Schematic representation of potential profit opportunity from steel reuse

In order to define the deconstruction costs we must take into account a number of different factors that can vary depending on the location, the market status and the fuel prices but the magnitude of the final cost will not change significantly. More specific a deconstruction process includes the cost of the process itself, the machinery (including fuel consumption and operators), the labour to manage the process, the trucks to load the reclaimed material and the transportation costs. Finally as it will be discussed later on this section the capacity of the market to absorb the reclaimed components also defines the financial feasibility of deconstruction as if the components are reclaimed and remain as stock they can rise storage costs and eventually end up to recycling carrying the unused cost of deconstruction.

Implementation in the toolbox

In order to explore the financial aspects of deconstruction and reuse and compare with those of demolition and recycle the above mentioned approach was taken into account. In order to do so and in order to avoid any inconsistences in fluctuating prices of new and scrap steel and demolition and deconstruction costs the user is called to provide these prices as input depending on the local market price. Part from these prices the user is called to provide an additional price per element that might be necessary for the modification and preparation of the elements for reuse. The deconstruction and demolition costs - given per square meter - include a number of expenses as these derive during the processes. The expenses included are:

- **Demolition process**

Demolition costs including the equipment and workers involved in the demolition process

Transportation and Storage costs including the transportation of the debris from demolition to the landfill, the transportation of the recyclable elements to the recycling plant and the storage costs that might be required for the debris in order to be further modified for recycling.

Project costs including the required equipment placed on the construction site for the operation and completion of the demolition process.

Profit and Risk including permits, cost an average 3% added value to the sum of the previously mentioned costs to cover the interest of the contractor. From this final price the total revenues from selling the scrap steel for recycle must be extracted.

- **Deconstruction process**

Since the scope of this thesis is the steel structures and more specifically the structural frames of the steel structures the demolition costs can be distributed to its elements equally.

Deconstruction costs including the removing of the various layers of the building before reaching the structural frame. Those layers are consisted from the external layers of cladding, the HVAC equipment and the composite floors and finally the removing of the structural components.

Project costs including all the necessary equipment like fences, ramps, toilets etc on the construction site along with the machines required for the operation and completion of the deconstruction process. Also the added costs due to the duration of the deconstruction process as it is expected to last more than the demolition. Finally the costs for the survey of the building and the inspection of the components before the process begins along with the costs for the certification of the components before reuse (as discussed in Paragraph 3.2.6).

Profit and Risk including permit costs add an average 10% to the sum of the above mentioned costs to cover the interest of the contractor as deconstruction is an unknown process with underlying risks that might de motivate contractors to get involved if the profit margin is not efficient.

The estimation and precise calculation of these costs are out of the scope of the current research as the main objective is to provide a tool for the quick assessment on the early stage of the design process and as such a general price for the demolition and the deconstruction process as these provided from local contractors, who themselves include the above mentioned costs in their final charge, is considered adequate for the current assessment.

After the assessment of the environmental impacts of the two cases the shadow costs of the reuse and the recycle scenarios will be calculated and added to the estimated initial costs. The shadow costs will be calculated based on the values of the Product Stage of the Environmental Product Declaration (see Section 3.4.3).

Taking into account these parameters the financial assessment proposed in our strategy is calculating a set of eight different values reflecting the financial yield of the concept of deconstruction. The aim is to provide the user with a set of results that can be easily comparable for a better understanding of these impacts. The financial indicators calculated during this assessment are presented in Table 3.1 along with the formulas for their calculation.

Financial Indicators	Calculation formula
Final Recycle Cost / m^2	(DemolitionCosts * Area - ScrapPrice*Quantity + newPrice*Quantity + ShadowCostsRecycle) / Quantity
Final Recycle Cost / tonne	(DeconstructionCosts * Area - AdditionalCosts*no. of Sections + ShadowCostsReuse) / Quantity
Final Reuse Cost / m^2	(DemolitionCosts * Area - ScrapPrice*Quantity + newPrice*Quantity + ShadowCostsRecycle) / Area
Final Reuse Cost / tonne	(DeconstructionCosts * Area - AdditionalCosts*no. of Sections + ShadowCostsReuse) / Quantity
Profit margin / m^2	FinalRecycleCost/m^2 - FinalReuseCost/m^2
Profit margin / tonne	FinalRecycleCost/tonne - FinalReuseCost/tonne
Final Recycle Cost	FinalRecycleCost/m^2 * Area
Final Reuse Cost	FinalReuseCost/m^2 * Area

Table 3.1. Financial Indicators and thei respected formulas used in the strategy

Where:

DemolitionCosts:	The given demolition costs per sq.meter provided by local contractors
DeconstructionCosts:	The given deconstruction costs per sq.meter provided by local contractors
Quantiy:	The total quantity of steel (in tonnes) as calculated during the analysis
AdditionalCosts:	Any required additional modification costs per element after deconstruction
ShadowRecycleCosts:	The shadow costs of recycle as calculated in the assessment (Section 3.4.3)
ShadowReuseCosts:	The shadow costs of reuse as calculated in the assessment (Section 3.4.3)
no. of Sections:	The total number of sections of the building under assessment
Area:	The total area of the building under assessment

Environmental aspects

As calculated by Steel Construction Institute (SCI) through a formula that relates the environmental burden at each stage of recycling to those associated with the primary and previous re-cycling processes and to the re-cycling yield, the burden of each stage is gradually reduced but is expected to reach a constant minimum value after some iterations as shown in Figure. 3.25 (The detailed calculations can be found in Appendix I).

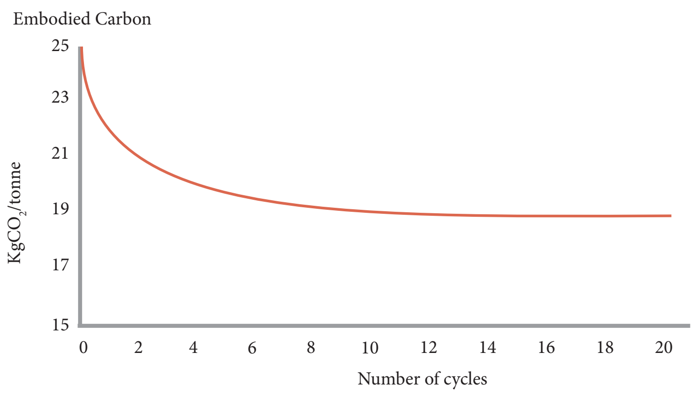


Figure 3.25. Impacts of environmental burden of recycling in relation to the number of cycles utilized

This is due to the fact that at the end of each cycle and in order to recycle the reclaimed components an extra energy is added to the process for the recycling to take place. On the other hand if we examine the effect of reuse on a closed system (each reclaimed steel section is either re-cycled or reused into the same cycle) we can consider that the benefits from the reuse of each component equals to the avoided burden that the recycling of this section and remanufacturing would bring. This assumption does not take into account the allocation of the by-products of recycling to other systems and assumes that the reclaimed steel has an unrestrained reuse yield meaning that every reclaimed element will be reused in the system.

The quantification of the environmental impacts of recycle and reuse is a process that, when it refers to more than one cycle, is difficult to quantify. Also it is a theoretical process as the reuse or recycle of steel sections in more than one cycles is not a common phenomenon and due to its low paste nature is difficult to record. The prices, the environmental burden of the involved material and processes and the efficiency of the recycling and steel manufacturing process are always subject to change. Finally the system boundaries that the user defines for the assessment of these impacts can differ significantly providing different results for each case.

Working in this direction R. Geyer, T. Jackson and R. Clift (Geyer et al.,2002) conducted a research to quantify the financial and environmental differences among reused and recycled components. To do so they worked on some assumptions that eliminated the risks that the above mentioned uncertainties might bring. They assumed a closed system where recovered end-of-life sections are recycled into or reused as sections again meaning that material flows and stocks remain constant. At the same time they assumed a steady system meaning that the energy consumption per tonne of steel remains also constant. As a closed system, inputs like scrap or iron ore for the BF and EAF route are not taken into account and the analysis focuses on the interaction between components. The writers produced results for three different scenarios where the parameters that determine the material flows are the reuse yield r_c, the component recovery rate C_c and the material recovery rate C_m .The scenarios were defined by these parameters where the first scenario assumes an unconstrained reuse yield, meaning that every reclaimed component will be reused in the system. The second scenario assumes a limited technical feasibility (LTF) where only part (r_c*C_c) of the deconstructed sections (C_c) are refabricated and re-marketed and the third scenario, the limited market demand (LMD) where all C_c deconstructed sections are refabricated but only a percent r_c*C_c is absorbed by the market. The results focus on three main cases. One is the case of total recycle, the second of total reuse and the third and one of special interest is the case of shifting from recycling to reuse.

For the last case the results of their research showed that when the reuse yield is unconstrained then the benefits from reuse are substantial resulting to 2.5 lower environmental impacts and 1.5 reduced costs in comparison to recycling (Figure 3.26). For the scenario of LTF where the reuse yield is equal to 0.33 meaning that only 1/3 of the reclaimed sections can be reused, the results revealed that increasing the deconstruction rate after a certain value doe not deliver any additional reduction to energy and cost savings Figure 3.27. Finally for the LMD scenario the results showed that while the reuse rate is increasing the environmental and costs impact decrease slightly and eventually increase to a point where they even surpass their initial values as the market is not able to absorb the reclaimed elements for reuse as the unused elements return to the EAF route for recycling or remain to stock yards with additional storage costs Figure 3.28.

Finally , for the first scenario, there was a focus on the calculation of the marginal cost per unit reduction of energy consumption expressed as the ratio dC/dE. This value indicates if the energy savings from a system change results also in cost saving and to what extent. The results showed a value of 0.98 meaning that every change in energy saving reflects almost in absolute values to cost savings.

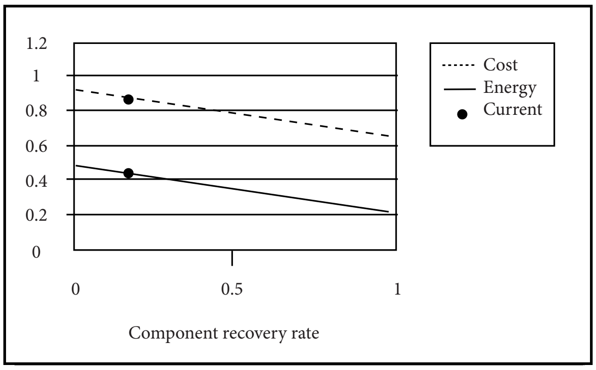


Figure 3.26. Shift from recycling to reuse- Normalised cost and energy as function of Cc (c = 0.99) (based on: Geyer et al, 2002)

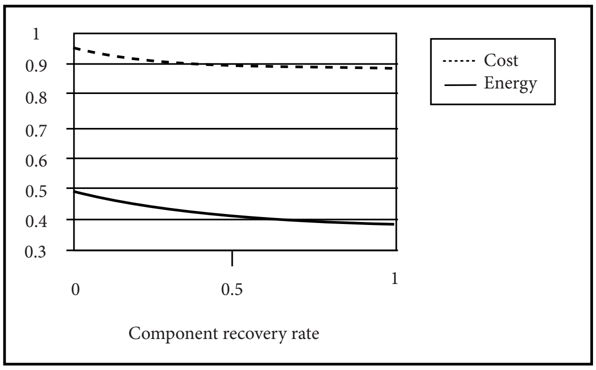


Figure 3.27. Shift from recycling to reuse with constrained reuse yield- Normalised cost and energy as function of c0 (c ~ 0.99) for LTF scenario (based on: Geyer et al, 2002)

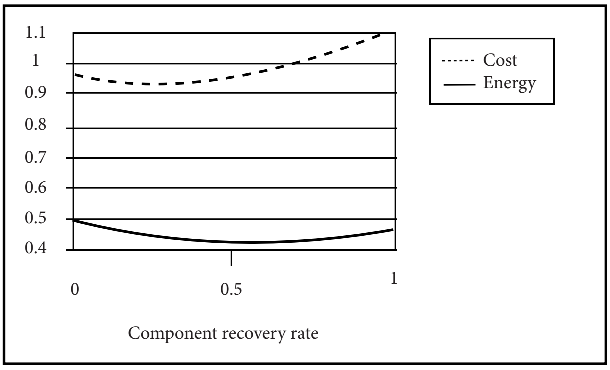


Figure 3.28. Shift from recycling to reuse with constrained reuse yield- Normalised cost and energy as function of c0 (c ~ 0.99) for LMD scenario (based on: Geyer et al, 2002)

One can conclude that the comparison among recycling and reusing components is not always a straight forward process and depends highly on the nature and constrains of the system. The basic parameters that influence both environmental and financial impacts is that of the recycle and reuse yields of the system and the number of cycles that will occur during the system's life-span. Also the nature of the system, if it is a closed or an open system regarding the energy and material flows to and from other systems influence the final results significantly. So there is not a safe conclusion to draw although it is clear that when the question of designing for deconstruction or not arises offering a potential shift from recycle to reuse this shift is beneficial especially when we refer to a closed system of a building where all of its components are about to be reuse for the construction of a new building after the end-of-life of the initial one.

3.3. Embodied Energy & Embodied Carbon

In this section there will be a review of the Embodied Energy (EE) and Embodied Carbon (EC) factors and how they influence the performance of a design in terms of sustainability. In first there will be a focus on how EE and EC are becoming more and more a crucial factors to this extend due to the continuous reduction of operational energy through the entire life-cycle of a project. Forward on, the research will focus on the EE and EC of steel structures and how this is taken into account in the cases of recycle and reuse. A major question arising is weather the recycle process is actually an efficient sustainable measure as during the process the total EE and EC of the material is increasing significantly.

Embodied Energy

Embodied Energy (EE) is an accounting methodology which aims to find the sum total of the energy necessary for an entire product life-cycle.

Embodied energy is usually measured as the energy used for the production of a unit of a material, component or system of a building. It is expressed in (MJ) or (GJ) per unit of area (m^2) or volume (m^3) or weight (Kg) and their multiples. It is though a quite difficult calculation to make due to the large amount of data and the diversity of the sources it emanates. The embodied energy for buildings is divided to two main categories. The initial embodied energy and the recurring embodied energy.

The **initial embodied energy** in construction industry includes the nonrenewable embodied energy that is consumed for the extraction of raw materials, their transportation and process.

Initial embodied energy is divided into two subcategories.

The Indirect energy that is consumed for the extraction of raw materials and their process along with the fabrication of the components and any transportation energy involved in these processes.

The Direct energy that is consumed due to the transportation of the materials/components to the site and during construction process; and

The **recurring embodied energy** represents, as the name declares, the energy consumed for maintaining, repairing, restoring or replacing materials or building components of a structure during its life cycle.

Since the proposed strategy will deploy the Environmental Product Declaration (EPD) for the conduction of Life cycle analysis of the building under assessment these categories should be affiliated to the proposed modules as described in Section 3.4.2 and in EN 15804:2012 (Section 6). So the Indirect embodied energy is exposed in module A1 of the Product stage of an EPD while the Direct embodied energy is exposed in modules A2, A3, A4 and A5. The Recurring embodied energy is exposed in the Use and Maintenance stage of an EPD and specifically in modules B1 - B5.

Embodied Carbon

In the same terms the production and assembly of construction materials and components is producing CO_2 emissions mainly due to the use of fossil fuels for transportation and electricity generation and the use of carbonaceous materials. Like embodied energy also CO_2 emissions named as "embodied carbon" is divided to initial and recurring embodied carbon covering the different stages of materials and components life cycles in the same manner as embodied energy does. The metric unit to measure embodied carbon is ($kgCO_2$) per unit of volume (m^3) or weight (kg).

Among the two factors the main research so far was focused on embodied energy as the results were easily translated and understandable. Nowadays though Carbon emissions seem to attract the interest of the researchers and of the industry as legislation tends to focus on carbon emissions, a fact that makes essential to know the amount of carbon produced for the production of building materials. Secondly as the use of renewable energy sources is gaining more and more space with in industrial production even if it is used it has lower or no carbon emissions to air. Finally the calculation of embodied carbon includes also the emissions of greenhouses emitted during the actual production process and not only those produced for the process. (Tingley, 2012). It is important to highlight though the necessity of taking both factors into account simultaneously. As Brocklesby states achieving zero carbon emissions might result to increased embodied energy of the building. (Brocklesby, 1998). There is an argument that in these terms embodied energy should be taken into account in the definition of zero carbon buildings and the most characteristic example that highlights this argument comes from the Green Building Council of Australia that is stating: 'buildings need to have zero emissions in their construction, operation and embodied energy to be truly carbon neutral'.

The operational energy of a building though is considered to be the main contributor to a building's energy consumption during its lifetime. The last decade there is in fact much attention to reduce this demand and new technologies and innovations made this target possible. In return the embodied energy of a construction due to its components is acquiring a larger percentage of a buildings total energy consumption over its lifetime. In these terms it is essential to examine the EE and EC of structures and define ways to reduce them in the same terms that operational energy has been reduced. This can be accomplished either by changing the selection of building materials choosing materials that demand less energy and emit less carbon during their production or by re-using the existing materials from structures that have completed their life-cycle and are not in use anymore. This way the EE that is already used for their production and the burden of the CO_2 produced is not wasted, instead it is being re-used for another purpose extending the materials' overall life span.

Energy consumption and CO_2 emissions at the end-of-life of buildings

After a building reaches its end - of - life stage it is either demolished or disassembled. The energy consumption and CO_2 emissions during these processes is also something that must be taken into account. In general the acquisition of related data is not easy nor efficient since the different demolition practices, the diversity of tools and the diversity of their efficiency especially within a period of 50 years makes it difficult to validate the selected data and use them in a general form.

In order for designers and engineers to understand the impact of their choices and the ways they can influence the EE and EC of a structure it is essential to use life-cycle assessment tools for every material and component they are working on as the potentials for paradigm shifts in structural design due to the lessons learned from LCA could be significant. A 'cradle to gate' or 'cradle to grave' life cycle analysis though is not sufficient to expose the benefits from reuse or recycle. A systematic approach to allocate impacts and benefits among products/components that are being recycled or re-used is necessary for the designer to understand the potential benefits that such processes can bring. As described in the previous section, such approaches are not common practice and in many cases a method specified by the user must be implemented - always in accordance with directives - to take into account these benefits.

Allocation methods for Reuse and Recycle

A basic problem during this research was to define a way to allocate the environmental impacts of a product when this product has multiple life - cycles. If a product A has the same embodied energy as a product B but a longer life cycle then product A has less environmental impacts per year. Using these types of products/components in buildings can reduce significantly their environmental impacts. There is a lack of specific methodologies though that would address exact procedures for this allocation. Previous results from studies are sometimes conflicting as some support that the savings from reuse or recycle should not be taken into account for the assessment of the new building that they will be used for (Ramesh et al, 2010) while others (Brocklesby, 1998) assumed that recycled or reused materials no longer have an embodied energy once removed for a new use.

This diversity of approaches can also be found within standards and assessment tools that are currently used for the environmental assessment of buildings . Below there is a short review of the recommended approaches for this purpose from the related European directives, the Building Research Establishment (BRE) and SimaPro, a Life cycle analysis tool.

BS EN ISO 14040 and **BS EN ISO 14044:2006** , the European directives for the conduction of life cycle analysis of products suggest that allocation processes for reuse and recycle should follow those methods applied for the allocation of impacts between co-products. Specifically ISO 14044:2006 states that whenever the avoidance of allocation is not possible the inputs and outputs of the system shall be partitioned between products or functions in a way that reflects the underlying relationship between them. While in section 2.1 it is mentioned that impacts from raw materials processed to produce products, in case of a second use of the product shall be attributed to the first use while those impacts coming from materials used for repair or replacement shall be attributed to the reuse. This way ISO highlights the need to carefully examine if the material is part of an open or a closed loop as different allocation procedures apply. A closed loop procedure apply to those materials that their properties do not inherit any changes so as the reuse or recycling process displaces the virgin material the allocation is avoided. Open loop allocation procedures apply where again no inherit change to the material properties occurs but the material is recycled into a different system. It is also suggested that allocation should be based, with a preference sequence, on physical properties or on economic value or on the number of uses of the material.

Building Research Establishment (BRE) a former governmental and currently private organization in UK responsible for research, consultancy and testing of British construction sector and owner and operator of BREEAM certification system suggests a much more completed methodology where the allocation procedure is based on the economic value. This means that the user has to define what is a base material and a base point for it. So for a steel section in case of recycling allocation would be taken up till the point that is useful for the section, that is the steel slab which would be called the base material. While for the reuse of it the base point would be after the section manufacture and the base material would be the section (Tingley, 2012). One of the main problems of this method is rising from the fact that is hard to predict the value of carbon or material prices and how to incorporate inflation and predict scrap prices.

SimaPro is the most widely used software for life cycle analysis within construction industry. SimaPro besides 'cradle to gate' and 'cradle to grave' assessment methods has also a method to deal with future reuse and recycling. The results of the product's impacts assessment have both positive and negative values. Positive values represent the environmental impacts caused during its life cycle while negative results demonstrate the potential advantages that recycling and reuse might bring. These advantages represent the difference between the impacts caused by deploying new virgin materials and the avoided impacts from deploying them due to reuse or recycle.

Implementation in the toolbox

The assessment and exposure of the embodied energy and embodied carbon of the building under assessment is undertaken in order to provide an extra assessment indicator to the users and help them understand the impacts of their design choices.

In order to assess and expose the total embodied energy and embodied carbon of the structural elements of the building under assessment and allocate the results to the reuse and recycle scenarios that the user will define it was crucial to follow one of the existing methods or form and describe one according to the directives mentioned above. Before moving to the allocation process it is important to define the boundaries of the system that is about to be assessed.

System boundaries

The boundaries set for the assessment of the embodied energy and embodied carbon are covering the production process of the components for the initial building including raw material extraction, transportation and process of them for the production of the required components. This energy and carbon as described above are represented as the initial, indirect energy used and are exposed in module A1 of the Product stage of an EPD. The data used for this assessment are based on the Inventory of Carbon and Energy (ICE) provided by the university of Bath. The referred system is considered closed meaning that the potential benefits arising from the reuse or recycle of the components will be allocated from the initial to every next design in the same system.

Allocation process

The preferred methodology used for the allocation process for the reuse scenario is based on the European directives' suggestions and particularly on the suggestion of allocating the impacts based on the number of potential reuses of the component. So after the assessment of EE and EC of the components of the building the results are equally divided to the times that the building is planned to be reused. In order to demonstrate the results of the allocation they will be divided to scenarios. Each scenario is based on the times that the building is reused and will follow the scheme of Figure 3.29.

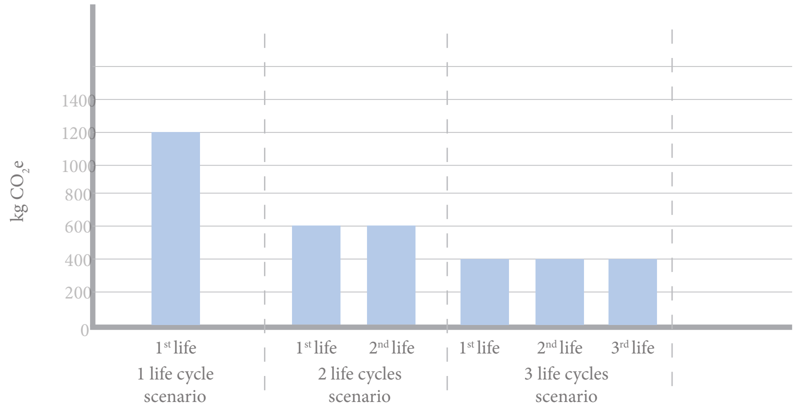


Figure 3.29. Embodied carbon schematic allocation diagram for reuse scenario

Regarding the recycle scenario the allocation scheme that is explained in Paragraph 3.2.7 will be used to calculate the EE and EC for each cycle. The formula explained in Appendix I can be applied, as explained, to any environmental indicator as it refers to the potential benefits for a Kg of steel. As such it will be used to calculate the EE and EC for each cycle of the process. The approach is schematically shown in Figure 3.30.

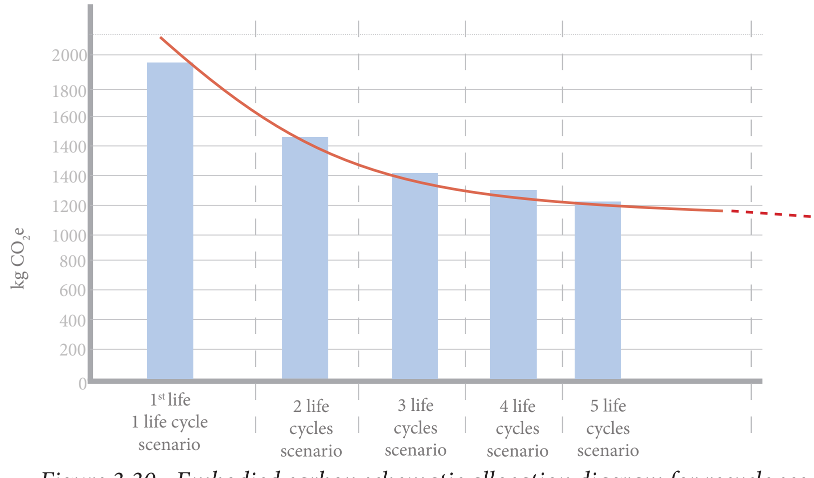


Figure 3.30. Embodied carbon schematic allocation diagram for recycle scenario

In both scenarios the allocation is taking place only regarding the components that are already manufactured for the initial building for the reuse case and remanufacture under the same conditions for the recycle case. In case more components are needed the EE and EC required to produce them will be accumulated to the new building's impacts.

For the purposes of the toolbox the assessment is limited to two life-cycle scenarios as the scope is to perform an assessment for the two proposed scenarios. As such the embodied energy and carbon for the Reuse scenario is divided by two while for the Recycle scenario in multiplied my (1-0,28) where 0,28 is the reduction ratio as calculated by the SCI formula (see Appendix I).

3.4. Life-cycle Assessment (LCA) and EPD

This section will go through Life-cycle assessment methodology and how a LCA is a decision maker regarding sustainable driven designs. A LCA can expose the actual impacts a material or process has on the environment and is of particular interest to examine how the LCA factors can be translated in order to become comparable. In this section there will be an overview of the developed approach that will be implemented later on in the proposed strategy and how these approaches are complying with the related European directives (ISO 14040 and ISO 14044) developed for the initial LCA approach.

3.4.1 Introduction

A Life-cycle Assessment (LCA) *"addresses the environmental aspects and potential environmental impacts (e.g. use of resources and the environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e. cradle-to-grave)"* as described in ISO 14044:2006, 'Environmental management - Life cycle assessment - Principles and framework'.

An LCA study can be divided in four phases:

- the goal and scope definition phase,
- the inventory analysis phase (LCI phase)
- the impact assessment phase (LCIA phase)
- the interpretation phase (LCI phase)

(ISO 14044:2006)

The scope of a LCA, including boundaries and level of details, depend on the subject intended to study and can differ considerably along with the depth and the breadth of an LCA scope.

The LCI phase is the second phase of a LCA study and is an inventory in/output data regarding the system under research.

The LCIA phase is the third phase of an LCA study and provides additional information for the assessment of the LCI results of a product's system.

While LCI phase is the last phase of the LCA process and is the summary of an LCI or LCIA or th combination of both, in favour of further discussion, recommendations and decision-making regarding the goal and scope definition of the study.

A Life-cycle assessment study on a building level can reveal to the designers and engineers the overall environmental impacts of their decisions regarding the materials used and chosen geometries. A LCA study is taking into account the total life cycle of the product under assessment starting from the extraction of raw material till the end-of-life and disposal. In the described LCA methodology in ISO 14044 (section 4.3.4) allocation process for reuses and recycle are taken into account. If these allocation processes are implemented into a LCA assessment study can reveal the potential benefits of extending a product's life cycle be reusing it partially or as a whole. In these terms a LCA study is considered adequate for the purposes of this research. The requirement that arise though is to form a strategy that can be applied for the allocation of the impacts of a steel structure to a new design within after the end of its first life cycle. Below there is a schematic representation of the production, reuse and recycle flow of steel products.

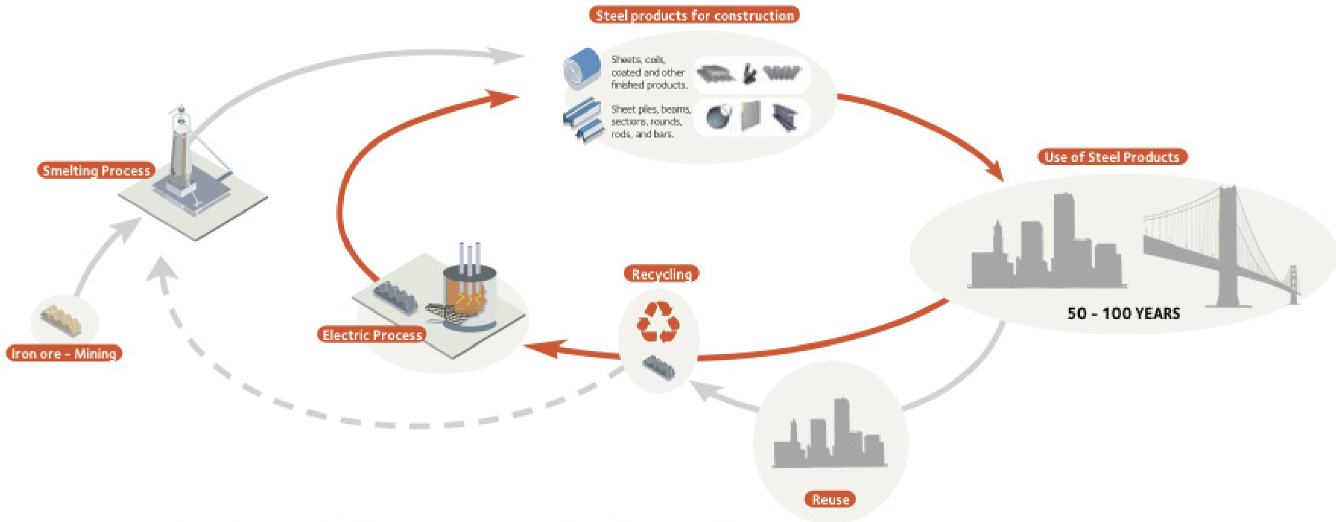


Figure 3.31. Production, Use, reuse and recycle flow of steel products (www.arcerolmittal.com)

Current researches on the topic have shown that a modular structure might have slightly higher environmental impacts on their initial installations in comparison to a fixed structure but these results are changing after the end of the first life-cycle scenario. The fixed structures end up having significantly higher impact as an LCA includes factors as Primary Energy Demand (PED) that represents the energy consumed to produce and manufacture materials and components or other indicators as Construction/Manufacturing Waste (C/MW) generation where modular structures are scoring very low as the usual demand for new material is less than 5% while on fixed structures reaches almost 100% reflecting to an also very high amount of waste production. (HearmanMiller Healthcare, 2009)

3.4.2 Environmental Product Declaration (EPD)

As both businesses and end-users give gradually more attention to the environmental impact of the products they produce and use there is a constant effort for collection and compilation of relevant environmental data. This data are in return used to produce more accurate life-cycle assessments (LCA) providing this way the opportunity for constant improvements of products and services regarding their total environmental impact. These assessments though have different ways to be presented and sometimes are not provided in a clear and comparable form for evaluation.

In order to promote the use of this data there is a need for a transparent and easy to validate form of communication. The Environmental Product Declaration known as EPD is a mean to do so providing to the manufacturers a standard approach to assess the environmental impacts of their products and to the users an effective framework for direct product comparisons. (UL, 2011)

Besides that EPDs contribute to achieve the primary goal of LCA which is to improve harmful production practices that have impact to the environment and preserve the availability of natural resources. These goals are promoted through EPDs because they can be used as diverse tools depending on the parties of the industry they are referring to and the purpose they are conducted. So they can be used as management tools for the monitoring improvement of environmental data communication tool for environmental product information in order to promote an overall awareness, evaluation tool for decision making processes, procurement tool for governmental, institutional or corporate environmental objectives and finally as an action tool for the public in order to identify and evaluate efforts regarding the improvement of products environmental impacts.

Environmental product declaration studies though are still optional for any kind of product or process, though the fact that are anymore included into building certification schemes such as DGNB (the German Sustainable Building's Council) make them more and more popular to the involved parties promoting their use.

Differences between LCA and EPD

An EPD is a particular form of Life Cycle Assessment that provides environmental information in common formats and rules known as Product Category Rules(PCR). It is a Type III eco-label meaning that provides information according to fact-based documents related to specific categories. Such labels, in contrast to labels of Type II and Type I, require independent validation for the environmental impacts of a product providing this way more transparent results. The difference between an LCA and an EPD is that an LCA is a component of an EPD that evaluates the impacts of a product throughout its life stages providing a clear overview of the resources, energy, raw materials and water consumed for the production, use and end of life of a product. Although an LCA can provide the needed data to improve a single products impact over time it can not be easily used to compare products within same categories. In order to do so LCAs of different products must be conducted under the same set of PCRs but still require an EPD to provide a transparent and easy to understand platform for the evaluation of the product's environmental impacts.

Product Category Rules (PCRs)

A PCR is the document that defines the type of information that needs to be calculated and exposed in order to ensure that the EPD reflects the environmental impacts of a product. It also provides guidelines for all the action related to the development of the declaration. ISO 14025 clearly states that in any case an existing PCR must be used whenever suitable but does not exclude the possibility for the user to create a new PCR if necessary. In order though to preserve transparency and ease of use it is asked that these PCRs are maintained publicly available. The procedure for the development of a PCR document is described in detail in ISO 14025:2006 Section 6.7.

Framework

The EPD's framework is developed and explained in ISO14025:2006 under the name "Type III environmental declarations – Principles and procedures" where quantified environmental information on the life cycle of a product are presented in order to allow comparison between products fulfilling the same purpose. According to this ISO the use of such declaration are primarily but not exclusively for B2B purposes, the data used are verified life cycle assessment, life cycle inventory (LCI) and information modules complying with the ISO14040 series regarding LCA processes and are subject to the administrators of a programme operator such as companies, associations, public agencies or independent scientific bodies. An EPD can be used either externally where the ISO proposes the obligatory review from an external party that will verify the reliability of the data used before being published or internally within companies contributing to the decision making progresses, environmental product development, site selection e.t.c.

The involved parties for the development of environmental labels include material suppliers, manufacturers, associations, users, purchasers, producers, NGOs, independent parties and others while in the related ISO it is strongly recommended that 'open consultation' should take place in order to ensure credibility and transparency in the operation of the program.

Comparability of results

Besides transparency that is ensured by requirements as those described above the EPD provides the possibility to the user to produce comparative results for the same or different products. In order though for those EPD results to be comparable ISO14025 sets some requirements. Some of the main requirements are described as follows:

- the product category definition and description to be identical
- the goal and scope definition of the LCA of the products according to ISO14040 to have
- Identical functional units
- Equivalent system boundaries
- Equivalent data description
- Identical criteria for inclusion of inputs and outputs
- Equivalent data quality requirements

data collection, calculation procedures and allocation of material and energy flows to be identical for the Inventory analysis

- Impact categories selection and PCRs, if any, to be identical
- Identical predetermined parameters for reporting of LCA data
- Equivalent materials and substances to be declared
- Equivalent instructions for the content and format of the Type III environmental declaration
- Equivalent period of validity

Modularity

Part from the comparability of the environmental impacts that an such a process can offer the EPD is also considered to be modular, meaning that for an example an EPD for cement can used with an EPD for aggregate to produce an EPD for concrete. In this case the LCA-based data for materials, parts or other inputs are referred to as information modules and represent part or the whole life-cycle for those materials or parts. Those information modules may be combined to develop a Type II environmental declaration only if they are adjusted with the PCR for the product category.

Application of LCA Methodology

To produce comparable and modular result the program operator must ensure that the information regarding general methodological aspects of Type III environmental declaration such as calculation methods, system boundaries and requirements for data quality, is made available.

There are though a set of parameters resulting from LCA that must be predetermined such as a set of impact category indicator results, a set of inventory results that represent elementary flows and a set of data like for example waste that do not represent elementary flows.
The related ISO provides two optional paths for the development of Type III environmental declarations as shown if FIGURE 2.10. These paths are:

- Option A: LCA study including the phases: goal and scope definition; inventory analysis (LCI); impact assessment (LCIA); interpretation
- Option B: LCA study including the phases: goal and scope definition; inventory analysis (LCI);

interpretation

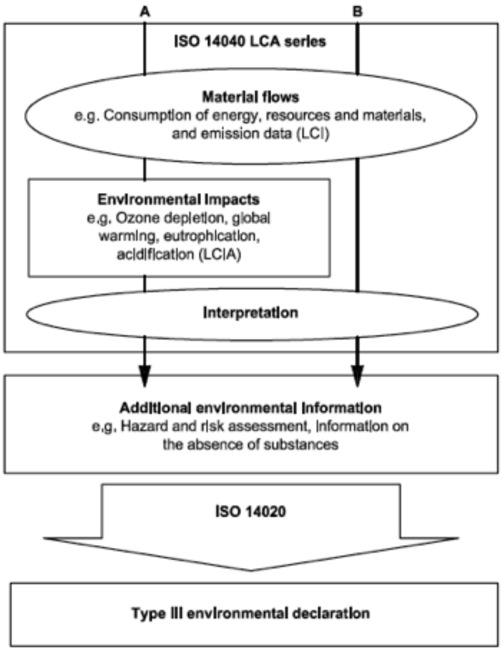


Figure 3.32. Different options for Type III environmental declarations (ISO 14025:2006)

Data use from LCA methodology

An EPD should include relevant data from LCA and LCI studies and /or information modules. For each of these subcategories of the LCA methodology a set of data categories are required but this requirement does not limit the program operator of including more depending on each study's needs. The required set of data for each category are:

1. for the LCI analysis and according to the PCR:

   - Consumption of resources including energy , water and renewable resources
   - Emissions to are, water soil

2. Indicators from the life cycle impact assessment (LCIA):

   - climate change - Global Warming Potential(GWP),
   - depletion of the stratospheric ozone layer,
   - acidification of land and water sources,
   - eutrophication,
   - formation of photochemical oxidants,
   - depletion of fossil energy resources, and
   - depletion of mineral resources;

3. other data such as quantities and types of waste produced

Finally a set of additional environmental information related to the environmental issues other than those derived from LCA, LCI and information modules, shall be included, when relevant in a Type III environmental declarations. In order to identify the significant environmental aspects there is a set of data that should be taken into account and are described in ISO14025:2006 section 7.2.3 along with the requirements for additional environmental information.

EPD for building products

The sustainability assessment of Buildings as formed and described in the European standards (NEN-EN 15978) are not only focused on the environmental performance of the building. Sustainability includes and requires the product to perform equally on environmental, social and economic level. For this purpose a series of European standards developed by CEN/TC 350 have been developed to assess the Sustainability of construction works in every of these three levels and for every level of construction works. The work program and the related directives are shown in the diagram below.

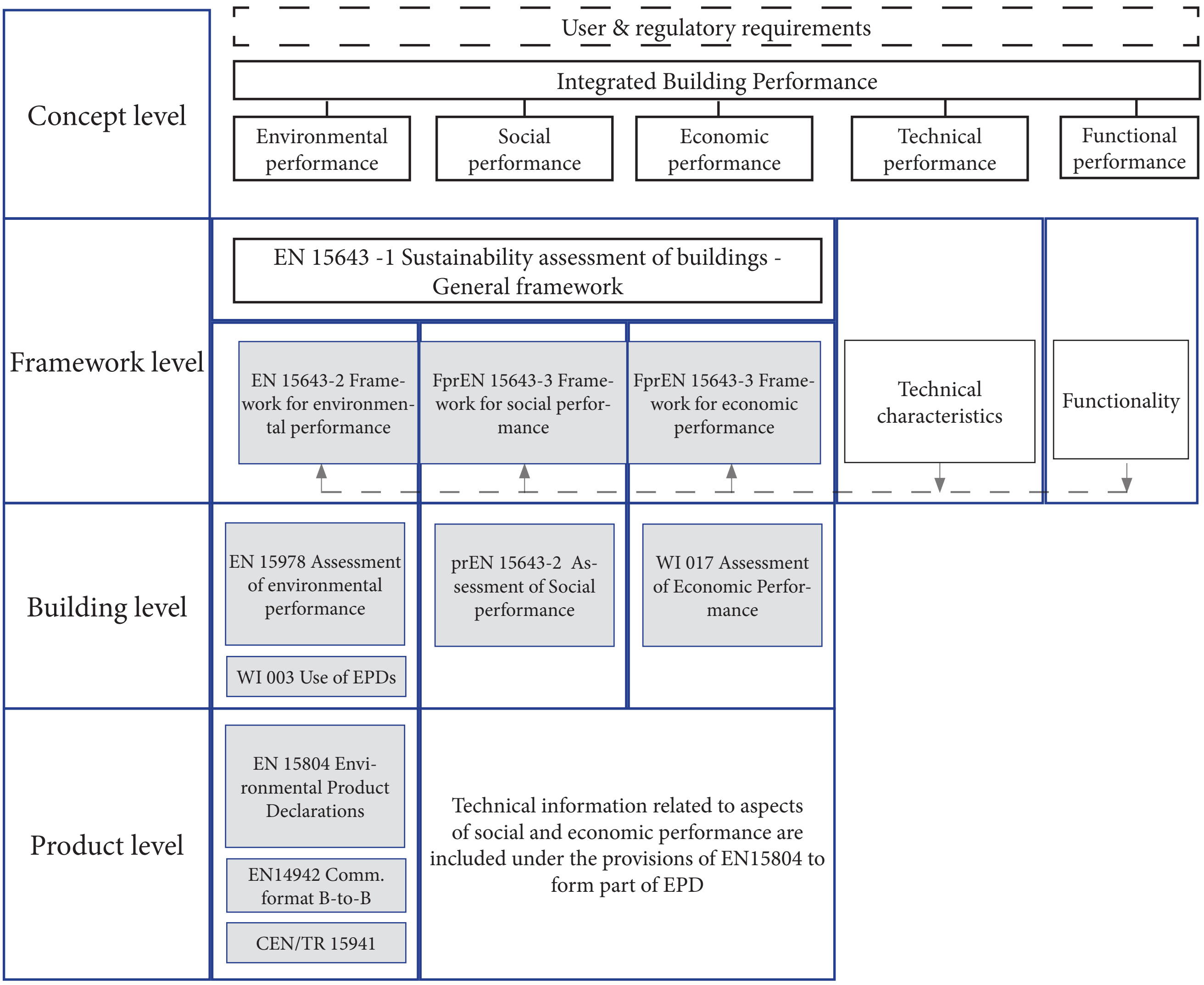


Figure 3.33. Work program and related directives (NEN-EN 15804:2012)

Implementation in the toolbox

The ISO series for sustainability of construction works part from ISO14025 include among others EN 15804:2012 that is a valid standard for conducting EPD for construction products and EN 15978 for the assessment of the environmental performance of buildings. Since part of the scope of this thesis is to provide assessment for the structural components of structures this section will only focus on how an EPD is conducted according to EN 15804 and how the results are interpreted according to EN 15978. Since EPD allows the user to combine data under specified conditions due to its modularity as described above, the assessment of the total structural skeleton of each structure will be conducted by setting identical criteria for all the components that form it and by aggregating the end results of their assessment. On a building though, it is necessary to adapt some factors such as the Required Service Life and Estimated Service Life to produce liable results that will reflect in a robust way its environmental performance, as it will be explained in detail later on.

The aggregation process to form a final assessment for a building is shown in the Figure 3.34 below. In this figure the different levels of aggregation and aggregation steps are presented as suggested in EN 15978.

In the current thesis the aggregation process from element level to building level is being applied in order to form EPDs for the structural frame of the building. The aim of these EPDs are not for publishing reasons but currently only for internal use and in order to give the user the chance to have comparative results among different design choices. The user might use the EPD as decision making asset, so in these terms an external review of the EPD is not required.

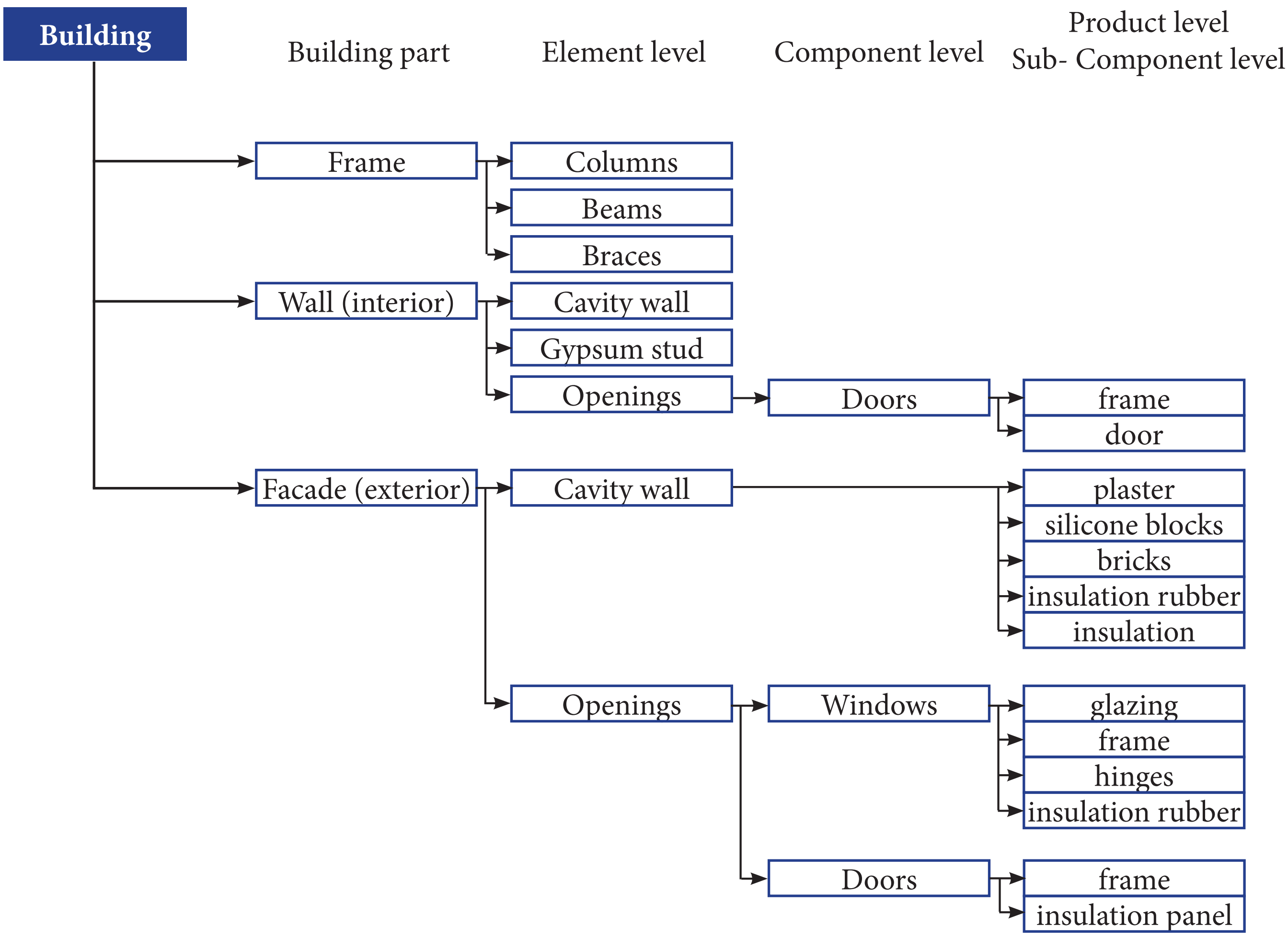


Figure 3.34. Example of different levels of aggregation (EN 15978:2011)

Since the objective of this thesis aims to provide through a tool the necessary framework for the users to assess their design choices in an early design stage the parts of social and economic performance as these apply to EPD framework will not be taken into account. The required data to perform these assessments demand further investigation and are mainly influenced by local factors , social assessment data need to be gathered and evaluated by region and economic related data differ for each location and a generalization and assumptions might lead to misleading results. So these parts are currently out of the scope of this research but could be implemented under the same framework in a later stage.

Life cycle stages and Modules

The information provided by an EPD covers all the life cycle stages of a product and is subdivided into 4 different modules that represent the "cradle to grave" part of it and an extra module that declares the reusing or recycling benefits that the product can return after the end of the first stages. The module groups are formed as "Product stage", "Construction process stage", "Use stage", "end – of life stage" and "Benefits and loads beyond system boundary" and subdivided accordingly to A1-A3, A4-A5, B1-B7, C1-C4 and D as shown in Diagram 3.1. The module of product stage including A1-A3 stages is the only mandatory in order for the EPD to apply to the EN 15804. The rest are optional. There are three different approaches regarding the modules covered from the EPD. One that can cover only the product stage representing a "cradle to gate" approach, one that can include further life-cycle stages representing a "cradle to gate with options approach" and finally one that covers the whole life cycle of a product including product stage, installation to the building, use and maintenance, replacements, demolition, waste processing for re-use, recovery, recycling and disposal and is representing a 'cradle to grave' approach. The last is also covering information module D and is the one that is going to be applied for the assessment of the impacts of the preliminary design along with re-use and re-cycling options and their impact for the purposes of this thesis.

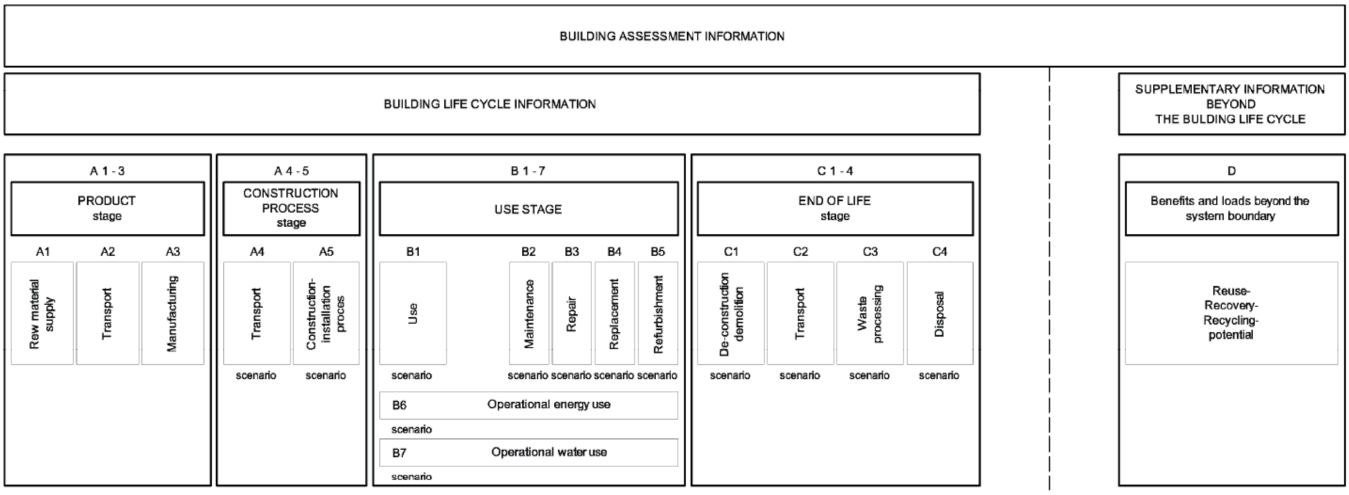


Diagram 3.1. Types of EPD with respect to life cycle stages covered and life cycle stages and modules for the building assessment (ISO 15804:2012)

System Boundaries

The system boundaries are defined by the system boundaries of the different modules. These boundaries have been established according to IS) 15804:2012 clause 6.3.4 and EN 16978:2011.

Product stage (A1-A3)

The Products stage shall include the following information modules:

- A1: extraction and processing of raw material and process of secondary material input
- A2: transport of raw material to the manufacturer and production of pre-products
- A3: Manufacturing of the products and packaging

The Modules A1, A2 and A3 are usually aggregated in on module A1-A3 but may also be declared separately. The provided data for early design process decisions are preferably aggregated as stated in clause 9.4 of EN 15978:2011. Due to this specification and the purpose of this toolbox the rest of the data for the information modules will also be provided in an aggregated form.

Construction process stage (A4 – A5)

The construction process stage shall include the following information modules:

- A4: transport of construction product from the factory gate to the construction site
- A5: installation of the product to the building and the wastage produced from the installation process

The transport and installation process depend on the building where the construction product is used. For the assessment on a building level resources such as water used during the installation, energy for extra on-site operations or storage and waste processing are included.

Use stage (related to building fabric) (B1-B5)

The Use stage related to building fabric shall include the following information modules:

- B1: use or application of the installed products
- B2: maintenance
- B3: repair
- B4: Replacement
- B5: refurbishment

Module B1 includes all the emissions to the environment that the use of the product might produce during its use while modules B2, B2, B4 and B5 covers all the necessary actions for the maintenance of the products during the building's life cycle including any extra actions such as transportation, use of water and energy, waste production and end –of – life processes related to the maintenance process.

Use stage (related to the operation of the building) (B6-B7)

The Use stage related to the operation of the building shall include the following information modules:

- B6: Operational energy
- B7: Operational water

Operational energy and water use modules include the total use of each during the operation of the product (building) along with the environmental aspects and impacts of the processes associated to this use like transportation of any waste produced during the use.

The operational water use accounts from the moment the building is delivered to the user while operational energy can be assessed through standard assessment procedures.

End - of - life stage (C1-C4)

The end-of - life stage of a product starts when it is replaced, dismantled or deconstructed from the building or at the end of the building's life cycle. And does not provide any further functionality.

The stages related to this information module are:

- C1: deconstruction, demolition
- C2: transport to waste processing
- C3: waste processing for reuse, recycling and energy recovery
- C4: disposal and associated processes

During this stage the materials leaving the system are considered as waste until they reach their end-of-waste state. According to EN15804 clause 6.4.3 this stage is reached when a material is commonly used for specific purposes, has a demand or an existing market for it, fulfils technical requirements for specific purposes and its use is not leading to adverse effects.

The benefits from the use of materials reached their end-of-waste state or from utilizing energy arising from waste disposal processes of these materials are presented in Module D of the EPD.

Module D (Benefits and loads beyond the product system boundaries)

The system boundaries for module C and D are set when the products under assessment have reached their end-of-waste cycle. Module D includes all the net benefits of reuse or recycling or energy recovery from materials reached this boundary from Construction stage A4-A5, Use stage B1-B7and end-of-life stage C1-C4. Any outputs from Product stage A1-A3 are considered co-products if they provide any value or as waste if not so there is no Module D declarations arising from this Module. In Figure 3.35 the scheme of Module D input flows is shown.

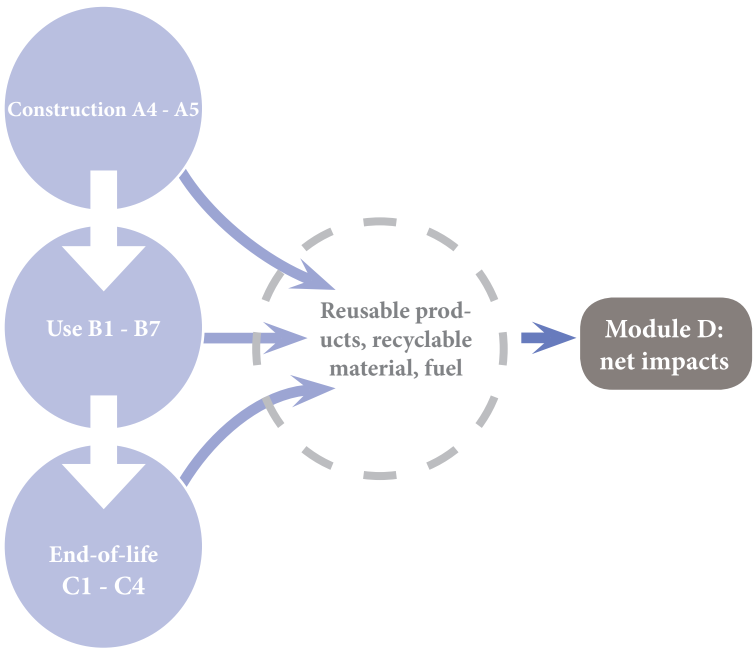


Figure 3.35. Module D input flow

Declared units

In order to ensure that the material flows of every module are normalized (in mathematical sense) and can be expressed in a common basis in order to be able to produce data that are comparable and possible to aggregate we need to define a declared unit. The declared unit is used for EPDs that cover one or more life cycle stages of a product and must comply to one of the required forms as stated in the directive that are:

- an item or an assemblage of items, e.g 1 brick, 1 window;
- Mass (kg)
- Length (m)
- Area (m2)
- Volume(m3)

In cases though where there is a need to provide a different unit the user must provide information on how to convert this unit ioot the required ones. The system boundaries in relation to the structure of EPD and the related modules is shown in Diagram 3.2.

Environmental Indicators

The environmental indicators taken into account for the proposed strategy developed in this research follow the proposed indicators as described in NEN-EN 15978 Section 11. These indicators are presented in Tables 3.2 - 3.4 below.

Main Environmental Indicators	
Indicator	**Unit**
Global Warming Potential, GWP	Kg CO_2 equin
Depletion potential of the stratospheric ozon layer, ODP	Kg CFC 11 equiv
Acidification potential of land and water, AP	Kf SO^{2-} equiv
Eutrophication potential, EP	Kg $(PO_4)^{3-}$ equiv
Formation potential of tropospheric ozone photocemical oxidants, POCP	Kg Ethene equiv
Abiotic Resources Depletion Potential for elements, ADP elements	Kg Sb equiv
Abiotic Resources depletion Potential of fossil fuels, ADP_fossil fuels	MJ, net calorific value

Table 3.2. Main environmental Indicators

Resource Input indicators	
Indicator	**Unit**
Use of renewable primary energy excluding energy resources used as raw material	MJ, net calorific value
Use of renewable primary energy resources used as raw material	MJ, net calorific value
Use of non-renewable primary energy excluding primary energy resources used as raw material	MJ, net calorific value
Use of non-renewable primary energy resources used as raw material	MJ, net calorific value
Use of secondary material	Kg
Use of renewable secondary fuels	MJ
Use of non-renewable secondary fuels	MJ
Net use of fresh water	m^2

Table 3.3. Resource Input Indicators

Waste Production Indicators	
Indicator	**Unit**
Hazardous waste disposed	Kg
Non-hazardous waste disposed	Kg
Radioactive waste disposed	Kg

Table 3.4. Waste production Indicators

Implementation in the toolbox

The selected unit for the production of the EPD results in the DesignforDeconstruction toolbox is chosen to be tonne(tn) of steel as the provided data for the different information modules use this declared unit. The information data used to perform the assessment are taken from the database of "Bauwen met staal", the Dutch national organization for the use of steel products in construction (http:// http://www.bouwenmetstaal.nl/).

Service Life

On product level in order to conduct an LCA and to produce an EPD a Reference Service Life (RSL) for the product under assessment must be provided. This factor is based upon empirical, probabilistic, statistical or research data and shall always take into account the intended use. The RSL is provided by the manufacturer who must take into account different factors such as the intended use, the functional performance, the internal an external environmental conditions and the usage conditions along with the maintenance frequency. In the case of steel construction products though a RSL is not provided as these factors can differ drastically for each scenario of use.

On a building level the user, in order to carry out an assessment must provide a Reference Study Period (RSP) along with a Required Service Life (ReqSL) under which the assessment will take place. In general the RSP and ReqSL are equal but any deviation from this case must be clearly stated. The deviation is expressed through a ratio of RSP/ReqSL that affects the results of the EPD in the use stage (module B1 – B7) and in Module D. Since though the assessment is based on the building life cycle the values of impacts and aspects must first be calculated for the ReqSL.

In case that the ReqSL in shorter than the RSP the impacts on the results are following the routine shown in Figure 3.36. In any other case when the ReqSL is larger than the RSP the user must provide scenarios for refurbishment or for the demolition and construction of an equivalent new building.

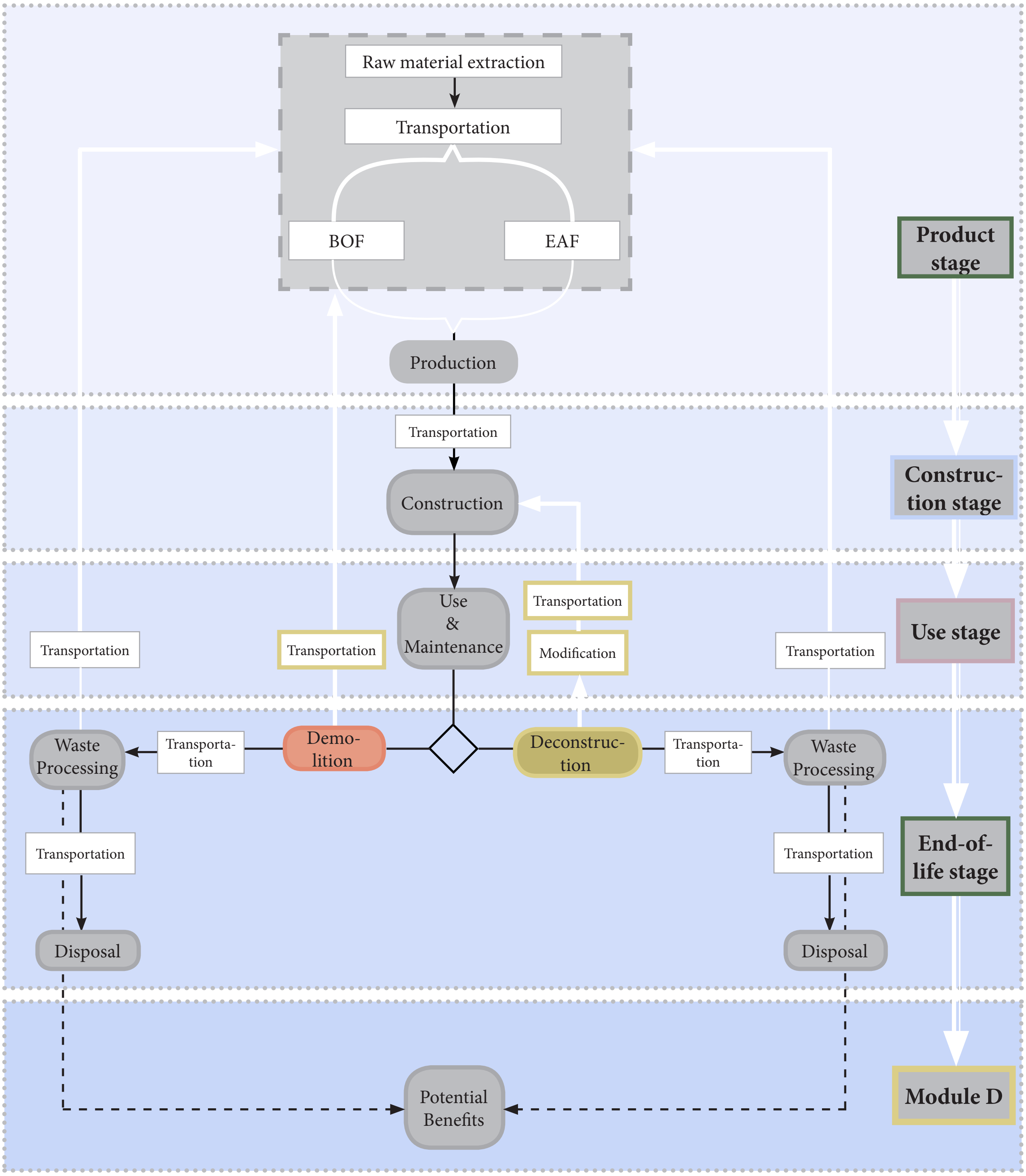
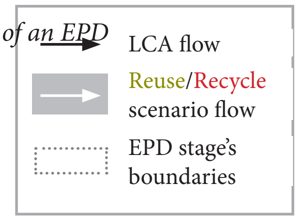


Diagram 3.2. Schematic representation of the ssystem boundaries in relation with the modules of an EPD



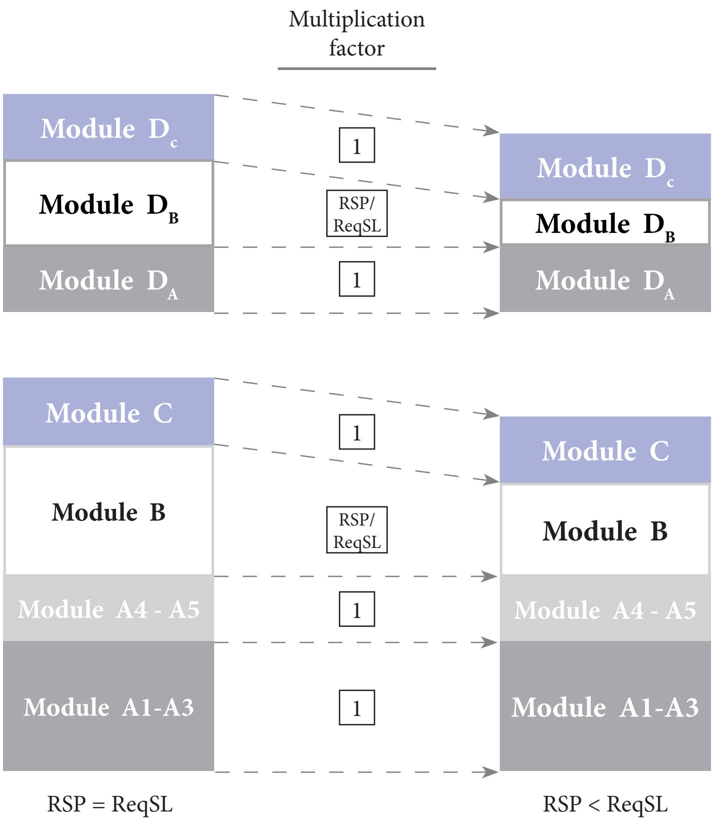


Figure 3.36. Adjustment of quantified impacts for RSP < than ReqSL (EN15978 :2011)

Implementation in the toolbox

Since the primary goal of the toolbox is to provide assessment results for buildings that are potentially subject to deconstruction and reuse after the end of life of their first life cycle, there is a need to provide a conceptual framework that will allocate the potential benefits as provided in information module D in order to perform the assessment of the new building. The scope though is to provide comparative results not only among different design option but also among different scenarios for the end of the life cycle of the initial building. These different scenarios are aiming to provide assessment results for the cases of reuse and recycle of the components and how these two options will affect the new design.

In these terms there is a need for some basic assumption that will form the boundaries of the final EPDs. The assumptions made are:

The first construction along with its impacts as calculated in the EPD belongs to the same closed system along with every next construction under assessment.

The building is formed by steel structural sections that can be deconstructed intact and re-used in the same manner.

The deconstruction and the demolition process have different energy demands for their execution. Usually the deconstruction process is a more delicate procedure demanding more labour and machinery to be completed. The values included in the End of Life stage of an EPD and more specifically in the C1 module reveal the potential deconstruction or demolition burden that is expected for the assembly under assessment. As the deconstruction and demolition burdens are considered as an added burden to the Product stage of the new design the values of this module will be added to the Product stage of the new scenarios. In order though to take into account the potential difference between the two processes a ratio between Deconstruction and Demolition processes will be applied (as an input). This approach is not expected to provide precise results as the exact difference is difficult to be calculated and can vary depending on the location and the efficiency of the contractor but it can capture adequately the difference in energy demands,

The Constructions Stage A5 (installation into the building and wastage from installation) has the same impacts both for reuse and recycle scenario. Since the provided data for stage A4 and A5 are aggregated and the purpose of the assessment is to provide comparative results among different scenarios this stage will be excluded from the assessment of the new structures as the Construction Stage A4 that provides information about the impacts of the transportation of the components from the manufacturer to the building site will differ for both scenarios as will be explained later in this section.

The Use stage (B1-B7) along with the End-of-life stage (C1-C4) has the same impacts for both scenarios.

Regarding the allocation process of data from the results of the first design to the new one and in order to evaluate the benefits of each option, since there is no specific description in the directives that could be used as guidelines for this purpose there were also some assumption made. These assumptions could form the basis of a PCR for the assessment of reused elements but in order to do so the results require further validation and a detailed analysis of the relations of the input and output flows between the modules of the first and second construction is required. The assumptions made are the following:

For the scenario of Reuse:

For the assessment of the new construction for the information module "Product stage" and since the components are assumed to be reused intact the Product stage will carry only the data from Product stage from the first construction. Both belong to the same closed system and there is no further need for production of new components that would add to the existing impacts. If there is a need for more components to be used then the impacts caused by their production will be added to the Product stage of the new construction. Also since the EPD results expose the impacts of the End-of-Life scenarios the module C1 exposes the impacts caused by the deconstruction process. As such these impacts will be add to the Product stage of the new structure.

For the Construction stage as explained above the data from the first EPD will be assigned to the new one. The extra input for this module will only be the impacts from the transportation of the material (module A4) from the old site to the new including the impacts of any other additional transportation if needed. The impacts arising from the installation of the components (module A5) will not be taken into account for both scenarios as the results will be the same as the initial EPD since the design is considered identical.

For the Use stage and end-if-life stage the impacts for the new design will be identical to those of the initial design as they are considered identical.

The benefits arising from the reuse, recycling or energy production (module D) will be the same for both designs with no allocation since module D projects the potential benefits of an existing component or structure after the component reaches the end-of-waste cycle.

For the scenario of Recycling:

In order to allocate the benefits that will result from the recycling of the existing components the result data from Module D will be allocated to the impacts of the new structure. The benefits will be allocated multiplied by 0,535 that is the provided value from material recycling and reuse in the related EPD database This allocation is based on the scheme shown in Diagram 3.3. In this scheme the theoretical allocation of the recycled or reused scrap is presented. The values shown in this diagram are not reflecting the value used in the proposed allocation process since this is deriving from the provided data. We consider the system closed so the Product stage of the new structure will result as the sum of the impacts of building a new structure from the beginning and the multiplied results from module D of the first structure (the results of Module D for steel structures as provided have a negative value, in many cases though for other products the results might be positive). Here also the End of Life (C1) stage impacts will be added to the new building's Product stage. In order to cover any differences between Demolition and deconstruction process an extra parameter named "Deconstruction/Demolition" ratio is implemented as an input for the user. This ratio will declare the expected added burdens of the deconstruction process in comparison to demolition.

For the Construction stage the process of data allocation will follow the same route as for the scenario of reuse and the data of the new structure will include the data from the old one and the impacts of the transportation of the material to the recycling plant and from the recycling plant or manufacturer to the new building site. In both cases the user of the tool will be called to input the data regarding the distances that need to be covered for this purpose.

For the information modules of the Use stage the process of allocation will be identical to the Reuse scenario.

For Module D the results of the new construction will only include the potential benefits that arise from the new structure since the benefits of the first scenario have already been aggregated as described.

The schematic representation of the data allocation processes is shown in Diagrams 3.4 and 3.5.

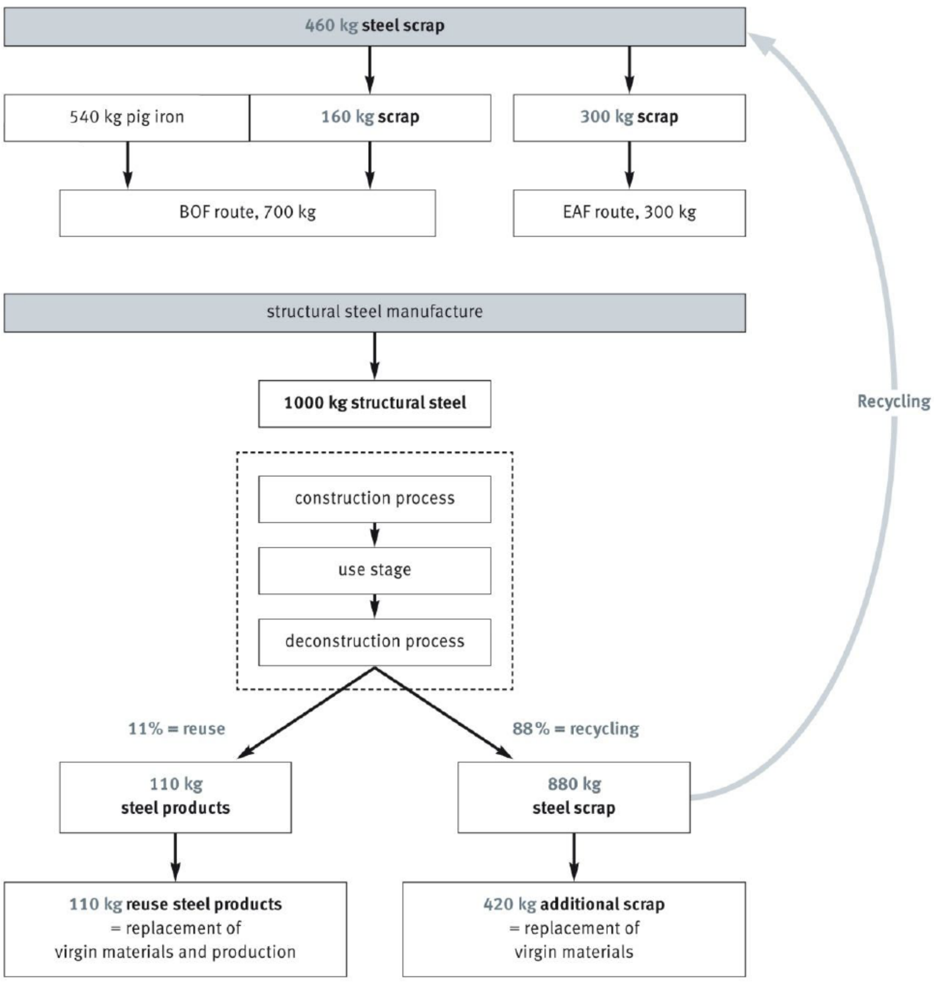


Diagram 3.3. Schematic representation of the Recycling potential (net scrap & reused steel products replacing new production from iron ore) (source: Siebers, Hauke, 2011)

For the transportation of material:

The transportation needs for each scenario are different. In the first case for the reuse process the components will most probably need to be transferred from the initial site to the new one while in the recycling process, in first hand the components must be transferred to the recycling facilities and the new elements must be transferred from the manufacturer to the ne construction site. The environmental impacts of these transfers will be calculated based on the data of the Nationale milieudatabase (NMD), the most commonly used database in the Netherlands and in return allocated to the Product stage of each scenario. In order to simplify the use of the toolbox there will be one component related to the calculation of the transfer impact. This way the user will be able to calculate the impacts of any transfer needed till the component reaches the site of the new building. This way the required distance to be covered in order for intermediate processes such as temporary storage of the components, possibly necessary for the completion of the reconstruction, can also be taken into account

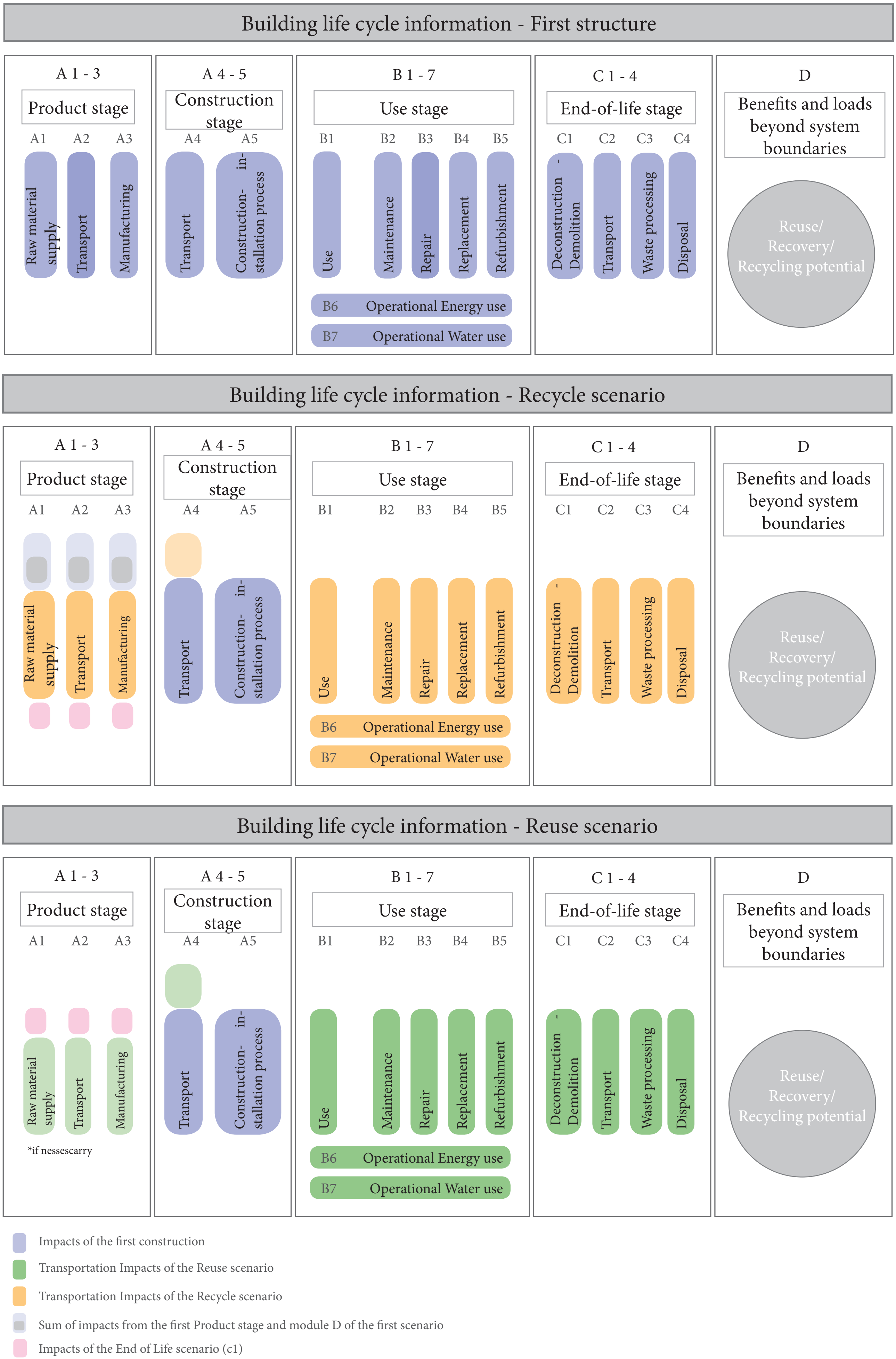


Diagram 3.4. Schematic representation of the allocation process for the Reuse and the Recycle scenario

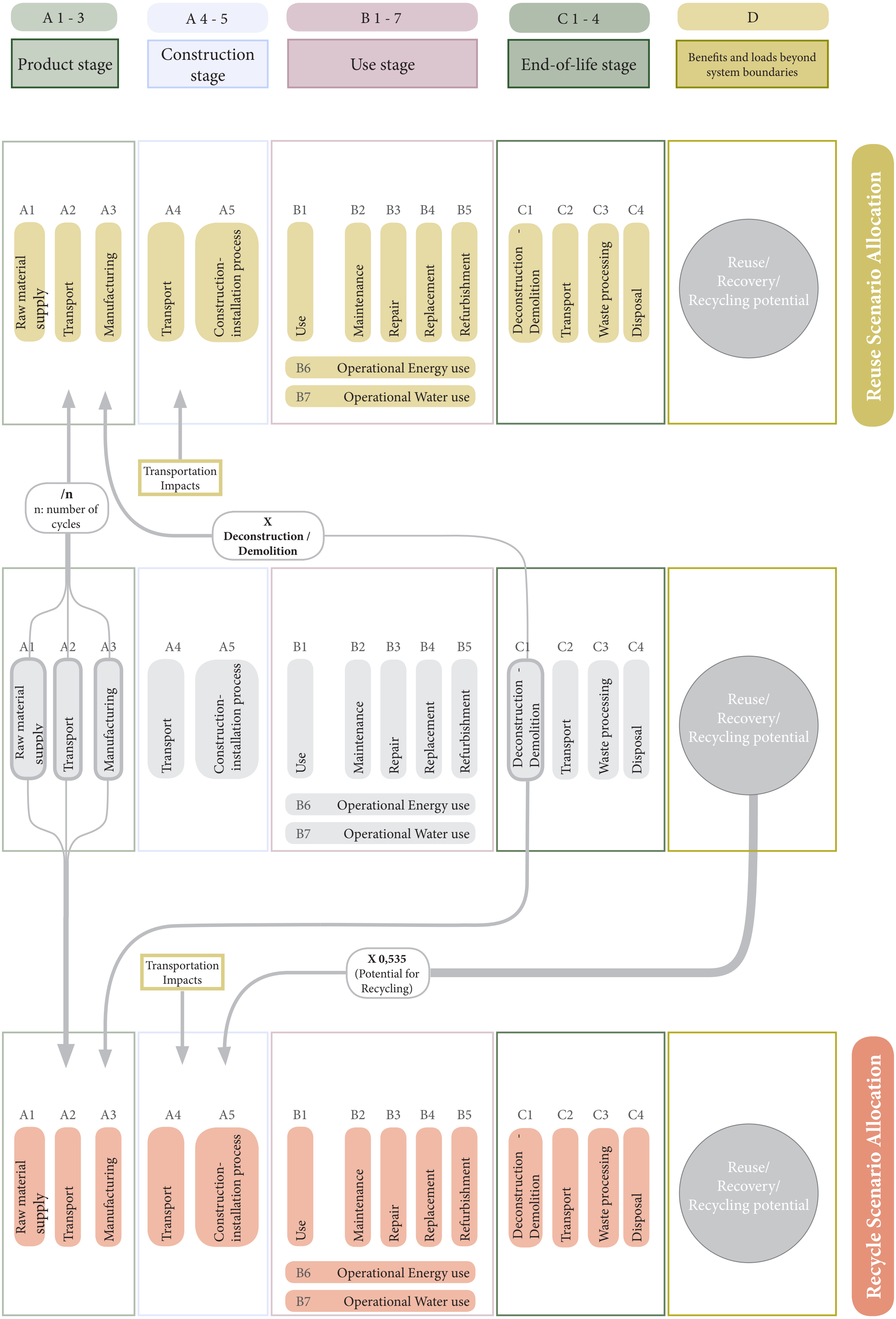


Diagram 3.5. Schematic representation of the allocation process for the Reuse and the Recycle scenario

3.4.3 Shadow prices

In order to evaluate the costs of the results of a Life cycle analysis the method of shadow prices can be applied. According to this method, developed by the Technical University of Delft, every environmental impact produced during the life cycle of a product has a weighing factor that reflects its value to society. These factors are called shadow prices and they are applied to calculate two different cost categories, the abatement and the damage costs. According to the Shadow Prices Handbook (Bruyn et al, 2010) Abatement costs represent the costs that need to be incurred to secure the environmental policy targets in question. While Damage costs represent the people's willingness to pay in order not to damage the environment. The general rule for the application of one of the two categories is that damage costs are applied when a project leads to changes in environmental quality and abatement costs are applied if it leads to changes in the efforts required to secure environmental targets (Bruyn et al, 2010).

Implementation in the toolbox

In the DesignforDeconstruction toolbox the method of damage costs will be applied as the LCA results indicate the total impact of a product to the environment and the environmental quality. The data used are provided by NIBE the units of shadow prices are expressed in Euros. The shadow prices used are the shown in Table 3.5.

In order to calculate the final costs per environmental indicator the final results from the Product stage conducted EPDs for each scenario will be multiplied with the according shadow price. Also the transportation impacts arising for each scenario will be translated into shadow costs using the same approach. The weighing of the shadow prices though for steel manufacturing through BOF and EAF route are different. At the same time the ratios of BOF to EAF production are fluctuating depending on the location and capacity of the steel manufacturers. In order to provide precise results and take this differences into account the users are called to provide this ratio as input in the related component.

Environmental impacts	Unit	Shadow Prices (€)
Global Warming (GWP)	kg CO2 eq	0,05
Ozone Layer Depletion (ODP)	kg CFC-11 eq	30,00
Human Toxicity (HT)	kg 1,4 - DB eq	0,09
Ecotoxicity, Fresh Water (FAETP)	kg 1,4 - DB eq	0,03
Ecotoxicity, Marine Water (MAETP)	kg 1,4 - DB eq	-
Ecotoxicity, Terrestric (TETP)	kg 1,4 - DB eq	0,06
Photochemical Oxidation (POCP)	kg C2H4	2,00
Acidification (AP)	kg SO2 eq	4,00
Eutrophication (EP)	kg PO4 eq	9,00
Abiotic Depletion Factor (ADF)	kg Sb eq	0,16

Table 3.5. Shadow prices of environmental impacts

3.5. RFID Technology

Finally a brief review of RFID technology will be presented. This section will deal with the use of RFID tags from the construction industry and the benefits that this technology can bring in terms of management and also cost and waste reduction

3.6.1 RFID tags in Construction Industry

Radio Frequency Identification (RFID) is a technology that receives more and more attention from the construction industry. From asset and progress management, to the locating of underground and in-wall utilities/objects, to the integration of RFID with building information modelling (BIM), the potential benefits of RFID to the construction industry will be a topic that receives more and more attention in the future. (J.M. Taylor) RFID refers to an automatic identification technology which utilizes radio frequencies to transmit or capture data. This technology uses tags (transponders) and readers (interrogators) to communicate and transmit data. This data is gathered through this communication and stored to a host like a computer or data centres. Tags are consisted of a antenna and a micro-chip and are encapsulated in a protective covering and are divided into passive and active tags. Passive tags are activated only when a reader scans them while active tags contain a battery and are always on transmitting data or are activated in specific time increments.

The RFID technology is widely used in many industries such as retail chains, product tracking, inventory and supply management but construction industry can also benefit in a wide range of application if the RFID is utilized in a structured way. There are already some examples where it was successfully implemented, such as the access and safety site management of University of California, San Francisco (UCFS) Medical Centre at Mission Bay (http://www.rfidjournal.com/articles/view?10471) where RFID tags were used for the monitoring and safety of workers on the construction site or at a power plant expansion project by Bechtel corporation in the Northern United States where the technology was deployed in order to speed up end ensure the proper components' management on the construction site.

In this content RFID technology can also be utilized in order to promote DfD. The idea of tagging, during the manufacturing phase, every component of a construction with a tag containing all its necessary information in order to give it a unique identity will make it easier for the designer to define their future purpose. Also it will simplify the process of identification for the future user of the components as he/she will be able to quickly scan and read their properties and origin. The lack of such information is currently stating the reuse of reclaimed structural components not feasible as the uncertainty of their origin and quality is creating a big risk for their reuse.

The concept of RFID tagging is not implemented in the developed toolbox but is referenced in this research as it is an author's strong belief that it can complement the concept of deconstruction and the general efficiency of construction processes. The use of RFID tagging can be considered as a strong recommendation for the enhancement of the proposed strategy in the future.

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4

Product Development

This Chapter will focus on the development of the tool itself that is the main objective of this thesis. In the beginning there will be a description of the scope and the end users of the tool followed by a detailed description of the framework. After that an explanation will be given on how the tool was implemented in the SustainabilityOpen framework along with the development of the system's architecture. In the second section of the chapter there will be a structure break-down where the functionality of all the custom components will be explained.

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4.1. Tool Box Description

The DesignforDeconstruction toolbox is developed to serve the scope and objectives of this research as briefly described during the introduction chapter. The toolbox is developed in Microsoft Visual Studio using C# programming language based on .NET Framework 4.0. It is finally implemented in the SustainabilityOpen framework (see Section 1.5) following the proposed structure of Design-Analysis-Assessment as shown in Figure 4.1.

4.1.1 Scope

The DesignforDeconstruction toolbox is developed in order to be used in the early design stage of a project. The intention is to provide a tool to the user that will assess the environmental and financial impacts of the concept of DfD when applied on a building design and assist in the creation of a management system that can support the concept on a management level. The assessment will be presented in form of Environmental Product Declaration on a building level, embodied energy and carbon indicators, shadow costs and financial evaluation.

The toolbox is providing a flexibility of use since the user is able to assess every design choice individually before ending up to the main objective that is to provide a comparative assessment between a scenario of designing for deconstruction and reuse of the building and a scenario of designing for a specific life cycle taking into account the recycling benefits that arise after the end of this life cycle. The focus is solely on steel structures and currently only on the structural frame of the structure.

The toolbox follows the SustainabilityOpen framework and incentive that is to provide tools that will promote sustainability in construction industry in every level. It is though applicable to any kind of steel structure of any form and can potentially be extended to other construction materials.

4.1.2 Users

The intended users of the toolbox are all those engineers involved in the development of a design. Starting from designers/architects and since the goal is to promote design for deconstruction an intensive collaboration with structural engineers is required following the logic of a total management process as this described in Section 3.4. Besides them the provided scheme for the support of the management system requires the participation of IT engineers and aims to provide incentives to the stakeholders involved in the process. In these terms the intended users of the toolbox are all those parties involved to a construction process who need to collaborate in order to deploy the concept of DfD.

4.1.3 Use Cases

In order to define the way the users will interact with the 'DesignforDeconstruction' toolbox there are two use cases provided.

- The first implies that there is a set up model in Rhino from which the user has to target all those components that constitute the construction and define their intended use (columns, beams, braces e.t.c). This way the deigned elements will be translated into physical objects by the designer components of the toolbox that will include and transfer all the necessary structural, and geometry information needed for the assessment of the construction.

- The second use case implies that the user has an empty canvas and designs the structure in a parametric manner. After that the user is called to assign the output geometries of the structure to the different design components that will then translate them into physical objects and follow the same sequence as the first use case. This use case allows for more informed choices as the user will be able to redefine the geometry of the design and assess directly the impacts of each alternative.

The two use cases are schematically represented in the following figures (Figures 4.1 and 4.2)

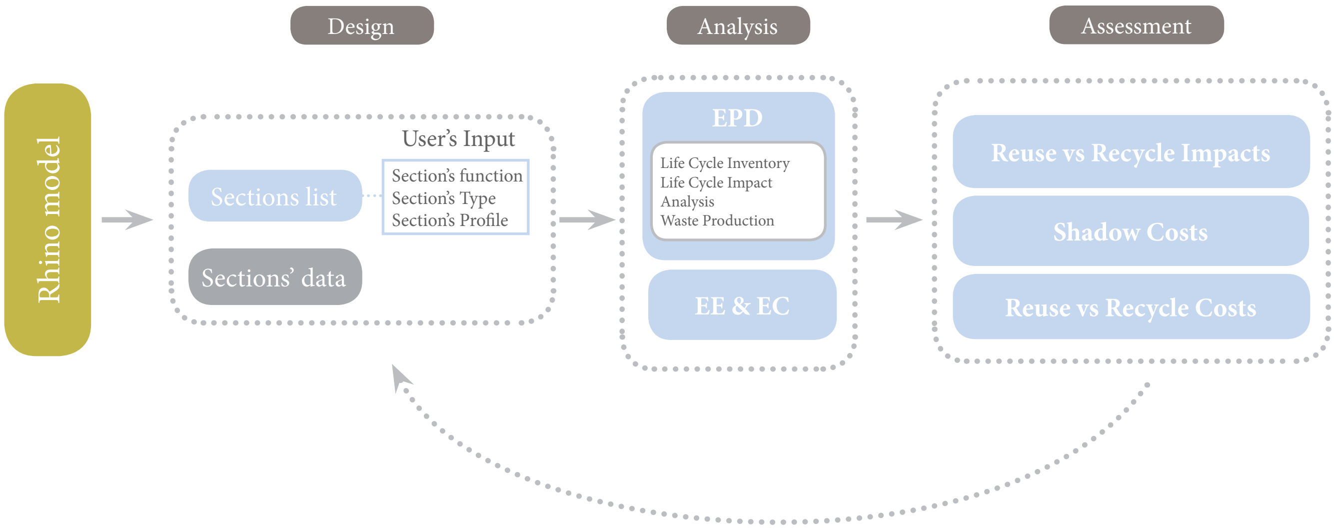


Figure 4.1. Second use case: Composition, analysis and assessment of a parametric geometric model

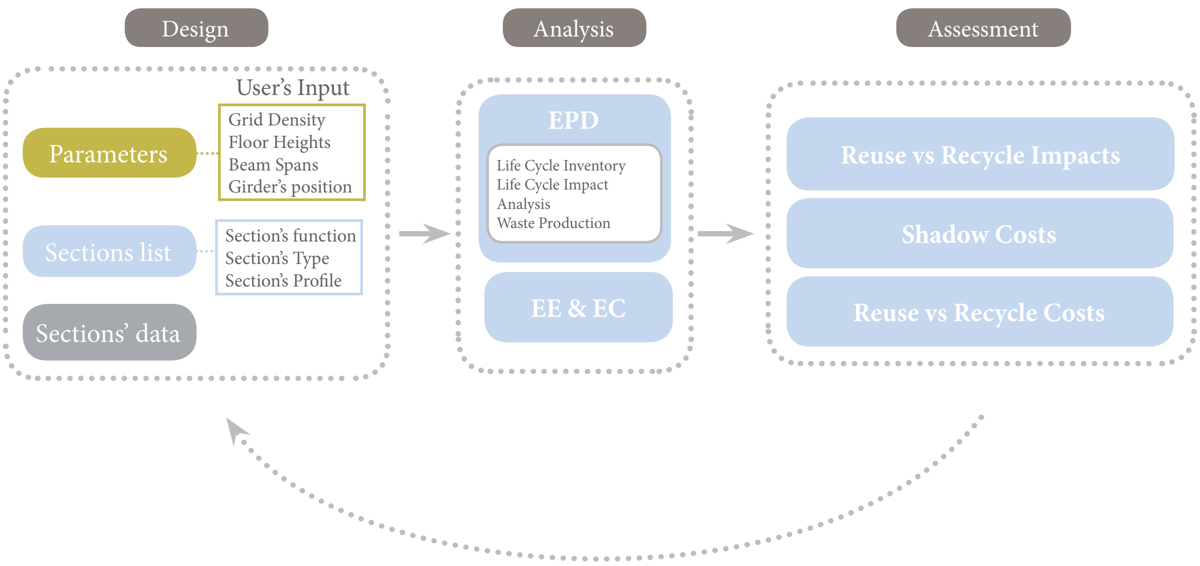


Figure 4.2. First use case: Analysis and assessment of predefined Rhino models

4.2. Underlying technology

As defined by Coenders (Coenders, 2007) Parametric associative systems are generating outputs, often geometries, from parameters and their associations, definable by users. This generation is replayed every time one of these parameters or their association sequence changes providing this way a consistent design logic defined by rules formed by these parameters and their associations. Under this logic "Design for Deconstruction" toolbox has been developed to produce assessment results and provide useful information depended on user-defined parameters and user-defined associations as will be explained later on this chapter.

The freedom of design choices that parametric and associative design offers is highly beneficial for the early design stage of every project as the ease of changing parameters and associations provide a design variety and as consequence a vast amount of information that can be used in the early stage of a project either as decision makers or in later stages where modifications may be required as an assessment tool for their impacts before their application.

Parametric and associative design is most commonly used for geometric models but rarely used for sustainability oriented purposes. The reason is mainly that the parameters that define sustainability in a project are usually complex to defined and vary depending on the aspect of sustainability the user is focusing on. Especially though if a user is interested in exploring the possibilities and benefits of implementing deconstruction in an early design stage then the available tools to do so are completely lacking from the market not only in the context of parametric design but also as commercial software tools that follow a straight forward design strategy. Due to this lack of tools and the wide range of technical and environmental aspects that the concept of deconstruction arises the development of such a tool has to be accompanied by costume parameters, encapsulated in components, that will define in the best possible way these aspects and their relations. Such components have been developed for the DesignforDeconstruction toolbox and inherit information regarding structural properties of elements, environmental impacts of materials and values for the assessment of the financial impacts of the concept. An overview of the components can be found in AppendixIV and an explanation of the architecture of the toolbox in Section 4.1.5.

4.2.1 Toolbox Architecture

The DesignforDeconstruction toolbox is designed in order to fit into SustainabilityOpen framework (Coenders, 2013). For this purpose it is composed by Design, Analysis and Assessment components. The diagram in Figure 4.3 shows the basic scheme of the toolbox and the custom developed components along with their alignment with the proposed SustainabilityOpen scheme.

Design

The Designer translates a Rhino's or a parametrically defined geometry into a Physical object, in our case into a Section, that will carry all the necessary information for the analysis and assessment to take place. The component inherits the related information from a local database. The data stored in this database are representing the existing commercial steel sections used in the European Union as provided by ArcelorMittal (http://corporate.arcelormittal.com/). An extra designer for generation of a simple building geometry has also been developed but mainly for demonstration purposes. As such its functionality is not adding any additional value to the toolbox.

Analysis

Once the geometries are translated into sections the output data of the designers are transferred to two Analysis components. The first Analysis component is carrying out a Quantity Take-Off analysis (QTO) where the total weight of the produced sections is calculated. The weight of the

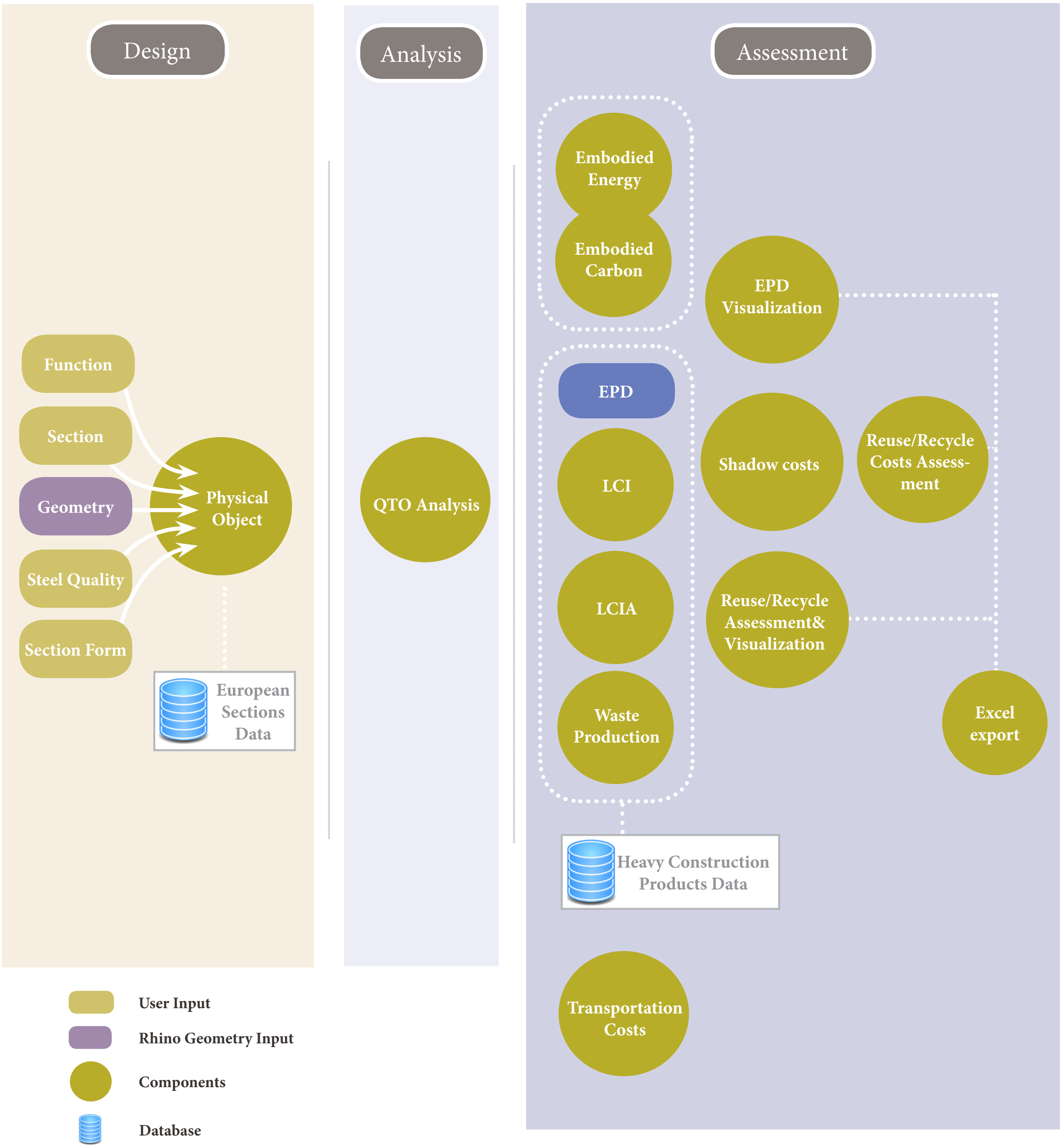


Figure 4.3. Layout of the toolbox showing the alignment with the Sustainability-Open framework and the follow-up processes

sections, calculated in tonnes of steel, will then be used for the assessments that follow. The second Analysis component is collecting all the information of the produced sections in order to export them in Excel spreadsheets as will be described later on this chapter. This component also gives the user the flexibility to use this information for any future potential extension of the toolbox.

The basic setup for the Design and Analysis components is shown in Figure 4.4.

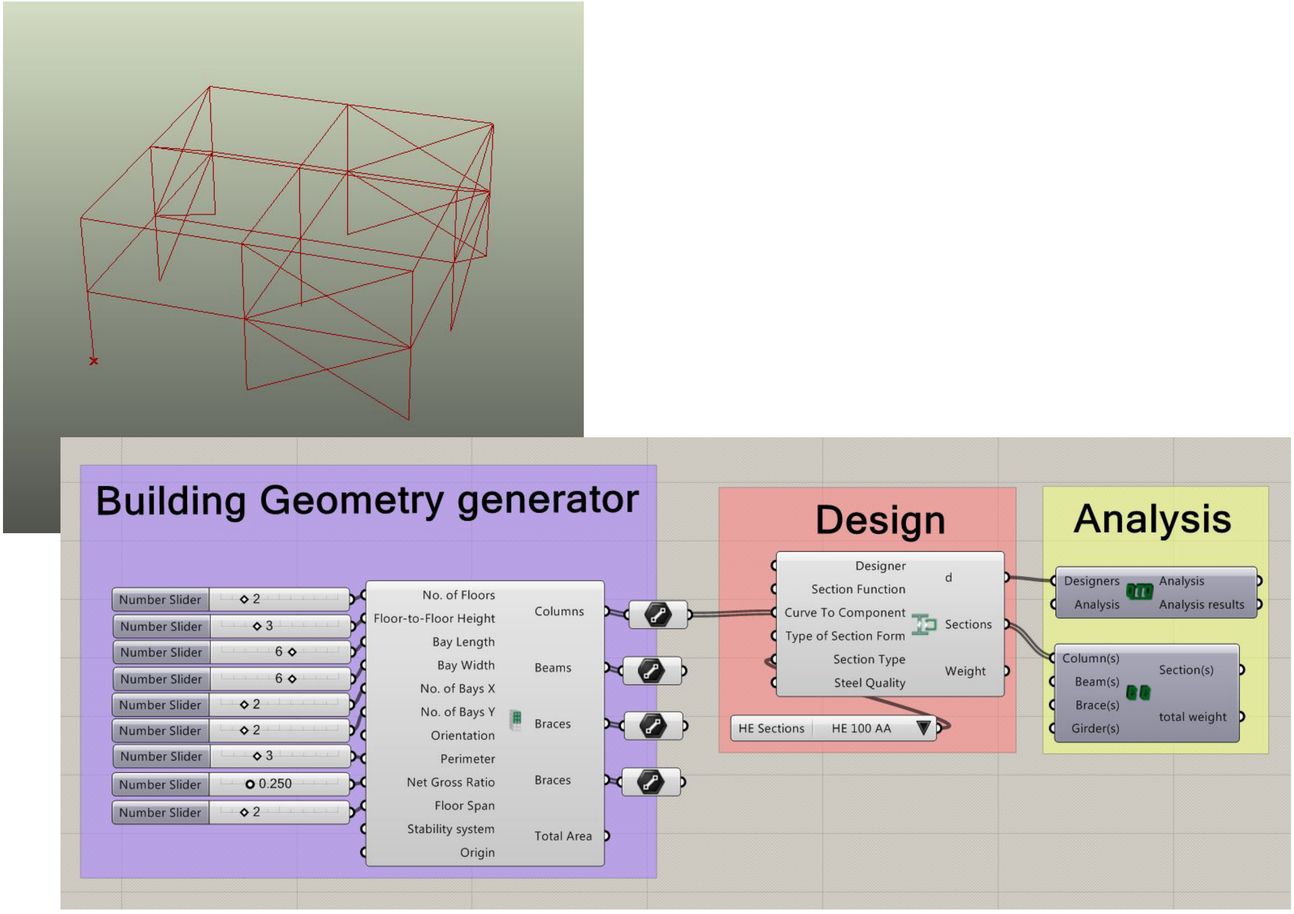


Figure 4.4. Basic setup of the Design and Analysis components in the Grasshopper3D's environment (the figure shows an example where only the columns of the produced building geometry are used the analysis)

Assessment

Finally the results of the QTO analysis component will be used by a set of components that will also return a visual output in Rhino's environment in order for the user to have a direct understanding of the impacts of his/hers choices. The assessment components are divided in two different categories. The first category is for a simple understanding of the environmental impacts of the design. For this purpose three components are developed to carry out an EPD assessment that is subdivided to a Life cycle inventory (LCIA) analysis, a Life Cycle Impact (LCI) analysis and a Waste production analysis. These analyses are complying to the requirements for the conduction of EPDs as described in Section 2.4.2 of this report. The data provided for this assessment are also stored in a local database as provided by 'Bouwen met Staal' (http://www.bouwenmetstaal.nl/). The results of this assessment can be visualized by an extra generic component that is dedicated to this purpose. Besides this assessment there is also a component for the assessment of the Embodied Energy (EE) and Embodied Carbon (EC) consumed and produced during the production of the initial components. This component is also assessing the potential EE and EC for the two proposed scenarios as described in Section 3.3.

The second category is dedicated to the assessment and visualization of the results between the Reuse and Recycle scenario. The assessment is again produced in the form of an EPD using the results produced from the first assessment category components and the user is called to input the RSP/ReqSL ratio of the new design - if known - in order to define and adjust the results of the EPD accordingly (see Paragraph 3.42.) The user is also called to input a ratio that reflects the added environmental burden of the deconstruction process in comparison to the demolition process (see Section 3.4) Finally the user must input the transportation costs that follow the deconstruction and demolition process as these will be calculated by a supplementary component developed for this reason.

After the assessment of the Reuse and Recycle scenario the results can be inserted into an extra assessment component dedicated to the translation of the impacts to shadow costs. This component requires as input the results of the Product stage of the assessment and the transportation impacts as calculated before. Finally the results of the shadow costs can be inserted into the last assessment component provided for a financial assessment of the Reuse and the Recycle scenario. Except from the shadow costs the user is called to input prices for the demolition and deconstruction process given per square meter of surface. These prices should be provided by local contractors along with the price of new and scrap steel and any additional costs arising from the need for modification of the reclaimed components for the case of Reuse. Finally the component requires the total amount of steel used and the total area of the building under assessment. The results of this assessment are provided separately for the demolition and deconstruction processes, per square meter and per tonne of steel so the user can have a clear understanding of the impacts of the two options.

The final results as derived from the assessment components can then be exported to Excel spreadsheets that will form the basis for the development of a management scheme necessary for the facilitation of the concept of Design for Deconstruction as described in Section 3.1

The basic setup for the Assessment components and the export of the results is shown in Figures 4.5 and 4.6 while in Figure 4.7 the general overview of the setup of the components is shown.

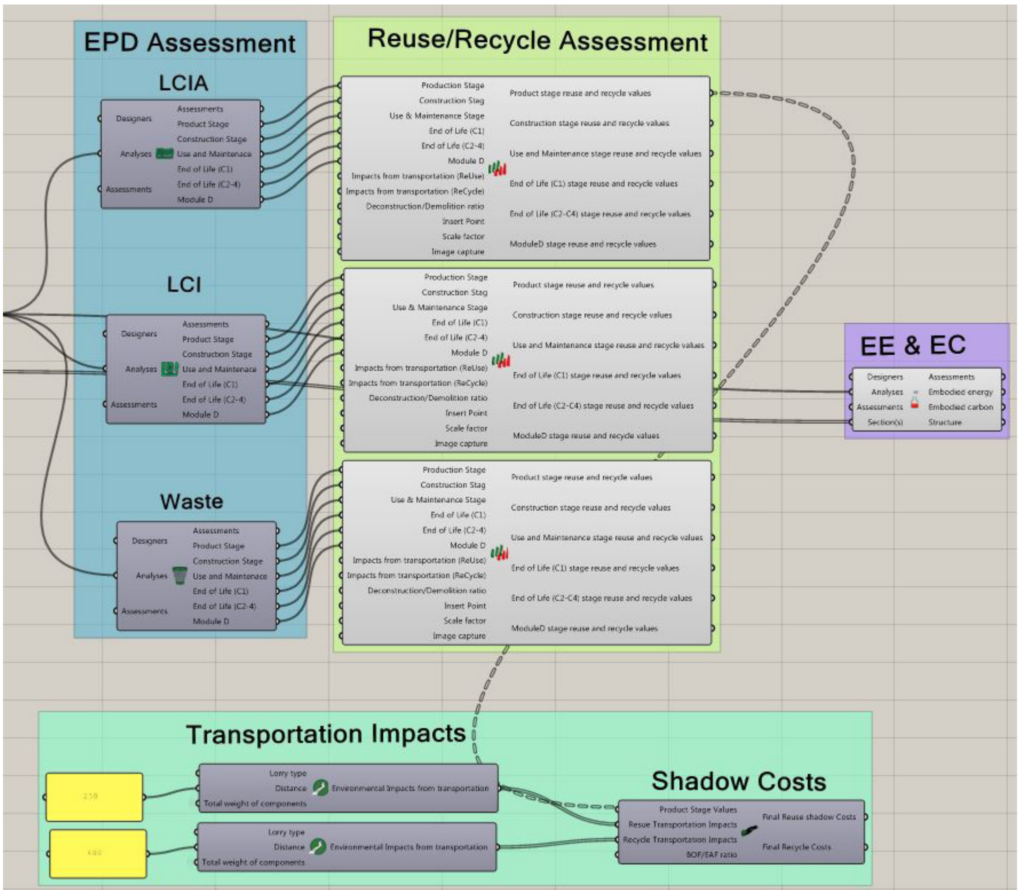


Figure 4.5. Basic setup of the Assessment components

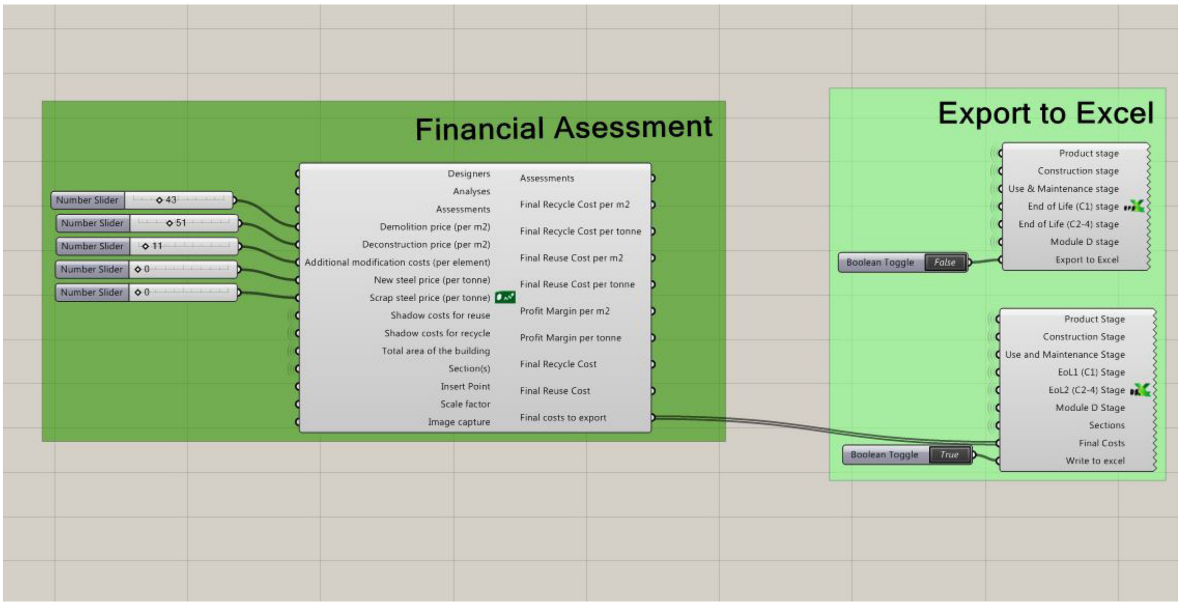


Figure 4.6. Basic setup of the Financial Assessment component and the components for the export of the results to Excel spreadsheets

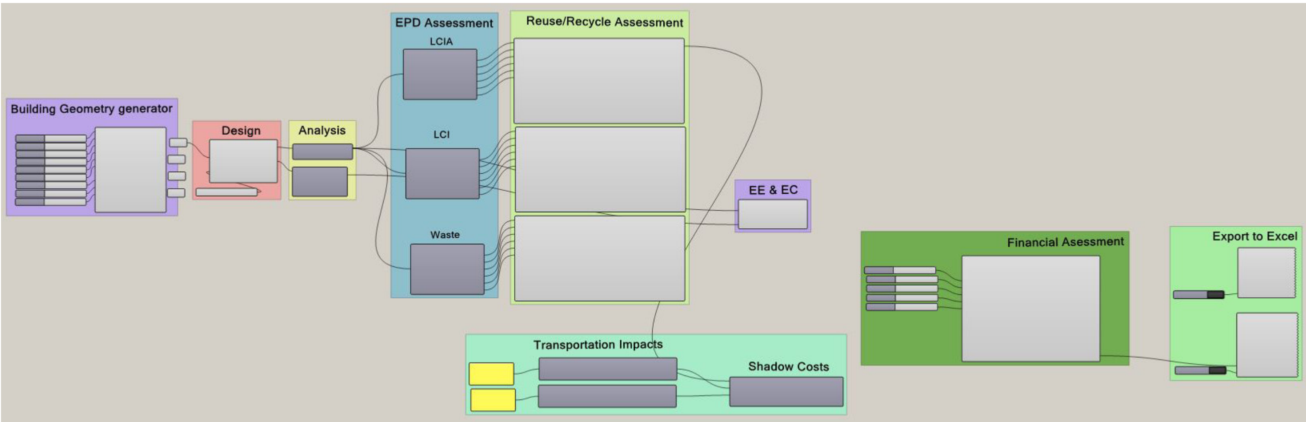


Figure 4.7. General setup of the components for a full analysis of a design

Finally in Figures 4.8- 4.10 one can see examples of the results visualization into Rhino3D's environment along with the related components.

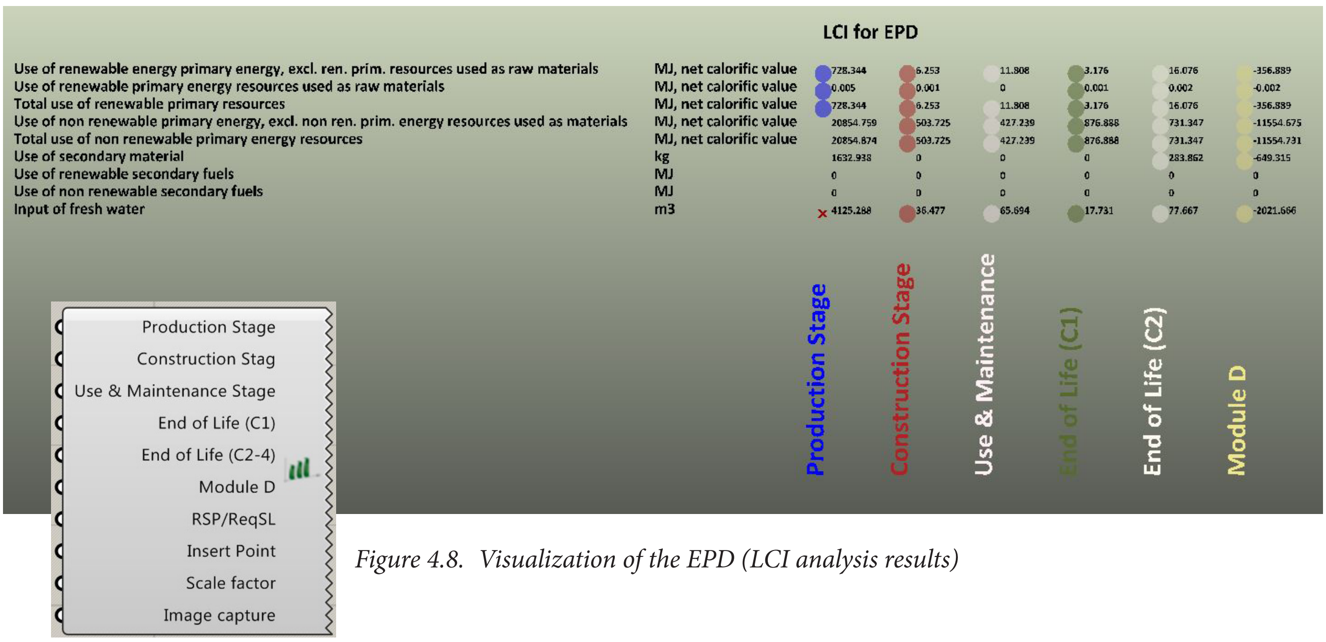


Figure 4.8. Visualization of the EPD (LCI analysis results)

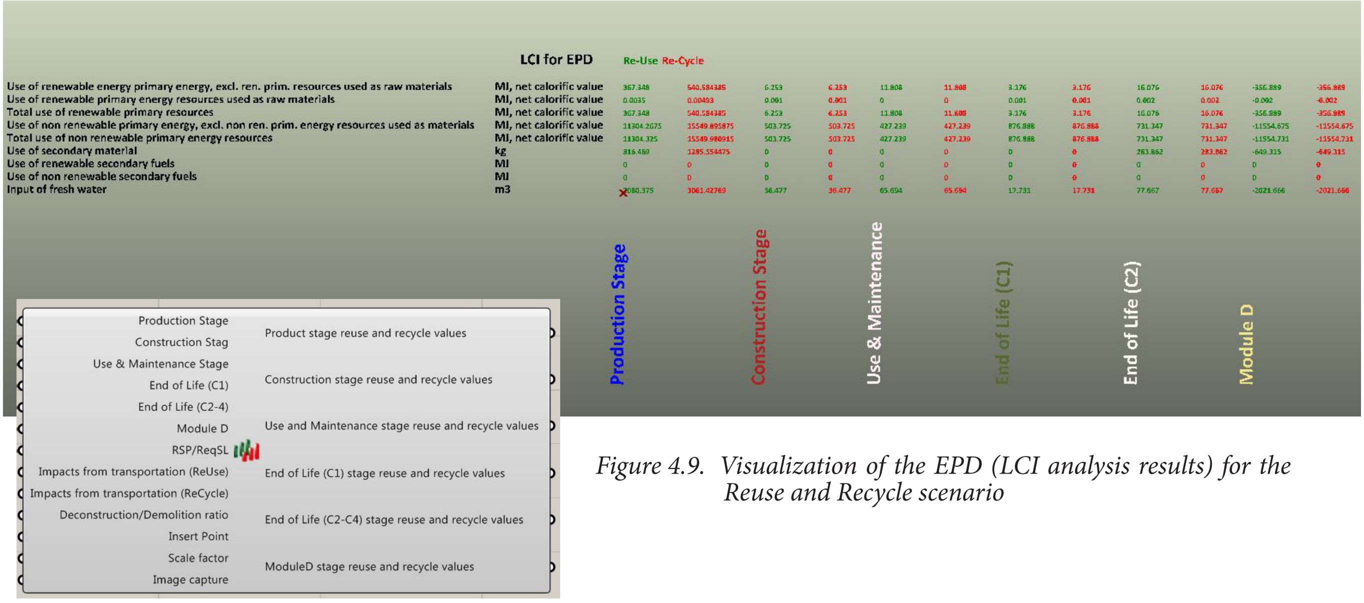


Figure 4.9. Visualization of the EPD (LCI analysis results) for the Reuse and Recycle scenario

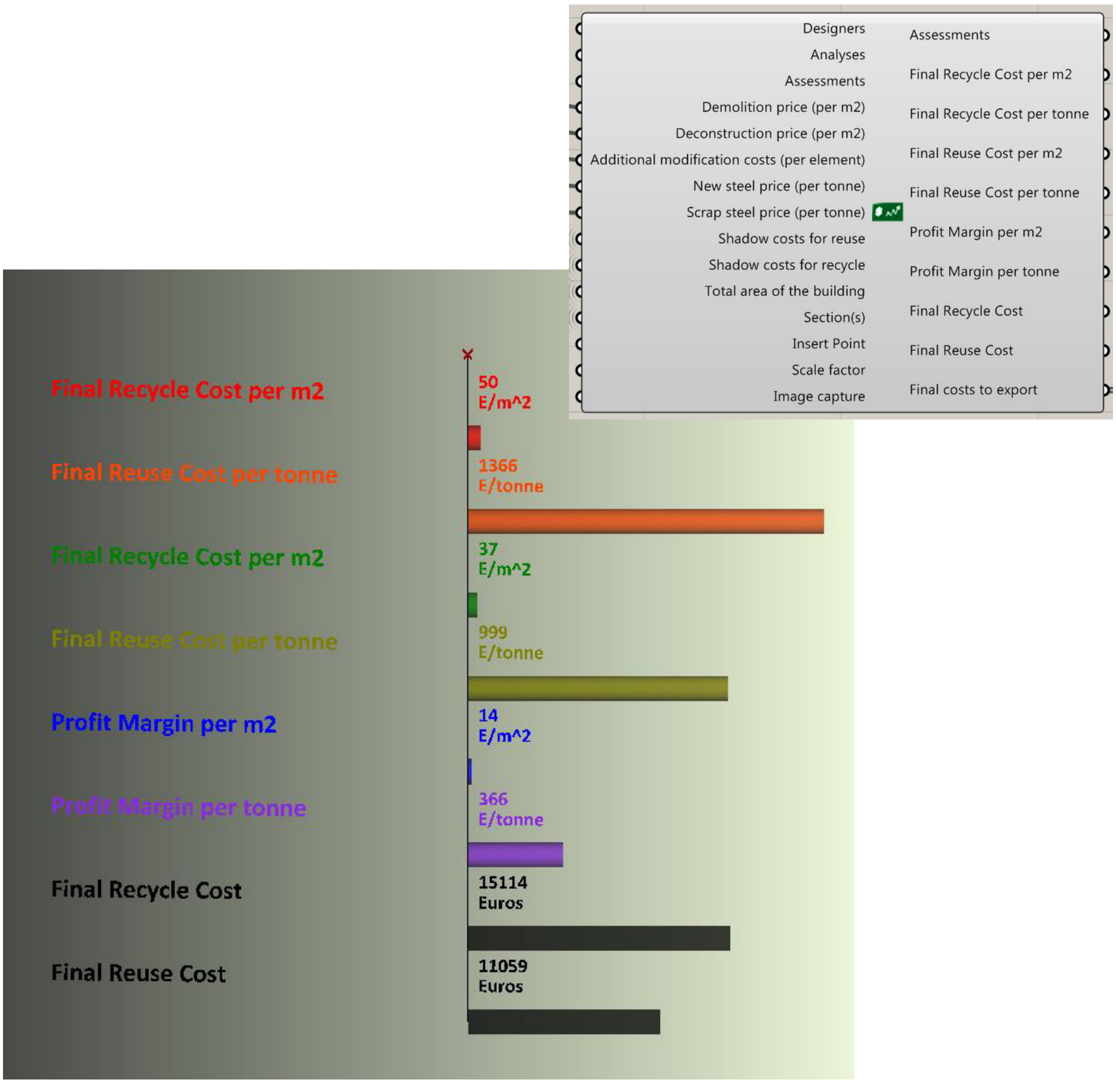


Figure 4.10. Visualization of the Financial assessment results

4.2.2 SustainabilityOpen framework

The “Design for Deconstruction” toolbox is built in order to be implemented in the SustainabilityOpen framework. As such the structure of the tool is developed in the .NET framework using C# programming language. The SustainabilityOpen framework offers an underlying structure that the basic components of the tool are lying on in order to inherit basic properties of the provided classes and implement the tool in the framework. In Figure 4.11 one can see the components that are implemented into SustainabilityOpen framework The custom classes and their relations with the classes provided in the framework are shown in Figure 4.12.

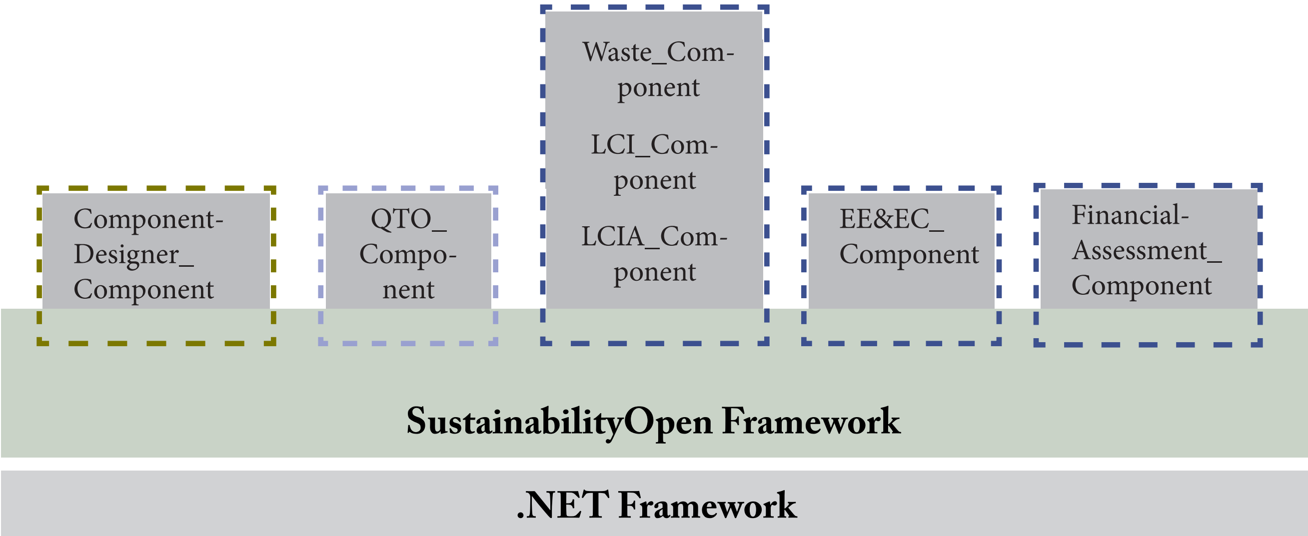


Figure 4.11. Schematic representation of the hierarchy of the frameworks used and the implemented custom components.

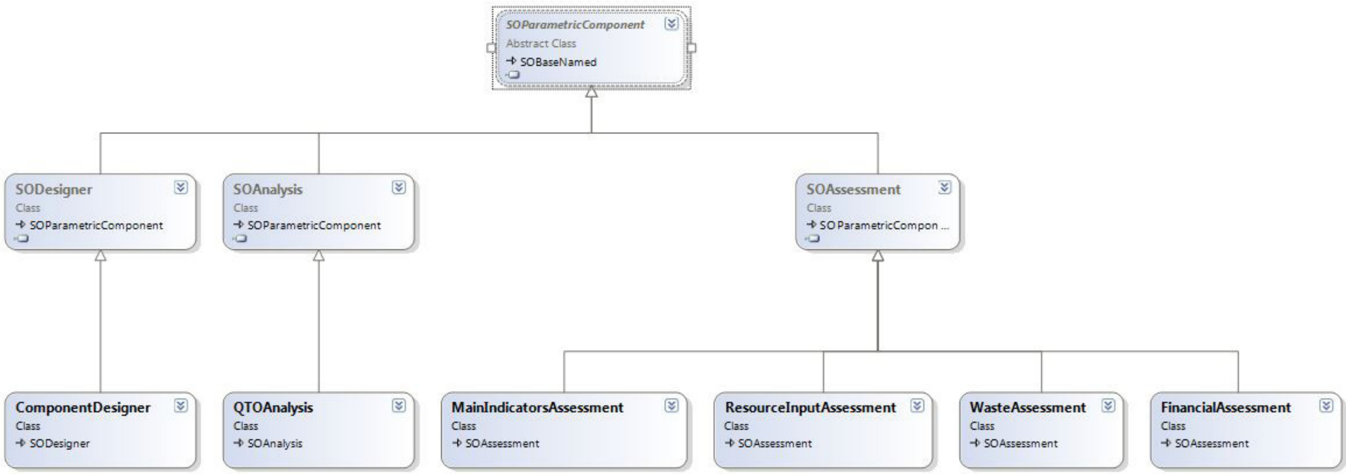
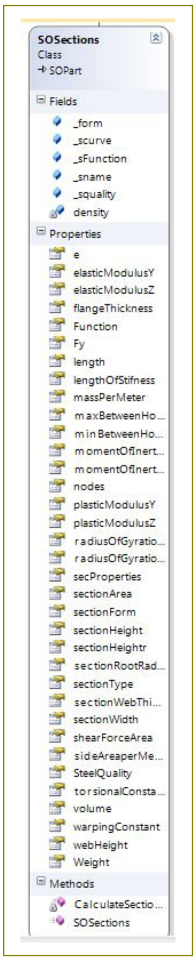


Figure 4.12. UML diagram showing the relation of the custom components with the SustainabilityOpen classes.

More specifically the SOBasedNamed class is an abstract class that serves the SOParametricComponent abstract class and the SOPhysicalObject abstract class. The first serves the three main components of the framework. The Design, the Analysis and the Assessment components while the second serves the SOPart class. These in return contain abstract methods which are overwritten by the basic components of the toolbox storing this way the data in one class making them accessible to the classes that derive from it.

The SODesigner class retrieves data from the ComponentDesigner class which is using the SOPhysicalObject class to form physical objects, in our case structural sections that will be used later for the analysis and assessment of the total structure. The SOPhysical object class is retrieving information from the SOPart class which in turn is formed by the custom SOSections class and StructuralSections class. These are the actual classes carrying the necessary data to form the structural sections. The structure of these classes and their relations are shown in Figure 4.13. The purpose of these classes is to form a physical object based on a provided curve. The curve will provide the length and the SOSections class will provide the necessary information that the section will carry. The SOSection class is connected to a database under the name "EuropeanSections_Data.mdf" where depending on the name of the section it retrieves and stores the data of the section like section area, mass, moment of interia, section width e.t.c that will later on be used for the assessment of the structure. The StructuralSection class acts as a constructor for the SOSection where the property of "weight" of the composed section is used as input for the required quantity argument of the constructor of the SOPart class.

Finally two extra external classes provide information to the SOComponentDesigner_Component regarding the material quality and its properties and the function of the composed section in the structure. These classes are called through an option list that is shown in the component so the user can select the desired material quality and function manually. The information is then added as a property to the composed section. The classes and the selection lists are shown in Figures 4.14 - 4.16. The information and dependencies between the classes is schematically shown in Figure 4.17.



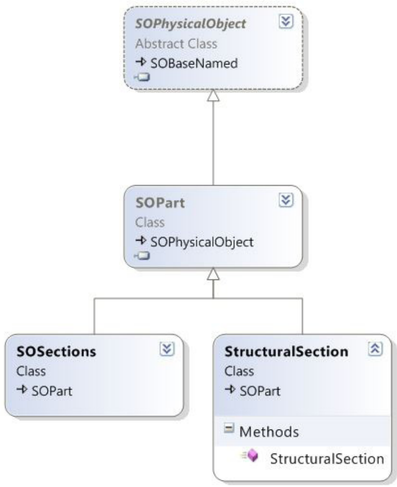


Figure 4.13. UML Diagram showing the relation of the Designer classes that translate a curve into a Section and the SOSection properties

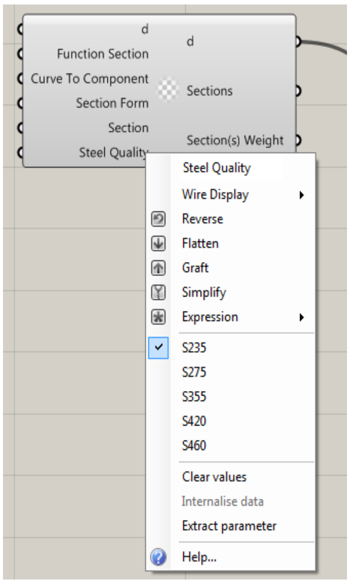


Figure 4.14. SteelQuality selection list

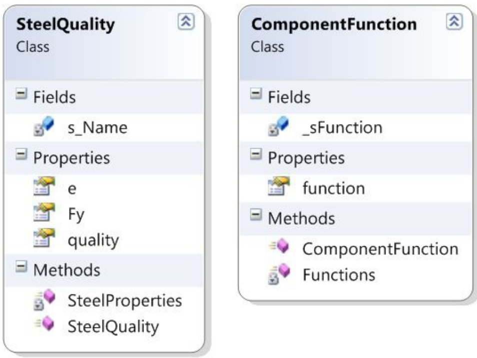


Figure 4.15. Design data provided by extra classes

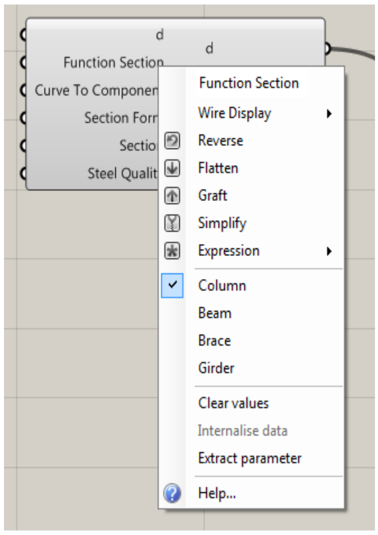


Figure 4.16. Function selection list.

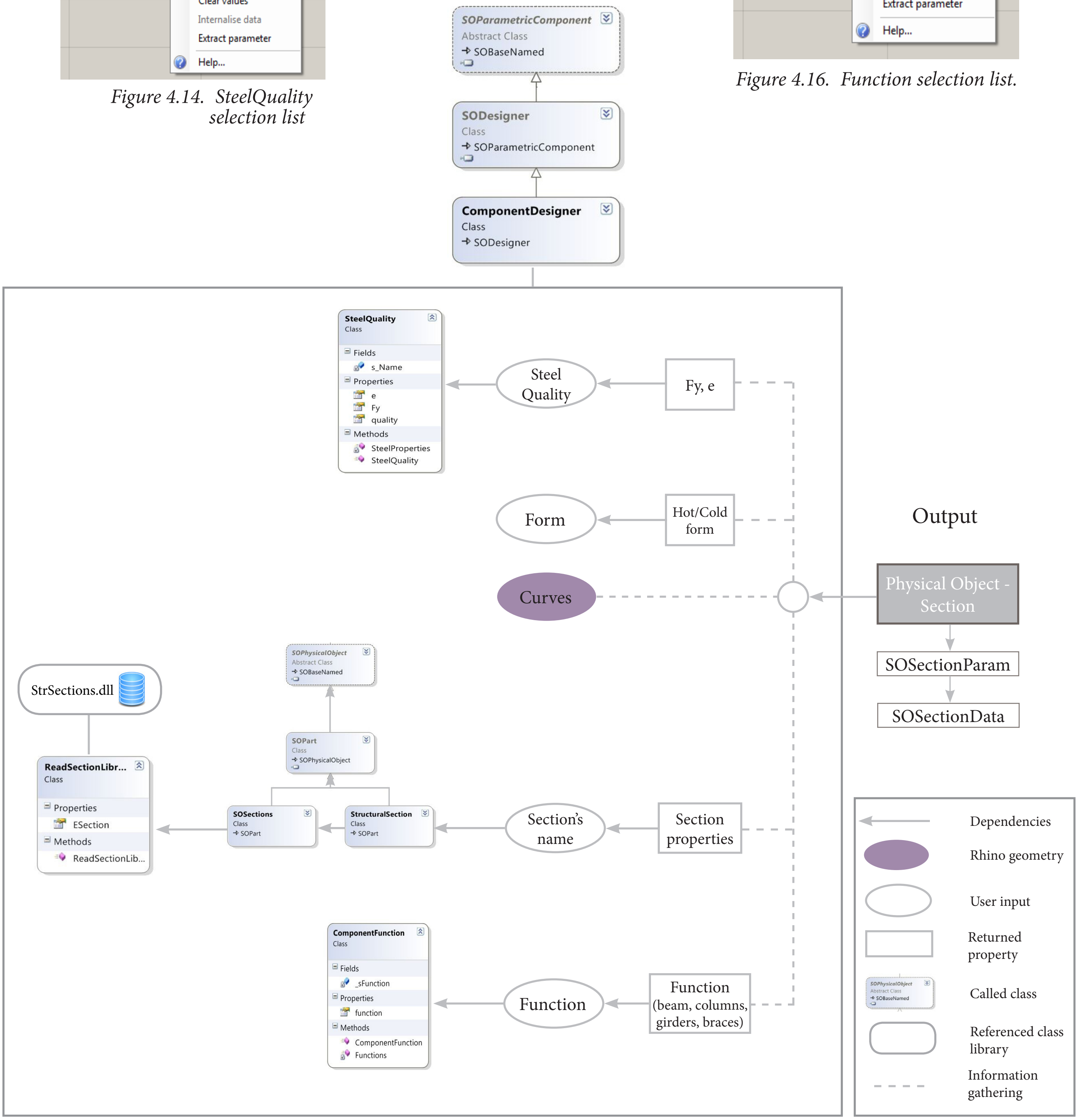


Figure 4.17. Data flow and dependencies within the SODesigner (ComponentBuilder_Component) class

The SOAnalysis class takes one or more designers as input and runs a specified analysis. In our case the only necessary analysis is the Quantity Take-Off analysis to calculate and accumulate the total weight of the provided components by the designers. The results of this analysis will then be used from the assessment components.

The SOAssessment class collects the results of the analysis and performs an assessment as described by the user. This description is provided through classes that inherit their properties from the SOAssessment class. These classes in our case is the FinancialAssessment class, the EmbodiedEnergy class, the MainIndicators class, the ResourceInput Indicators class and the WasteAssessment class. The later three classes are forming the Environmental Product Declaration assessment and retrieve information from a second database under the name "ConstructionProduct_Data.mdf". An example of the information flow and dependencies among SOAnalysis and SOAssessment MainIndicators class can be seen in Figure 4.18.

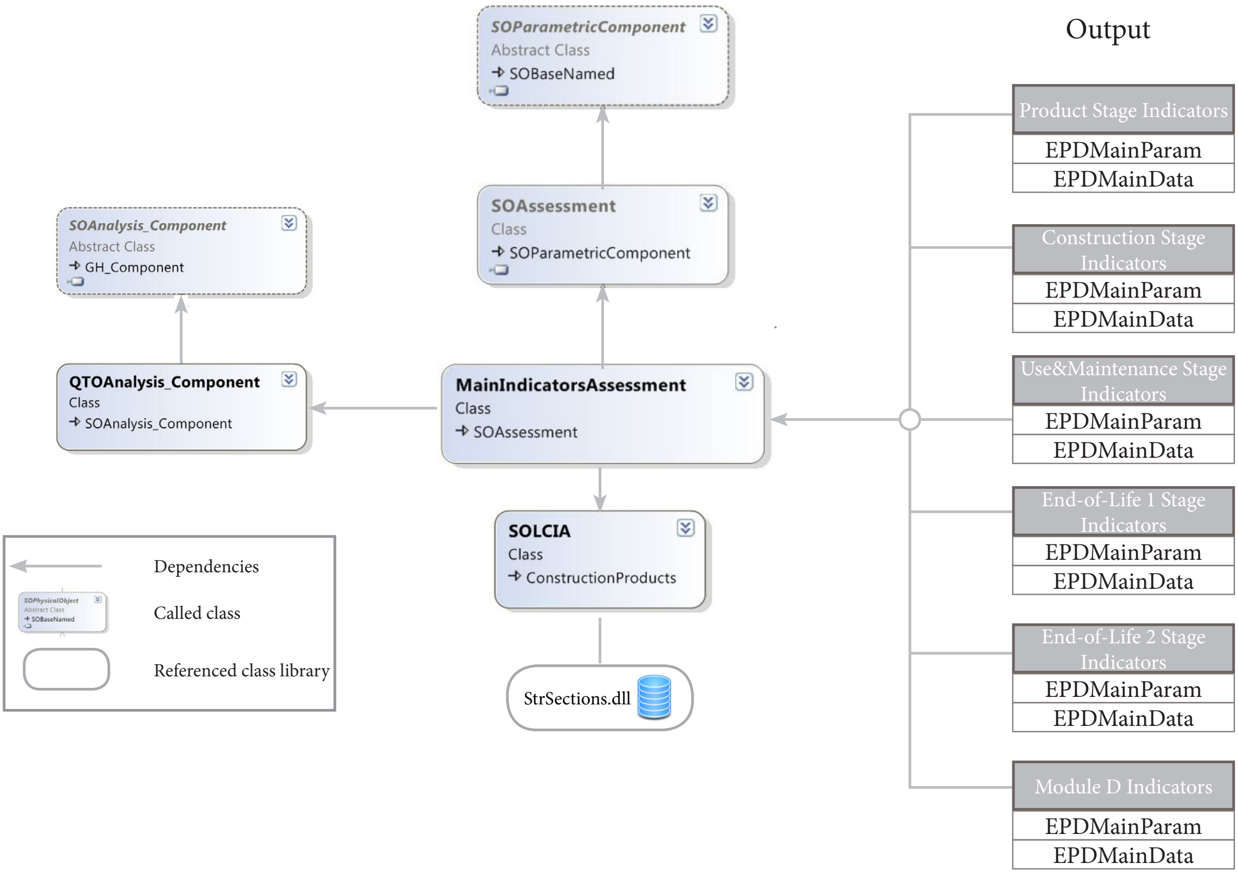


Figure 4.18. Data flow and dependencies within the SOAnalysis (QTOAnalysis_Component) and SOAssessment (MainIndicatorsAssessment) class

The SustainabilityOpen framework finally contains a layer for the visualization of the results acting as the user's interface. In order for components to load in the Grasshopper3D interface, an algorithm editor integrated into Rhino3D's modelling tool, must inherit their properties from the classes contained in this layer. So every class as described above has an extra class that inherits properties from the SODesigner_Component, the SOAnalysis_Component and the SOAssessment_Component as show in the UML diagrans in Figures 4.19 - 4.21.

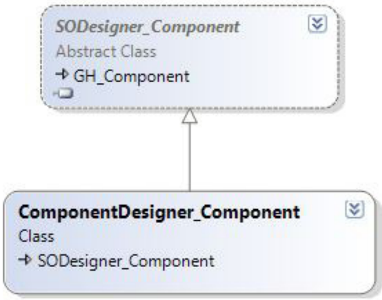


Figure 4.19. ComponentDesigner_Component diagram

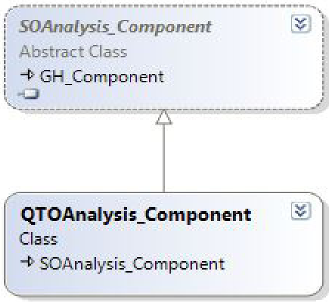


Figure 4.20. QTOAnalysis_Component diagram

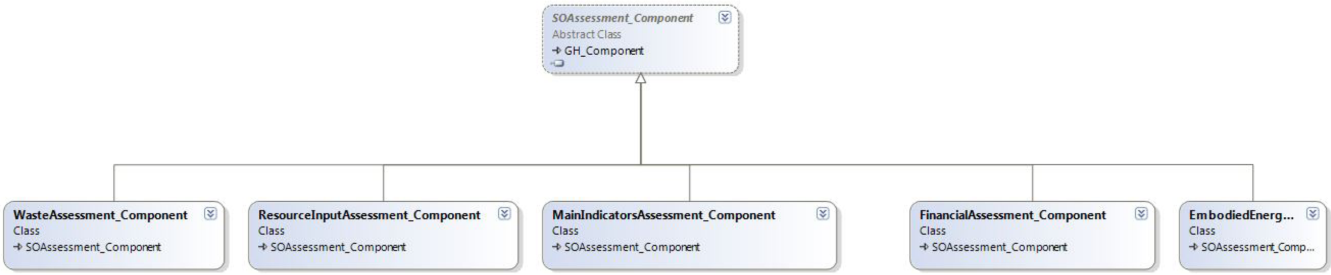


Figure 4.21. Structure of the visualization components and their relation to the SOAssessment_Component class

4.3.3 Custom Parameters

For the correct data manipulation and simplification of the components there was a need to create a series of custom parameters that derive their form from the Grasshopper.Kernel.Types.IGH_Goo class and define a new structure for the custom parameters. In order to form these parameters a xData class is created along with a child xParameters class of the GH_Param<xData> class which in return compromises the GUID of the parameter and the information that the user wants to be returned through the custom parameter. An overview of the custom parameters is given in Figures 4.22 and 4.23.

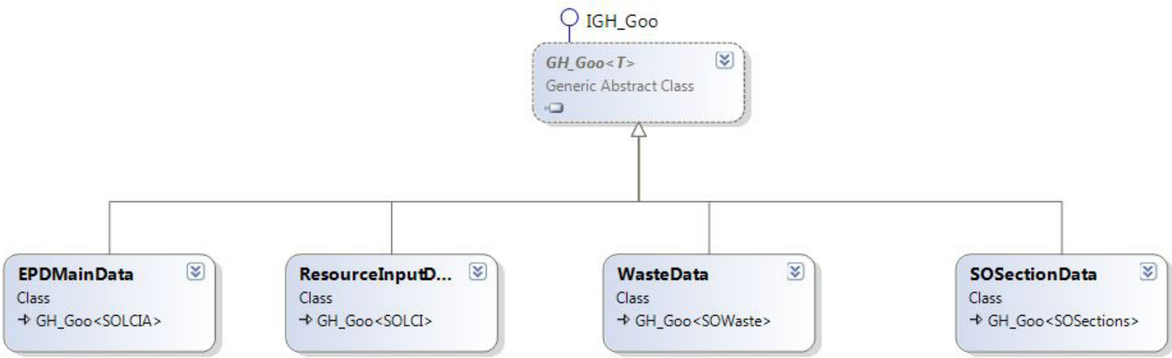


Figure 4.22. Custom Data classes and their relation to IGH_GOO class

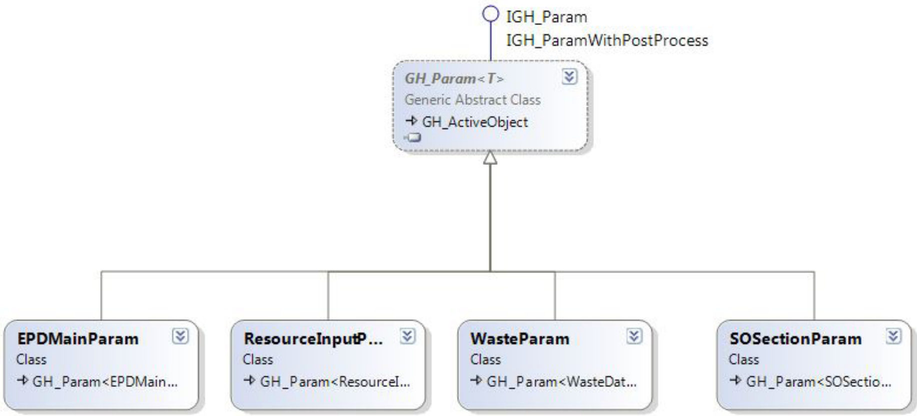


Figure 4.23. Custom Parameter child classes and their relation to GH_Param<T> class

4.2.4 User Interface Design

The custom components developed for the Grasshopper3D interface will be displayed in the interface in the form that the already existing components do. As the toolbox is integrated into Sustainability Open framework, the components will appear in the Menu bar under the SustainabilityOpen Category tab. This Category contains three main subcategories under the name Design, Analysis and Assessment. As described above, the custom components developed and implemented in the framework will appear under these three subcategories while the rest of the components in case the execute one of these three main function will also appear there accordingly else they will appear to new subcategories depending on their function in the Toolbox.

The custom components can be dragged into the canvas of the interface and connected (associated) to each other. The output of the components can become input for main Grasshopper components giving this way flexibility to the user to use the toolbox in an extended manner but also output from main Grasshopper3D components can act as input for the custom components. This is not the case in some components though that demand custom input parameters and provide custom output parameters as these were generated for specific needs of the tool. An extra attention was given to minimize the need for such components as the aim is to provide a tool that is flexible and can be used by the user in different ways so the only components that are part of this exception are those who needed to be tightly integrated in the flow of the toolbox to provide sensible results focused on the purposes of the topic. The custom made components are information carriers meaning that there is no visual output in the Rhino interface except from the Grapher_Assessment component and the FinancialAssessment component that provide visual graphs for the user to be able to see the results of the assessments and make informed choices regarding his/hers design options. Once the user decides the final design option an ExportToExcel component will provide the user the possibility to export his results to Excel sheets and store them for further use as will be proposed in the Recommendations of this thesis.

4.2.5 Visualization layer into Grasshopper

The classes of the visualization layer form the user interface of the toolbox. They collect user input, in predifined form, nessecary for the operation of the underlying classes and pass it on to the corresponding classes. As the toolbox is developed to be implemented into Grasshopper3D the custom components follow the same logic as the existing components of the program. Every Grasshopper component is a derived class from the abstract class GH_Component that is included in Grasshopper class library. The methods that provide the user interaction are:

- the RegisterInputParams(), that register the user's input
- the RegisterOutputParams(), that register the output as defined within the class`

While the SolveInstance() method, defines the way the class will manipulate the input data and provide the desired output. In the later the DA (Data Access) object is used to retrieve data from the user's input and store data as output. These methods are inherited and overridden from the GH_Component class.

In the case of SustainabilityOpen framework the components' classes inherit their methods from the SOParametricComponent class and override the initial mentioned methods of the GH_Component by calling the base class of the framework.

4.2.6 Component Overview

As described above the developed components will be assigned to three different subcategories following the logic of the SustainabilityOpen framework. Part from that there will be an extra subcategory called Utilities that will include a set of components that will complement the process of a whole analysis.

The Design component will offer the possibility to the user to design a basic structure if he/she decides to follow the first of the two use cases described in Paragraph 4.1.3 and to turn the produced geometry into Physical objects (structural sections) in order to move on to the analysis. The geometry needed is simple curves and the outcome of the designer is Section carrying useful parameters. This conversion is being accomplished using custom parameters and will be analytically explained later in this chapter.

The Analysis component will perform a quantity take-off analysis (QTO) in order to extract a useful information (the total quantity of used material expressed in tonnes of steel) that will be used for the assessment of the structure. Along with the QTA a component named ComponentCollector will collect all the produced sections and will return them as a collection that will be used later on the assessment phase.

The Assessment components are performing different types of assessments in order to provide the user with the information that will demonstrate the benefits or not of the concept of deconstruction that is the primary objective of this thesis. The assessment can be done in two phases. The first phase is being executed by a series of components that perform an assessment on the initial structure provides an Environmental impact assessment of the structure in form of an EPD for the building level using the data provided by Bouwenmetstaal. Also a component provides results regarding the embodied energy and carbon of the initial design so the user has a clear overview of the impacts of the initial design before moving to second phase. The components conducting the EPD are accompanied by a Grapher component that visualize the results into Rhino's interface. The second phase is realised through an assessment component that takes as input the assessment results of the first phase and return, again in form of an EPD results regarding two scenarios. The scenario of Reuse and the Scenario of Recycle. The results are directly exposed on Rhino's interface so the user can have a direct feedback of his design choice and the possible benefits that this choice can bring. For this assessment a set of components found under Utilities is created in order to give the user the opportunity to input the potential impacts of the transportation of material that will be required after the end-of-life of the first structure for the Reuse and the Recycle scenario.

Part from this assessment a set of components is used to perform a financial assessment of the two scenarios. The first component called ShadowCosts translate the impacts of the Product stage of the two scenarios and the transportation impacts into Shadow costs using values provided by NIBE database. The second component called FinancialAssessment collects these values along with values provided by the user for relevant deconstruction and demolition costs and returns a final price for demolition and a final price for deconstruction in order to quantify the potential economic benefits of the concept of deconstruction. This component also visualize the results into Rhino's interface so the user can have a direct feedback of his/her design choices.

An overview of the DesignforDeconstruction toolbox and its components in the Grashopper3D's environment along with the toolbox setup can be seen in Figure 4.24.

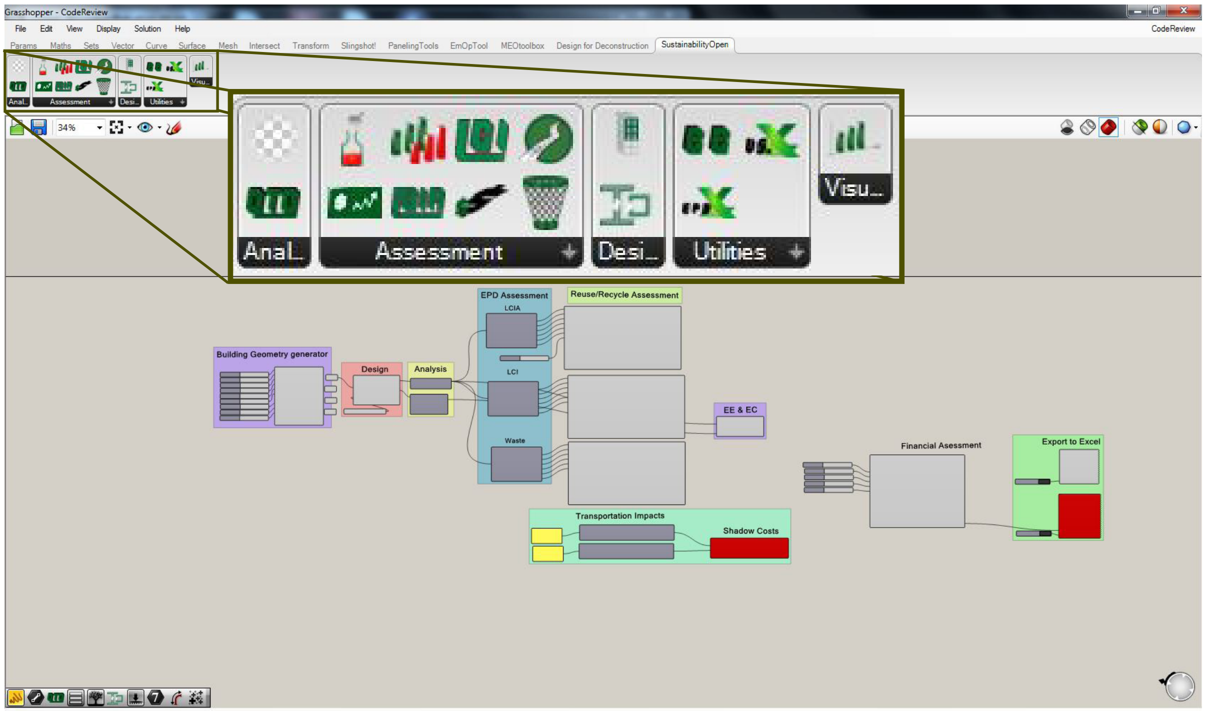


Figure 4.24. Overview of the toolbox components into Grasshopper3D's environment

4.3. Data management

4.3.1 Data flow

The "Design for Deconstruction" toolbox is built as mentioned before against C#, an object oriented programming language. Object-oriented programming focuses on objects rather processes . An object is an instance of a class, a self-sufficient module, that contains all the necessary information to manipulate its data structure called members. This way C# provides the opportunity to access data among classes indirectly through written functions called methods. This way specific data can be protected by encapsulating them in classes that are not accessible by the rest of the code. An example of this approach is given in Figure 4.17 where the information flow of the ComponentDesigner_Component is shown. In this example the SOSection class instantiates, through a method called CalculateSectionProerties, the ReadSectionLibrary class, a class that is connected to the EuropeanSection_Data database (built in the StrSections.dll class library) and retrieves information in order to create an "object" with the related properties. Here the constructor of the ReadSectionLibrary class takes a string as an argument which represents the name of the section that the user wants to retrieve data for.

Using Methods, code blocks containing a series of statements that together perform a task (msdn.microsoft.com) provides the advantage of reusing a piece of code multiple times avoiding the need of rewriting it. This approach is used multiple times within the code especially from the assessment components.

4.3.2 Databases

In order to provide the necessary data to the Design and Assessment components to produce the required results there was a need to connect the classes that represent these components with a series of data. As the amount of iterations for the designers might become really intensive especially for large scale projects the data needed to be provided in an efficient way. In order to do so the two SQL Server type databases were created and connected to the project using the Microsoft's SQLExpress data management system, a free compact version of Microsoft's SQL server. The databases are connected to a separate project under the name StrSections which creates a new class library that is then referenced to the initial project file. In order to extract results from the databases based on specific inputs the MSLinqToSQLGenerator class library was deployed. In order for the user to use the plug-in it is necessary though that he/she copies a file provided in the plug-in folder under the name "DESIGNFORDECONSTRUCTIONDB" to the C: Folder of their workstation. This way the user has the opportunity to populate or change the provided values of the databases. The two databases can be found under the names "ConstructionProducts_Data.mdf" and "EuropeanSections_Data.mdf" and contain information regarding the environmental impacts of the different life cycle stages of steel products and properties of European structural sections accordingly.

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5

Test & Validation

The current chapter will focus on the validation of the components of the tool. An explanation of the steps taken to test every component that reflects each step of the developed strategy will be given followed by a discussion and validation of these results.

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5.1. Basic Testing

After developing a strategy for the approach that had to be followed in order to meet the main research objectives, the steps needed to fulfil this strategy were gradually translated into components that would be called to fulfil specific operations. These operations are mainly focused on data generation, matching and handling, something that made the development of the components a demanding process.

Since the approach of the strategy is to quantify environmental and financial impacts of a design and finally export this data to spreadsheets for further use the first testing approach was to validate the accuracy of the produced results. After this step the produced data are transferred to the assessment components followed by a quantity take-off analysis. There a further manipulation was required to match the produced data with values from the connected databases in order to produce a first Environmental Product Declaration on a building level for the design under consideration. These results were also tested to ensure the correct magnitudes of the resulted values. These results are then used for further assessment. This time the assessment did not only require a data matching but also a data handling from secondary inputs like for example data coming from the TranspotationImpacts component. So a new validation of the produced results was required. At this stage the visualization of the data into Rhino's interface was a requirement since the user should be able to have a feedback on his/hers design choices and the existing Grasshopper components are not able to visualize efficiently the amount of data produced. In order to do so a visualization strategy was also implemented into the components that had to be tested against its robustness.

Finally and in order to ensure that the final step of the assessment route, that was expressed through a financial assessment of the two possible scenarios, produced the expected results through further data manipulation an extra testing step was required. After the validation of the results and in order to complete the developed strategy the most important of the produced results had to be exported into Excel spreadsheets, a step that also required testing regarding its accuracy.

Every one of the above mentioned tests took place using manually produced Excel sheets that followed the calculation logic that should be executed by each component separately. The validity of the results produced from the Excel sheets is considered guaranteed since Microsoft Excel is a commercial product and the calculation logic that was applied is based on simple multiplication of values included in the spreadsheets. The tests are explained in detail below.

5.2. Validation through spreadsheets

The first step where data are produced for further analysis and assessment is being held by the ComponentDesigner_Component which is called to translate geometries (Curves) into structural sections with specific properties. From these properties the most important value for the rest of the body of the tool was that of the total mass of the component(s) expressed in tonnes of steel. In order to test and validate the accuracy of its results a simple approach was used. Since the data that formed the "EuropeanSecions_data" database that carries the properties for different European structural sections was created using data provided by ArcelorMittal (http://corporate.arcelormittal.com/) in form of Excel sheets the data produced from the component were tested in comparison with the provided data. In order to complete this test three curves were turned into three sections - one for each main section form (European I Beams (IPE), European Wide flange beams (HE) and Wide flange columns (HD)). The results of the validation can be seen in Appendix II. In Figure 5.1 the basic set up for the first test in Grasshopper's environment is shown

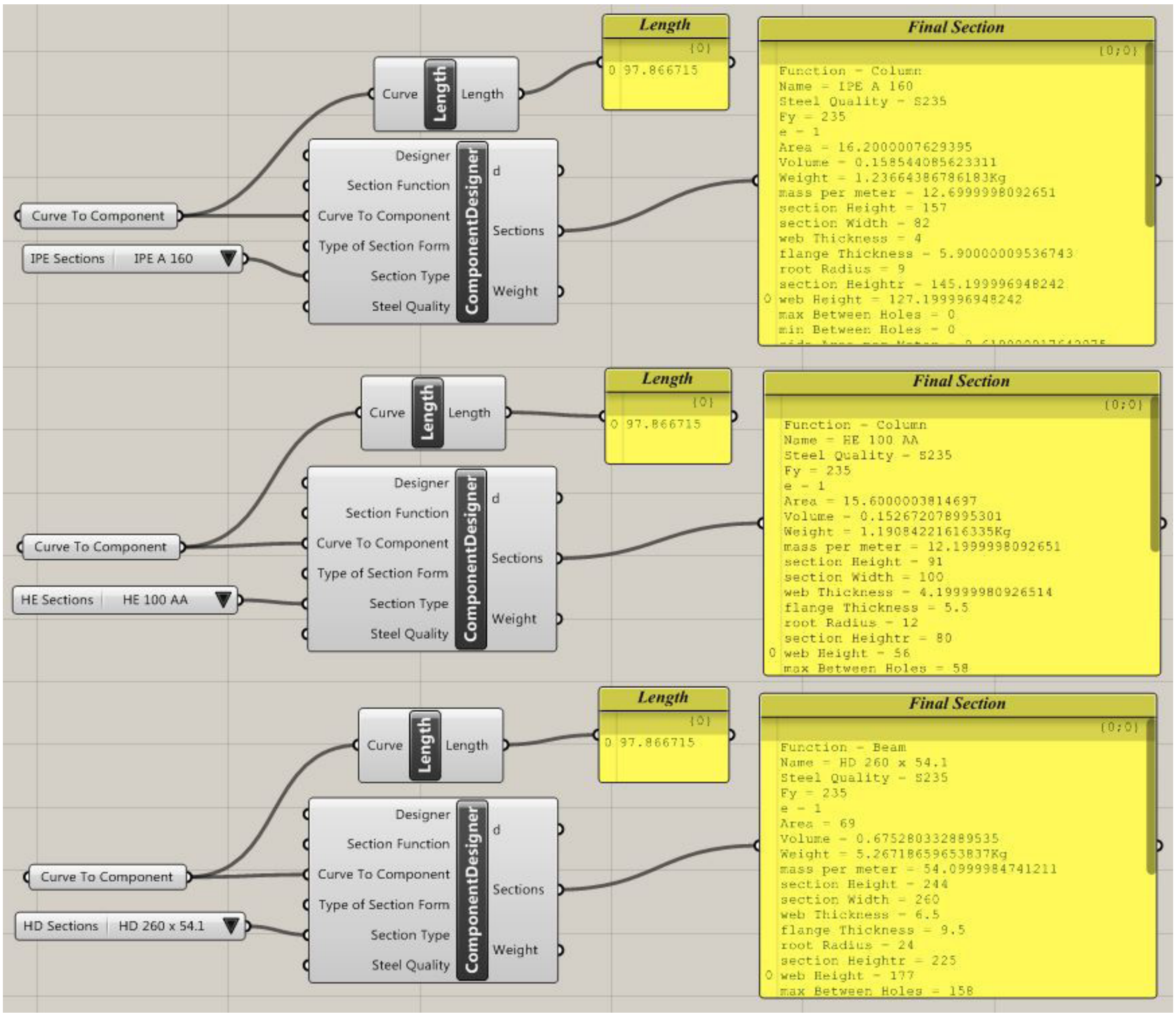

Figure 5.1. Basic set up for testing the ComponentDesigner_Component and the produced sections

The second test was regarding the assessment of the total weight of the component and the validation of the results in form of an EPD. For this testing the results of the first test were carried to the QTOAnalysis component and from there to the EPD components(LCIA, LCI and WasteAssessment_Component). The results were again tested against a spreadsheet created for this purpose which contains the data that were used in the "ConstructionProducts_Data" database. The analytical results of the validation can also be seen in Appendix II. In Figure 5.2 one can see the basic set up for this second test while in Table 5.1 the relative error between the manually produced results and those produced from the EPD components is shown, expressed in relative percentage. The relative error has been calculated as the difference between the produced values from the Excel sheet and the produced values from the components divided by the produced values from the Excel sheets so if:

Evalue = the produced values from Excel and
Cvalue = the produced values from the components

then

$$\text{Relative Error: RE} = \frac{\text{Cvalue - Evalue}}{\text{Evalue}}$$

Formula 5.1. Relative Error (RE)

It must be noted that the relative error is expressed as a percentage.

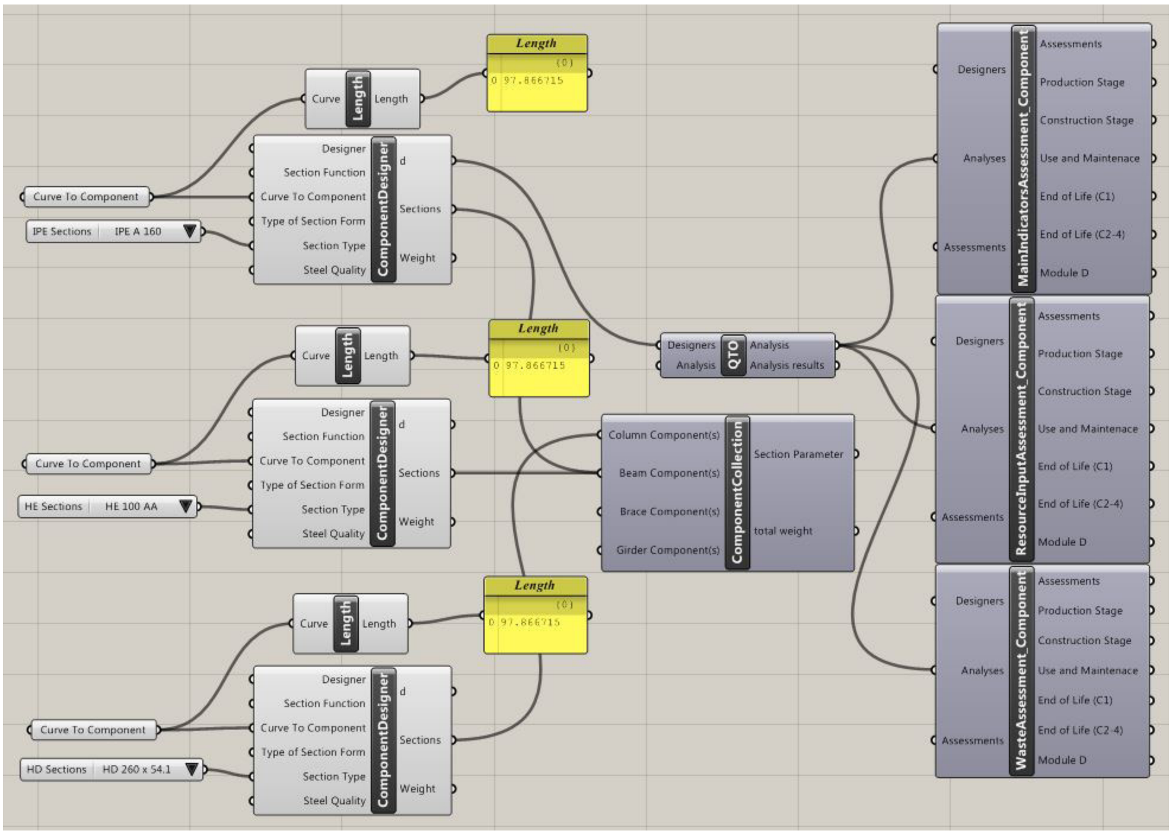

Figure 5.2. Basic set up for testing the EPD Assessment results

2011 EPD Heavy Construction Products	Unit	Product stage (A1,A2,A3)	Construction (A4,A5)	Use and Maintainance (B1,B7)
Environmental Profile				
Global warming potential, GWP	kg CO2	0,000691887	0,000695004	0,000692717
Depletion potential of the stratospheric ozone layer, ODP	kg CFK-11	1	1	1
Acidification potential of land and water resources, AP	kg SO2	0,000675551	0,000342615	0,001295937
Eutrophication potential, EP [EN15804/prA1]	kg PO43-	0,000589329	-0,000408909	0,004034107
Formation potential of tropospheric ozone photochemical oxidants, POCP	kg ethyl	0,000778045	-0,0142672	-0,013369645
Depletion of abiotic resources, elements	kg Sb	-0,322614163	1	1
Depletion of abiotic resources, fossil fuels	MJ	0,000691865	0,000691644	0,000691686
Resource input				
Use of renewable energy primary energy, excl. ren. prim. resources used as raw materials	MJ (n.c.f)	0,000691878	0,000688619	0,00068435
Use of renewable primary energy resources used as raw materials	MJ (n.c.f)	0,017137168	-0,00475682	-0,233322854
Total use of renewable primary resources	MJ (n.c.f)	0,000691878	0,000688619	0,00068435
Use of non renewable primary energy, excl. non ren. prim. energy resources used as materials	MJ (n.c.f)	0,000691861	0,000691691	0,000692049
Total use of non renewable primary energy resources	MJ (n.c.f)	0,000691861	0,000691691	0,000692049
Use of secondary material	kg	0,000691838	0	0
Use of renewable secondary fuels	MJ	0	0	0
Use of non renewable secondary fuels	MJ	0	0	0
Input of fresh water	m3	0,000691879	0,000693451	0,00069337
Waste Categories				
Hazardous waste disposed	kg	0,000691654	0,000693198	0,00069278
Non hazardous waste disposed	kg	0,000692183	0,00068583	0,000799082
Radioactive waste disposed	kg	0	0	0

2011 EPD Heavy Construction Products	Unit	End of Life (C1)	End of Life (C2-C4)	Module D (D)
Environmental Profile				
Global warming potential, GWP	kg CO2	0,000691005	0,000691088	0,000691756
Depletion potential of the stratospheric ozone layer, ODP	kg CFK-11	1	1	1
Acidification potential of land and water resources, AP	kg SO2	0,00046182	0,000481968	0,000687807
Eutrophication potential, EP [EN15804/prA1]	kg PO43-	0,00060914	0,002537677	0,001010747
Formation potential of tropospheric ozone photochemical oxidants, POCP	kg ethyl	0,000894055	-0,005797135	0,001067375
Depletion of abiotic resources, elements	kg Sb	1	1	1
Depletion of abiotic resources, fossil fuels	MJ	0,00069176	0,000691986	0,000691867
Resource input				
Use of renewable energy primary energy, excl. ren. prim. resources used as raw materials	MJ (n.c.f)	0,0006896	0,000688971	0,000691998
Use of renewable primary energy resources used as raw materials	MJ (n.c.f)	-0,039604762	-0,021758709	-0,002921393
Total use of renewable primary resources	MJ (n.c.f)	0,0006896	0,000688971	0,000691998
Use of non renewable primary energy, excl. non ren. prim. energy resources used as materials	MJ (n.c.f)	0,00069183	0,000691813	0,000691856
Total use of non renewable primary energy resources	MJ (n.c.f)	0,00069183	0,000691813	0,000691854
Use of secondary material	kg	0	0	0
Use of renewable secondary fuels	MJ	0	0	0
Use of non renewable secondary fuels	MJ	0	0	0
Input of fresh water	m3	0,000695046	0,000691676	0,000691815
Waste Categories				
Hazardous waste disposed	kg	0,000683206	0,000690352	0,000690597
Non hazardous waste disposed	kg	0,000845862	0,000698589	0,000691137
Radioactive waste disposed	kg	0	0	0

Table 5.1 Relative error for the EPD results

In all three sets of assessment results one can notice that the relative error is less than 1%. This proves that the magnitude of the results are the ones expected and the error is probably cause by the fact that the results produced by the components are rounded up to four decimals in order to be later on presented to the user through Rhino3D's interface in a sensible manner.

The third part of testing validated the results produced from the EPD_Grapher components. In this phase of the assessment the results from the EPD components are used to perform a comparative assessment between a Recycle and a Reuse scenario that is considered the core part of the followed strategy. (See Section 3.4.2). The set up for this test is shown in Figure 5.3 and the analytical tables with the results can be found in Appendix II. While in Table 5.2 the relative error between the manually produced results and those produced from the EPD components is shown, expressed in relative percentage. The relative error is again calculated following Formula 5.1 as described above,

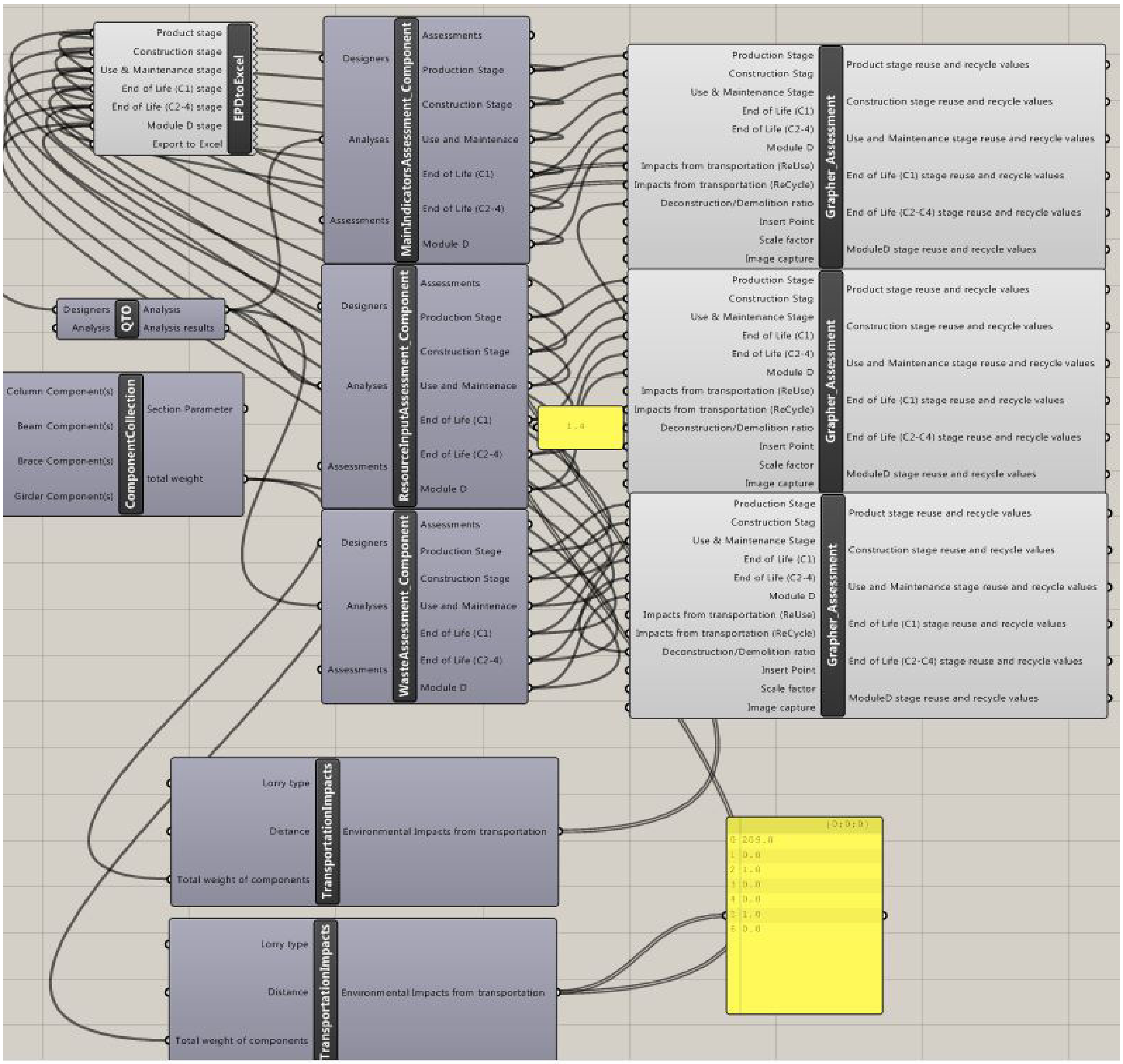

Figure 5.3. Basic set up for testing the EPD_Reuse/Recycle scenario

In the diagrams above one can see that the relative error is again 1% or less stating the magnitude of the produced results in desirable levels while the error is caused again probably due to the fact that the results of the component are rounded up to four decimals in order to be presented in a sensible manner.

The results for all the above mentioned tests were exported to Excel sheets through the components developed for this reason stating their function also successful while the components dedicated to visualize the results for the user were validated through visual identification of the above values and the values exposed in Rhino3D's interface.

2011 EPD Heavy Construction Products	Unit	Product stage (A1,A2,A3)		Construction (A4,A5)	
		ReUSE	ReCYCLE	ReUSE	ReCYCLE
Environmental Profile					
Global warming potential, GWP	kg CO2	0,000692	-0,064406	0,000254	0,000291
Depletion potential of the stratospheric ozone layer, ODP	kg CFK-11	1,000000	1,000000	1,000000	1,000000
Acidification potential of land and water resources, AP	kg SO2	0,000603	-0,247245	0,000152	0,000152
Eutrophication potential, EP [EN15804/prA1]	kg PO43-	0,000595	-0,192409	-0,000409	-0,000409
Formation potential of tropospheric ozone photochemical oxidants, POCP	kg ethyl	0,000789	-0,062811	-0,014267	-0,014267
Depletion of abiotic resources, elements	kg Sb	-0,368466	-0,565243	0,000209	0,000419
Depletion of abiotic resources, fossil fuels	MJ	0,000692	-0,064150	0,000692	0,000692
Resource input					
Use of renewable energy primary energy, excl. ren. prim. resources used as raw materials	MJ (n.c.v)	0,000692	-0,005213	0,000689	0,000689
Use of renewable primary energy resources used as raw materials	MJ (n.c.v)	-0,003032	-0,253249	-0,004757	-0,004757
Total use of renewable primary resources	MJ (n.c.v)	0,000692	-0,005213	0,000689	0,000689
Use of non renewable primary energy, excl. non ren. prim. energy resources used as materials	MJ (n.c.v)	0,000692	-0,059029	0,000692	0,000692
Total use of non renewable primary energy resources	MJ (n.c.v)	0,000692	-0,059028	0,000692	0,000692
Use of secondary material	kg	0,000692	0,000692	0,000000	0,000000
Use of renewable secondary fuels	MJ	0,000000	0,000000	0,000000	0,000000
Use of non renewable secondary fuels	MJ	0,000000	0,000000	0,000000	0,000000
Input of fresh water	m3	0,000692	-0,005129	0,000693	0,000693
Waste Categories					
Hazardous waste disposed	kg	0,000690	-0,095674	0,000693	0,000693
Non hazardous waste disposed	kg	0,000693	-0,003208	0,000686	0,000686
Radioactive waste disposed	kg	0,000000	0,000000	0,000000	0,000000

2011 EPD Heavy Construction Products	Unit	Use and Maintainance (B1,B7)		End of Life (C1)	
		ReUSE	ReCYCLE	ReUSE	ReCYCLE
Environmental Profile					
Global warming potential, GWP	kg CO2	0,000693	0,000693	0,000691	0,000691
Depletion potential of the stratospheric ozone layer, ODP	kg CFK-11	1,000000	1,000000	1,000000	1,000000
Acidification potential of land and water resources, AP	kg SO2	0,001296	0,001296	0,000462	0,000462
Eutrophication potential, EP [EN15804/prA1]	kg PO43-	0,004034	0,004034	0,000609	0,000609
Formation potential of tropospheric ozone photochemical oxidants, POCP	kg ethyl	-0,013370	-0,013370	0,000894	0,000894
Depletion of abiotic resources, elements	kg Sb	1,000000	1,000000	1,000000	1,000000
Depletion of abiotic resources, fossil fuels	MJ	0,000692	0,000692	0,000692	0,000692
Resource input					
Use of renewable energy primary energy, excl. ren. prim. resources used as raw materials	MJ (n.c.v)	0,000684	0,000684	0,000690	0,000690
Use of renewable primary energy resources used as raw materials	MJ (n.c.v)	-0,233323	-0,233323	-0,039605	-0,039605
Total use of renewable primary resources	MJ (n.c.v)	0,000684	0,000684	0,000690	0,000690
Use of non renewable primary energy, excl. non ren. prim. energy resources used as materials	MJ (n.c.v)	0,000692	0,000692	0,000692	0,000692
Total use of non renewable primary energy resources	MJ (n.c.v)	0,000692	0,000692	0,000692	0,000692
Use of secondary material	kg	0,000000	0,000000	0,000000	0,000000
Use of renewable secondary fuels	MJ	0,000000	0,000000	0,000000	0,000000
Use of non renewable secondary fuels	MJ	0,000000	0,000000	0,000000	0,000000
Input of fresh water	m3	0,000693	0,000693	0,000695	0,000695
Waste Categories					
Hazardous waste disposed	kg	0,000693	0,000693	0,000683	0,000683
Non hazardous waste disposed	kg	0,000799	0,000799	0,000846	0,000846
Radioactive waste disposed	kg	0,000000	0,000000	0,000000	0,000000

2011 EPD Heavy Construction Products	Unit	End of Life (C2-C4)		Module D (D)	
		ReUSE	ReCYCLE	ReUSE	ReCYCLE
Environmental Profile					
Global warming potential, GWP	kg CO2	0,000691	0,000691	0,000692	0,000692
Depletion potential of the stratospheric ozone layer, ODP	kg CFK-11	1,000000	1,000000	1,000000	1,000000
Acidification potential of land and water resources, AP	kg SO2	0,000482	0,000482	0,000688	0,000688
Eutrophication potential, EP [EN15804/prA1]	kg PO43-	0,002538	0,002538	0,001011	0,001011
Formation potential of tropospheric ozone photochemical oxidants, POCP	kg ethyl	-0,005797	-0,005797	0,001067	0,001067
Depletion of abiotic resources, elements	kg Sb	1,000000	1,000000	1,000000	1,000000
Depletion of abiotic resources, fossil fuels	MJ	0,000692	0,000692	0,000692	0,000692
Resource input					
Use of renewable energy primary energy, excl. ren. prim. resources used as raw materials	MJ (n.c.v)	0,000689	0,000689	0,000692	0,000692
Use of renewable primary energy resources used as raw materials	MJ (n.c.v)	-0,021759	-0,021759	-0,002921	-0,002921
Total use of renewable primary resources	MJ (n.c.v)	0,000689	0,000689	0,000692	0,000692
Use of non renewable primary energy, excl. non ren. prim. energy resources used as materials	MJ (n.c.v)	0,000692	0,000692	0,000692	0,000692
Total use of non renewable primary energy resources	MJ (n.c.v)	0,000692	0,000692	0,000692	0,000692
Use of secondary material	kg	0,000692	0,000692	0,000692	0,000692
Use of renewable secondary fuels	MJ	0,000000	0,000000	0,000000	0,000000
Use of non renewable secondary fuels	MJ	0,000000	0,000000	0,000000	0,000000
Input of fresh water	m3	0,000692	0,000692	0,000692	0,000692
Waste Categories					
Hazardous waste disposed	kg	0,000690	0,000690	0,000691	0,000691
Non hazardous waste disposed	kg	0,000699	0,000699	0,000691	0,000691
Radioactive waste disposed	kg	0,000000	0,000000	0,000000	0,000000

Table 5.2 Relative error for the Reuse vs. Recycle scenario assessment results

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6

Case Study

This chapter is dedicated to the application of the tool on a case study. The main purpose of the study is to demonstrate the functionality of the tool and investigate how different parameters influence the impacts of the concept of designing for deconstruction. The case study is the structural frame of an industrial steel structure designed to be used as a storage space for a short period of time.

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6.1. Case Study description

The case under study is an assessment of the potential environmental and financial benefits that may arise from the reuse of a structural frame of an industrial steel building. The building is initially designed to serve as an agricultural/veterinarian unit for a farm in Greece, at the prefecture of Xanthi. It is chosen as it is an industrial building of common form that serves a function for a specific period and after the end of its functional life cycle either changes function or, most commonly, stays abandoned or is being demolished. As such the building is considered ideal for deconstruction and reuse as it is of simple geometry, formed by commonly used steel structural sections and simple connection. Also this type of buildings are relatively "naked" due to the low demands for thermal and sound insulation, without complex interiors making the deconstruction process even simpler. Finally the building can be considered ideal for deconstruction as it has only one story and does not suffer from severe loading nor it is subject to repetitive loadings that could state the components unsuitable for reuse due to fatigue phenomena. Finally the simplicity of the building's geometry allows for repetitive and symmetric use of structural frames resulting to steel sections of equal dimensions per function. A fact that can give high level of design freedom to the designer to design a new structure. The initial design of the building includes an extra floor that covers less than an eighth of the total surface designed to facilitate offices but is not included in the assessment process as it was supported by two extra steel column on the one side while the other side was attached to the main structure so it was considered that will not cause any significant change to the final assessment results. The loads though considered for this purpose did affect the final selection of steel sections and as such the results of this action are taken into account.

The design and the design details were provided to the author by Ir. D Pachoumis from the Department of Steel Structures of Civil Engineering of Democrition University of Thraki, who was the structural engineering of the project.

6.2. Project details

The building is located at the prefecture of Xanthi in Northern Greece in an area called Mandras ranch as shown in Figure 6.1.

Figure 6.1. Location of the case study building

Design details

The building is designed under Eurocodes 1 and 3 and the Greek code for seismic loads (E.A.K 2000). The loads and materials considered for the choice of the structural system and the adequate sections to meet the requirements of the above mentioned codes are:

I. Material

Reinforced concrete : C20/25
Concrete covers : C12/15
Steel rebars S500s (H)
Structural steel S275

II. Loads

Permanent loads

Concrete self-imposed load : 25.00KN/m^3
Floor coverings : 1.50 KN/m^2
HVAC Equipment : 0.30 KN/m^2
Ceilings : 0.25 KN/m^2

Imposed loads

Snow loading according to EC1 (2-3)
Wind loading according to EC1 (2-4)
Imposed loading according to EC1 (2-2)
Offices, coridors : 5.00KN/m^2
Gypsumboard walls (2+2) : 0.40 KN/m

Earthquake considerations

Seismic zone : I
Seismic ground acceleration A = 0.16g
Soil quality : B
Damping factor : 4

Total building area : 1082,5 m^2

For the assessment of the building only the structural steel sections are taken into consideration. The connections and the foundation blocks are not taken into account since they are currently out of the scope of the toolbox. The foundations are subject to assessment as the material used may influence the total outcome regarding both the environmental and financial impacts. On the other hand the connections are subject to further study as although it is not expected to influence the final outcome for the reasons described in Section 3.2.5 they are considered, technically, the most important aspect for the efficiency of the concept of Deconstruction.

The sections chosen for the current building are presented briefly in the table below. The detailed drawing of the structure can be found in Appendix III . A general view of the structure's geometry is shown in Figures 6.2 - 6.5.

Function	Amount	Designation	Length (m)	Volume (m^3)	Weight (tonnes)
Roof Beams	24	IPE 270	9,995	0,046	0,357
Columns	24	HE 240 A	5	0,0384	0,3
Roof Girders	154	IPE 120	4,978	0,006	0,051
Wind braces (Roof)	50	IPE 180	5,233	0,0125	0,0975
Wind braces (sides)	8	IPE 180	7,05	0,0232	0,183
Totals				3,76	29,8

Table 6.1 Sections used for the case study building

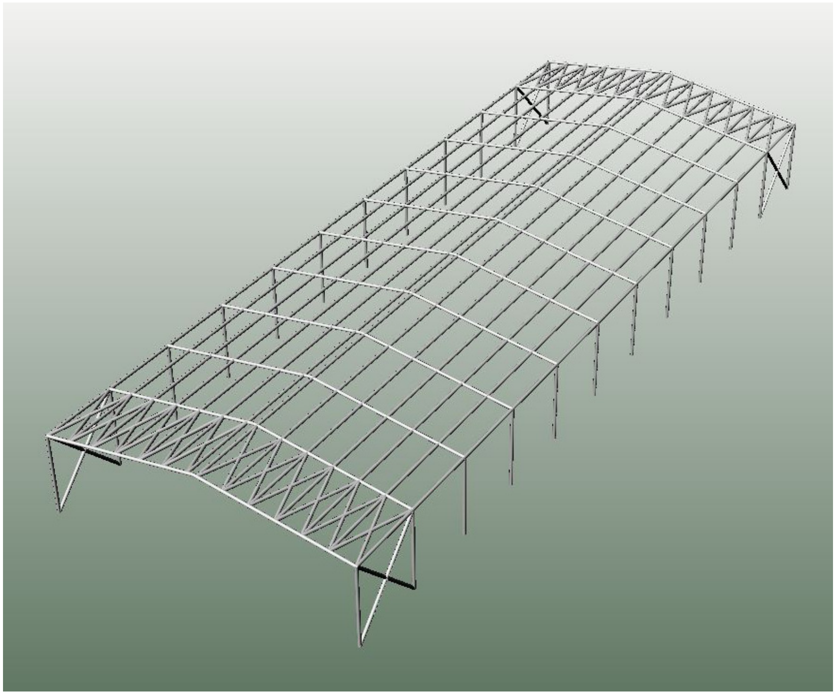


Figure 6.2. Perspective view

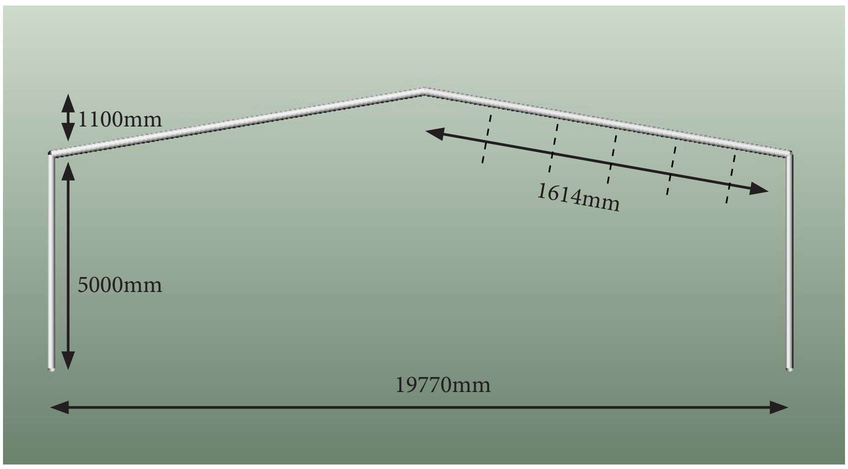


Figure 6.3. Front view

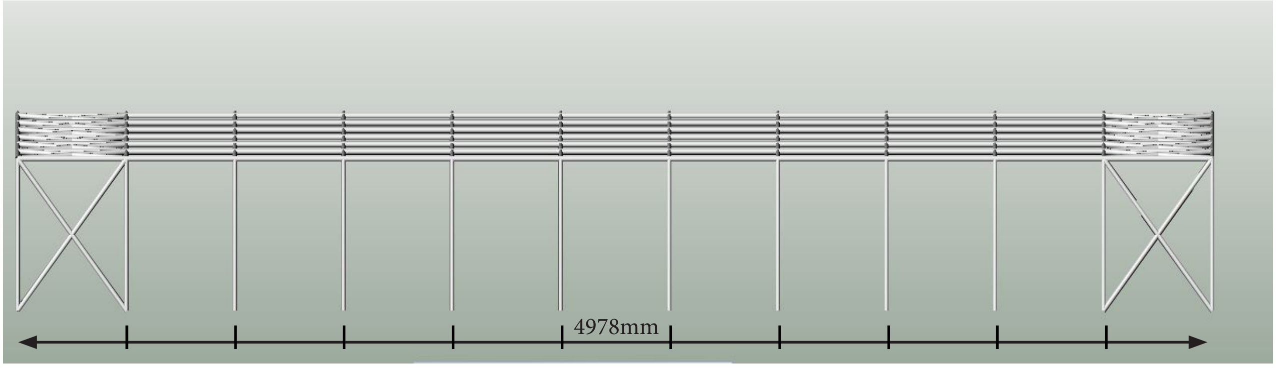


Figure 6.4. Side view

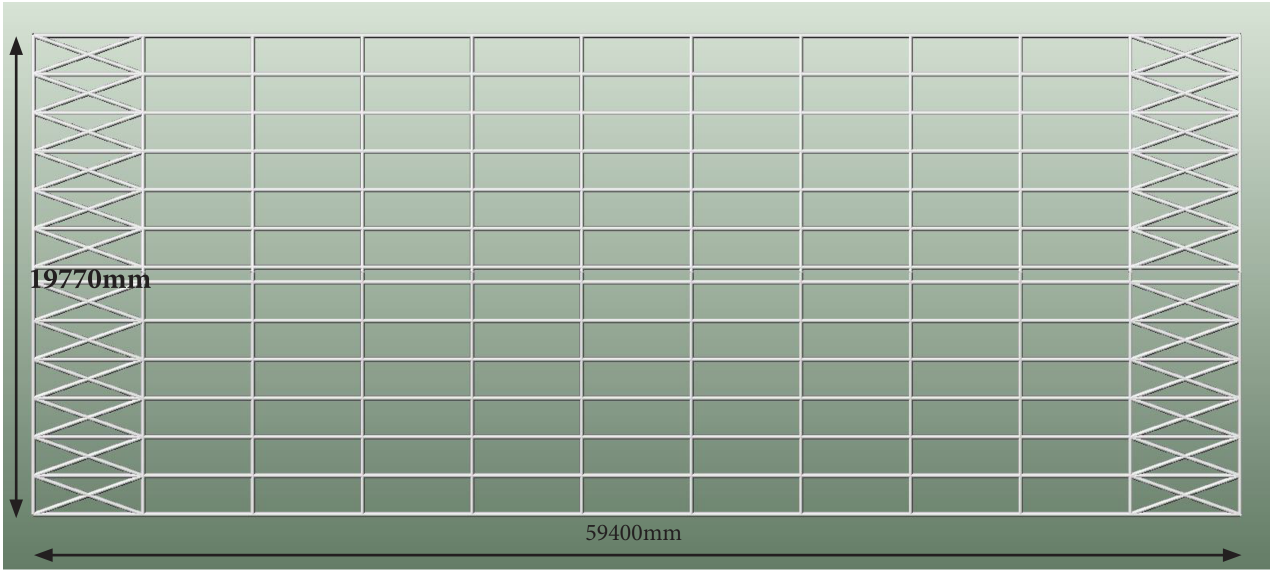


Figure 6.5. Top view

Step 1 - Turn curves into structural Components

The building has been parametrically defined in Rhino using basic Grasshopper3D components. The Produced geometry is divided to the according elements, so each set of the final curves represents a list of the above described components of the building. After that each set of curves is assigned to a separate ComponentDesigner_Components where the Designation of the elements along with the steel quality and function are defined. Each set of curve is then translated into structural component carrying all the necessary information for further analysis. The Design results are then assigned to a unique QTA Component that calculates the total amount of material used in the structure. The result of this analysis is 29,8 tonnes of structural steel, an amount that is then assigned to the EPD components in form of Analysis result, as defined from the SustainabilityOpen frmaework.

Step 2 - EPD Analysis

In Step 2 the analysis results are assessed to produce results in form of an EPD on a building level. The diagrams, as produced from the EPDtoExcel Component are presented in Figures 6.6 - 6.9. The results of these assessments that are related to the diagrams can be found in Table 6.2.

The results of the LCIA analysis are presented in two different diagrams for reasons of clarity.

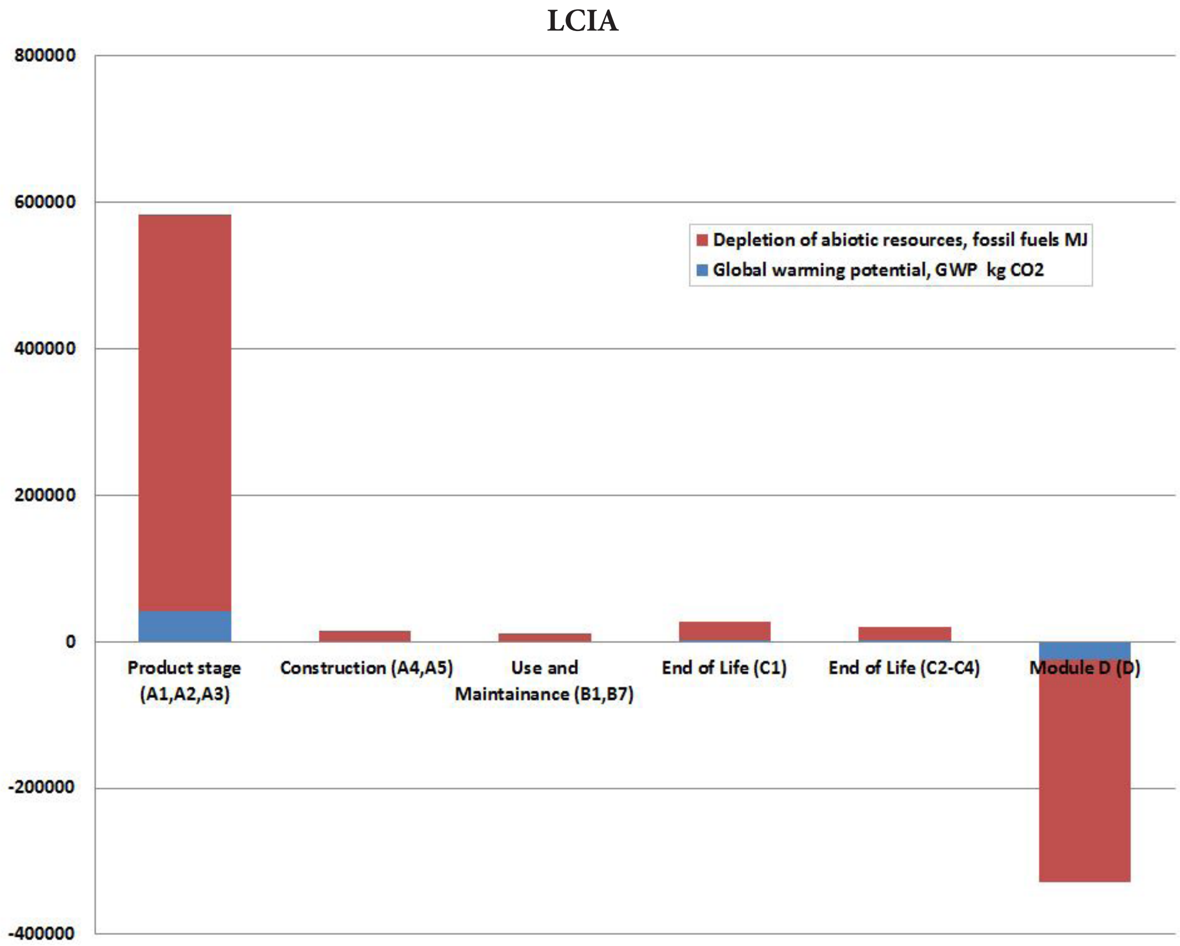


Figure 6.6. LCIA analysis results for the EPD assessment (Global Warming Potenetial, Depletion of abiotic resources)

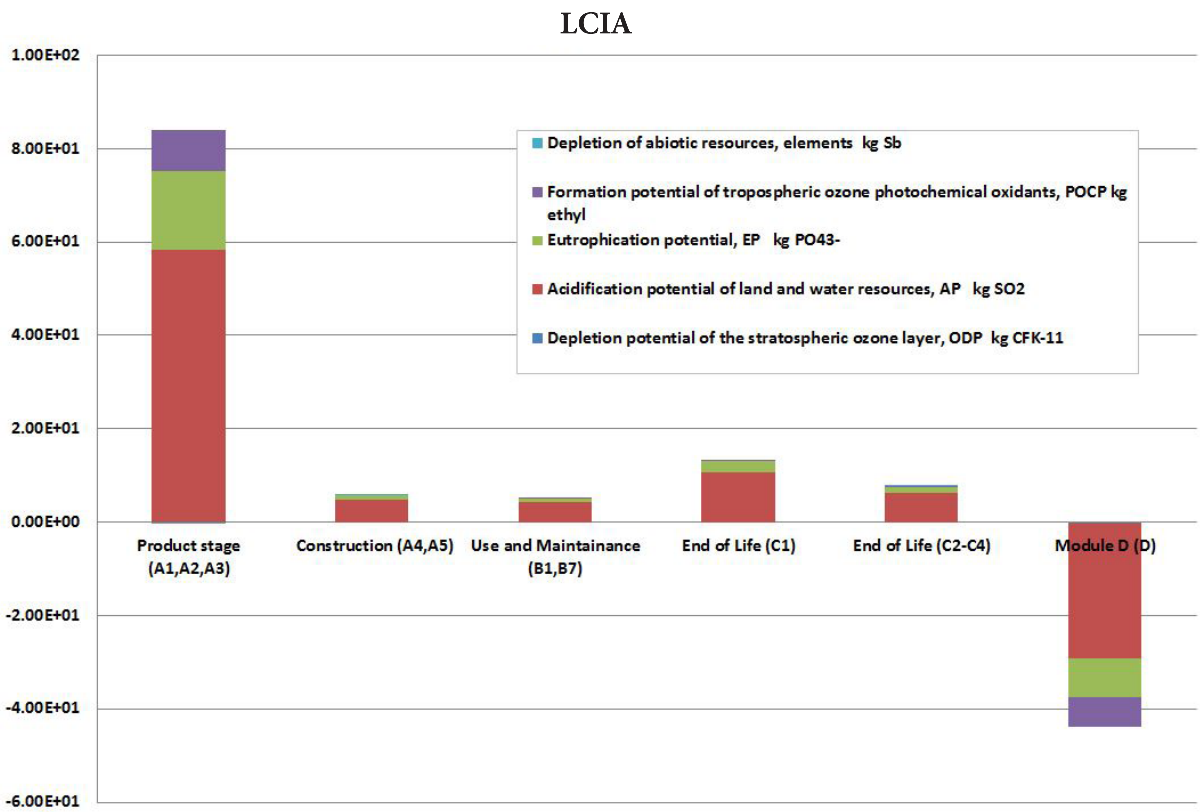


Figure 6.7. LCIA analysis results for the EPD assessment

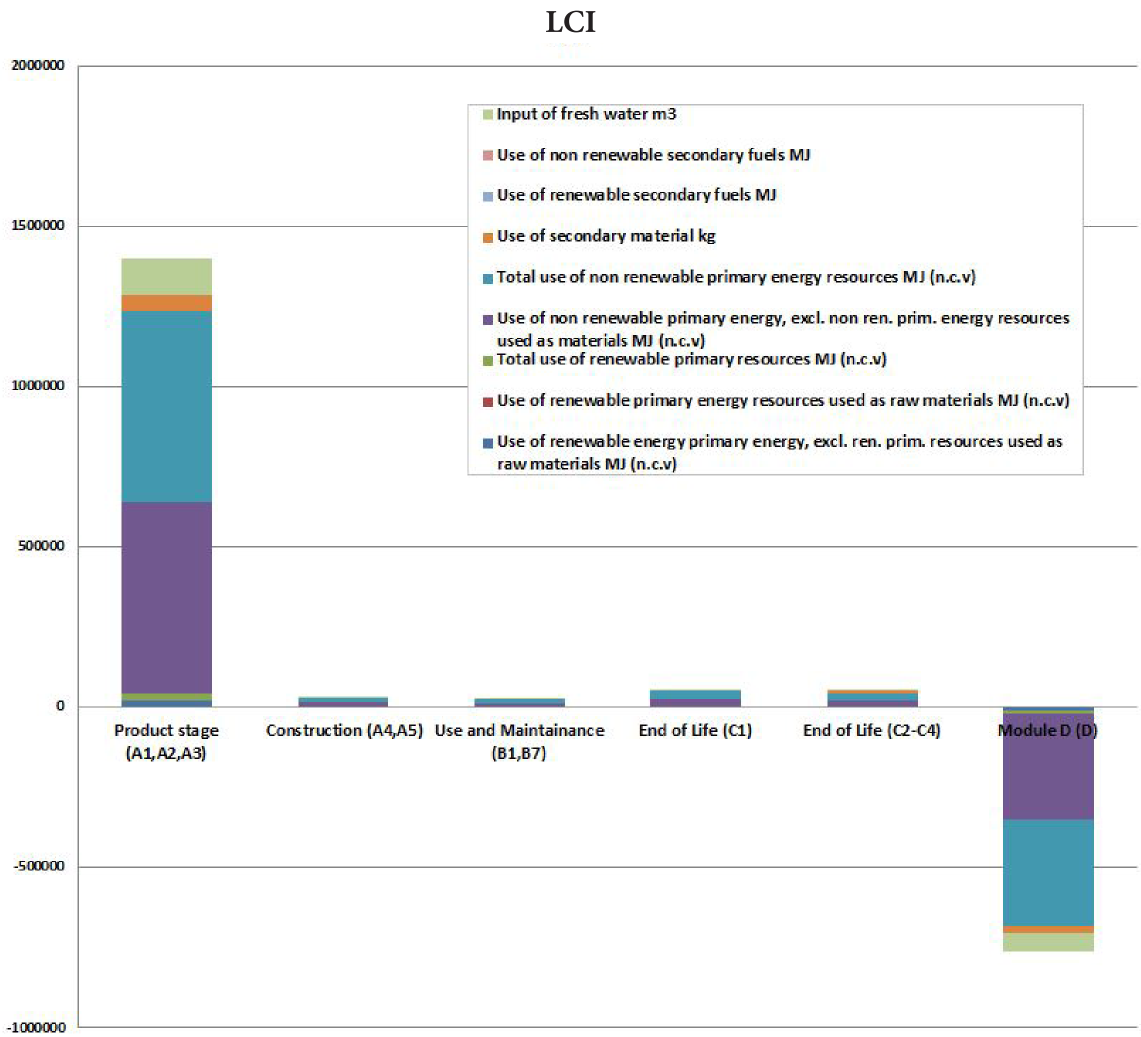


Figure 6.8. LCI analysis results for the EPD assessment

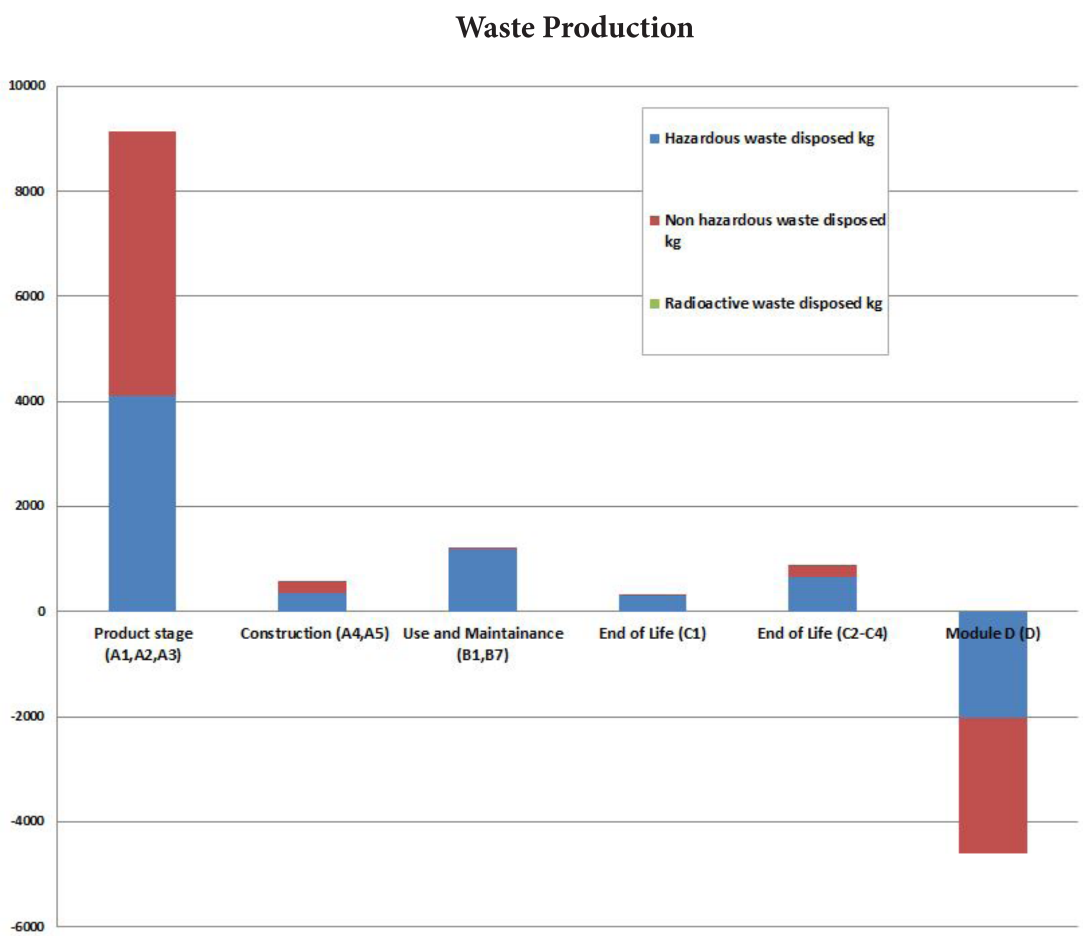


Figure 6.9. Waste Production analysis results for the EPD assessment

2011 EPD Heavy Construction Products	Unit	Product stage (A1,A2,A3)	Construction (A4,A5)	Use and Maintainance (B1,B7)
Environmental Profile				
Global warming potential, GWP	**kg CO2**	41422,886	892,204	776,041
Depletion potential of the stratospheric ozone layer, ODP	**kg CFK-11**	1,00E-03	0,00E+00	0,00E+00
Acidification potential of land and water resources, AP	**kg SO2**	58,284	4,699	4,259
Eutrophication potential, EP	**kg PO43-**	16,852	1,019	0,845
Formation potential of tropospheric ozone photochemical oxidants, POCP	**kg ethyl**	8,845	0,169	0,146
Depletion of abiotic resources, elements	**kg Sb**	-0,009	2,00E-03	0,00E+00
Depletion of abiotic resources, fossil fuels	**MJ**	542310,027	13654,884	10212,165
Resource input				
Use of renewable energy primary energy, excl. ren. prim. resources used as raw materials	**MJ (n.c.v)**	20889,588	179,336	338,657
Use of renewable primary energy resources used as raw materials	**MJ (n.c.v)**	0,145	0,041	0,01
Total use of renewable primary resources	**MJ (n.c.v)**	20889,588	179,336	338,657
Use of non renewable primary energy, excl. non ren. prim. energy resources used as materials	**MJ (n.c.v)**	598133,722	14447,298	12253,619
Total use of non renewable primary energy resources	**MJ (n.c.v)**	598137,006	14447,298	12253,619
Use of secondary material	**kg**	46834,18	0	0
Use of renewable secondary fuels	**MJ**	0	0	0
Use of non renewable secondary fuels	**MJ**	0	0	0
Input of fresh water	**m3**	118317,055	1046,203	1884,157
Waste Categories				
Hazardous waste disposed	**kg**	4100,08	352,514	1203,848
Non hazardous waste disposed	**kg**	5040,935	224,235	21,432
Radioactive waste disposed	**kg**	0	0	0

2011 EPD Heavy Construction Products	Unit	End of Life (C1)	End of Life (C2-C4)	Module D (D)
Environmental Profile				
Global warming potential, GWP	**kg CO2**	1839,953	1288,582	-24632,237
Depletion potential of the stratospheric ozone layer, ODP	**kg CFK-11**	0,00E+00	0,00E+00	0,00E+00
Acidification potential of land and water resources, AP	**kg SO2**	10,597	6,199	-29,083
Eutrophication potential, EP	**kg PO43-**	2,395	1,372	-8,302
Formation potential of tropospheric ozone photochemical oxidants, POCP	**kg ethyl**	0,344	0,218	-6,405
Depletion of abiotic resources, elements	**kg Sb**	0,00E+00	0,003	0,003
Depletion of abiotic resources, fossil fuels	**MJ**	24634,015	19449,805	-304045,127
Resource input				
Use of renewable energy primary energy, excl. ren. prim. resources used as raw materials	**MJ (n.c.v)**	91,079	461,086	-10235,898
Use of renewable primary energy resources used as raw materials	**MJ (n.c.v)**	0,028	0,046	-0,071
Total use of renewable primary resources	**MJ (n.c.v)**	91,079	461,086	-10235,898
Use of non renewable primary energy, excl. non ren. prim. energy resources used as materials	**MJ (n.c.v)**	25149,957	20975,698	-331398,742
Total use of non renewable primary energy resources	**MJ (n.c.v)**	25149,957	20975,698	-331400,348
Use of secondary material	**kg**	0	8141,412	-18622,944
Use of renewable secondary fuels	**MJ**	0	0	0
Use of non renewable secondary fuels	**MJ**	0	0	0
Input of fresh water	**m3**	508,531	2227,562	-57983,232
Waste Categories				
Hazardous waste disposed	**kg**	291,731	648,657	-2009,039
Non hazardous waste disposed	**kg**	14,283	251,382	-2583,151
Radioactive waste disposed	**kg**	0	0	0

Table 6.2 EPD results for the case study

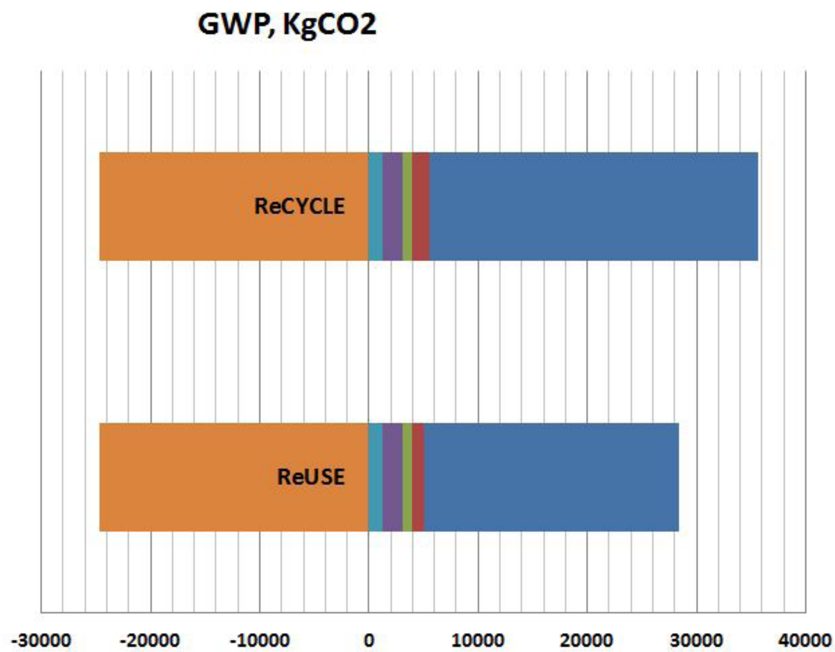
The results of the EPD assessment showed that the Product Stage of the building under assessment results the highest impact in comparison to any other stage of the building's life cycle. This fact is highlighting already the need to focus on the reduction of these impacts in order to achieve a more sustainable construction.

Step 3 - Reuse vs Recycle assessment

At this step the results from the EPD assessment are carried to the Grapher_EPD Component . There the two scenarios are formed and assessed with the input of several different parameters from the user. The produced results are the first set of results that will indicate from an Environmental point of view whether the concept of Design for Deconstruction is actually beneficial and should be taken into account from the early design process or not. For our case the tables with the results as produced from the component are presented in Appendix III. The produced diagrams are presented in Figures 6.10 - 6.25 while the difference among the two scenarios is presented in form of radar diagrams for clarity purposes in Figures 6.26 - 6.28. This difference is presented to demonstrate the difference between choosing the conventional design route and that of deconstruction. The results of these diagrams are produced by subtracting the results of the Reuse scenario from those from the Recycle scenario. The tables with the related values can also be found in Appendix III.

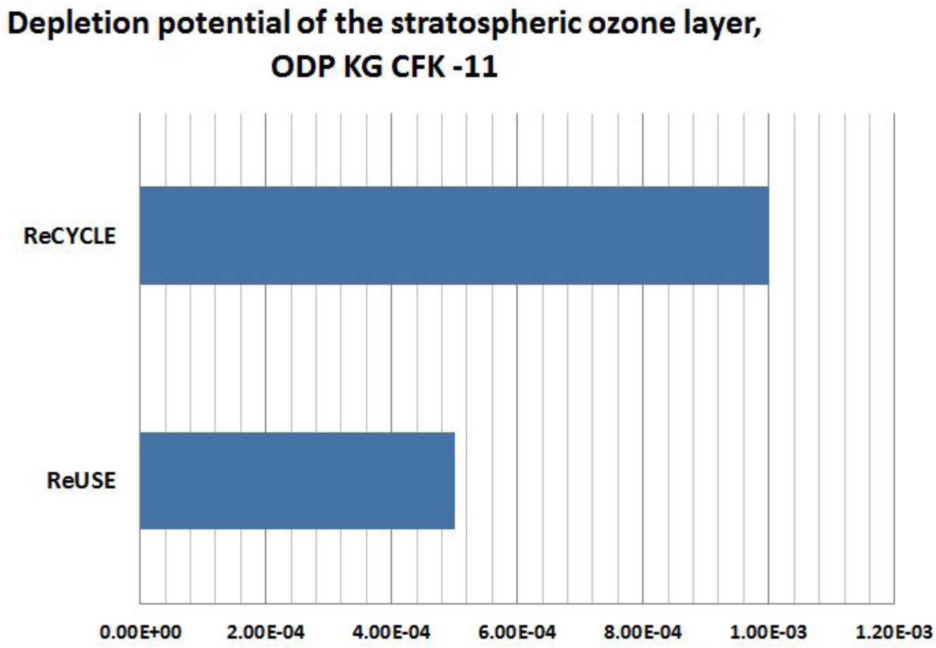
The figures below show only those indicators that have resulted to value other than zero. So From the LCI analysis the indicators “Use of renewable secondary fuels” and “Use of non renewable secondary fuels are not included”. Also from the Waste Production analysis the “Radioactive waste” indicator is not included.

LCIA Indicators



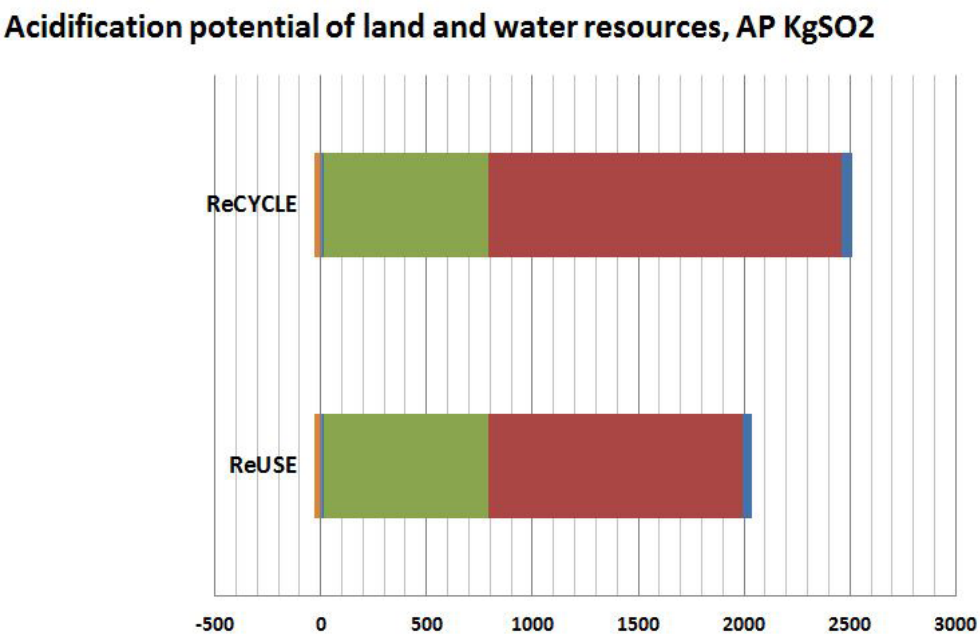
	ReUSE	ReCYCLE
Module D (D)	-24632.237	-24632.237
End of Life (C2-C4)	1288.582	1288.582
End of Life (C1)	1839.953	1839.953
Use and Maintainance (B1,B7)	776.041	776.041
Construction (A4,A5)	1202.204	1667.204
Product stage (A1,A2,A3)	23287.3772	30084.59221

Figure 6.10. Global Worming Potential (GWP)



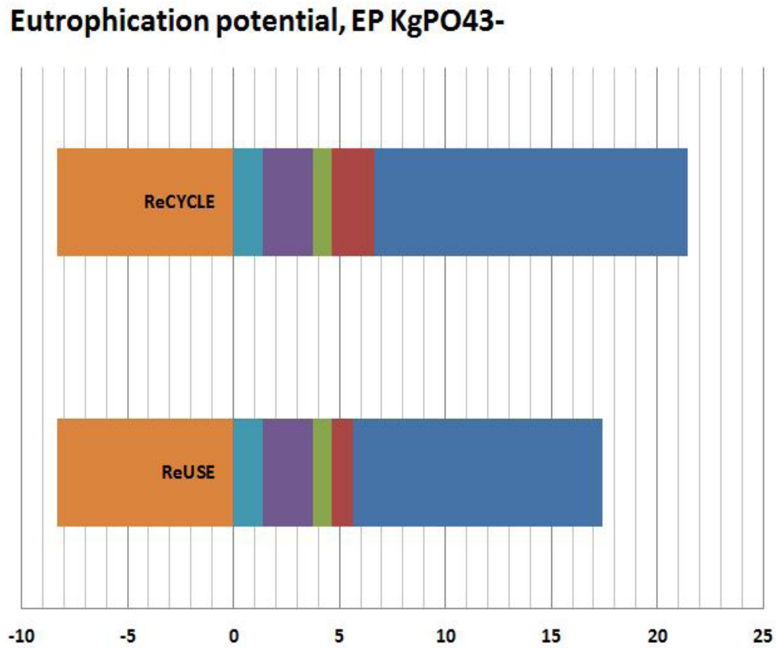
	ReUSE	ReCYCLE
Module D (D)	0.00E+00	0.00E+00
End of Life (C2-C4)	0.00E+00	0.00E+00
End of Life (C1)	0.00E+00	0.00E+00
Use and Maintainance (B1,B7)	0.00E+00	0.00E+00
Construction (A4,A5)	0.00E+00	0.00E+00
Product stage (A1,A2,A3)	0.0005	1.00E-03

Figure 6.11. Depletion potential of the stratospheric ozone layer, ODP



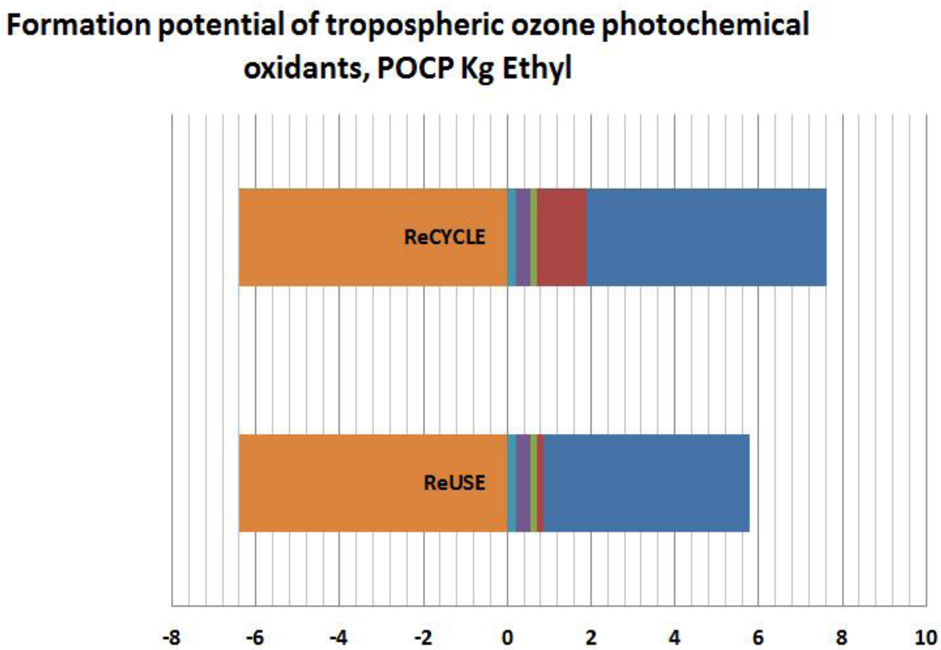
	ReUSE	ReCYCLE
Module D (D)	-29.083	-29.083
End of Life (C2-C4)	6.199	6.199
End of Life (C1)	10.597	10.597
Use and Maintainance (B1,B7)	776.041	776.041
Construction (A4,A5)	1202.204	1667.204
Product stage (A1,A2,A3)	43.9778	53.321595

Figure 6.12. Acidification potential of land and water resources, AP



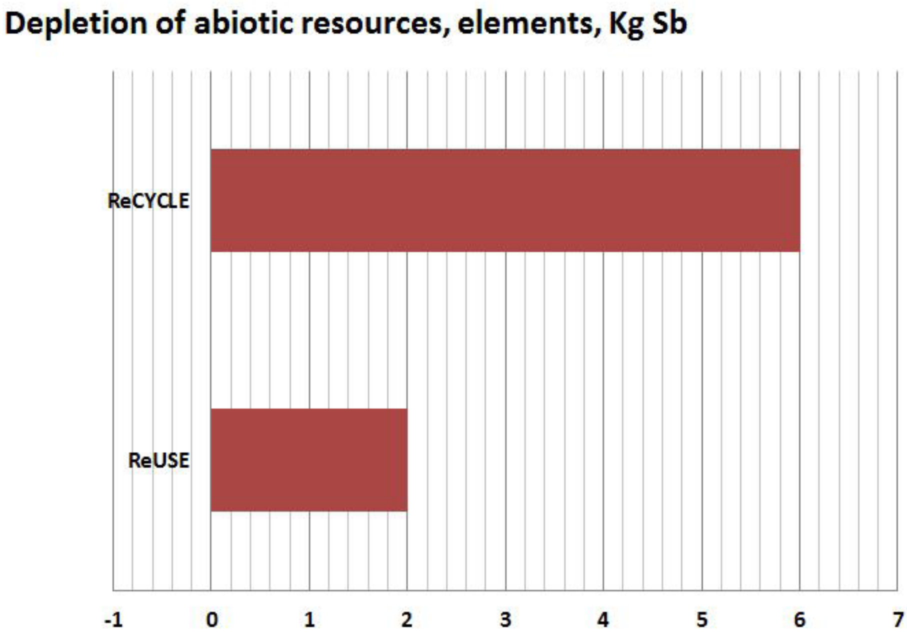
	ReUSE	ReCYCLE
Module D (D)	-8.302	-8.302
End of Life (C2-C4)	1.372	1.372
End of Life (C1)	2.395	2.395
Use and Maintainance (B1,B7)	0.845	0.845
Construction (A4,A5)	1.019	2.019
Product stage (A1,A2,A3)	11.779	14.80543

Figure 6.13. Eutrophication potential, EP



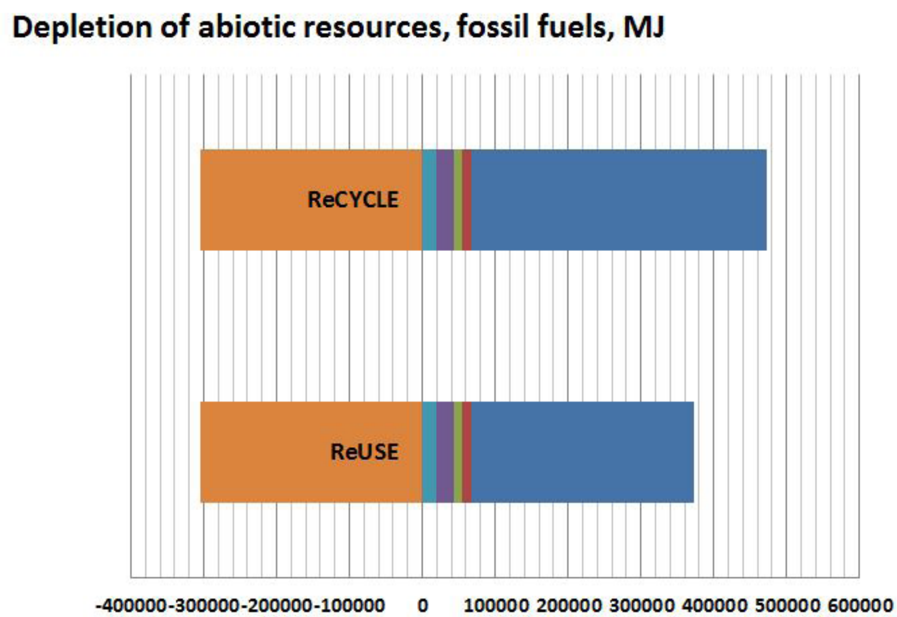
	ReUSE	ReCYCLE
Module D (D)	-6.405	-6.405
End of Life (C2-C4)	0.218	0.218
End of Life (C1)	0.344	0.344
Use and Maintainance (B1,B7)	0.146	0.146
Construction (A4,A5)	0.169	1.169
Product stage (A1,A2,A3)	4.9041	5.762325

Figure 6.14. Formation potential of tropospheric ozone photochemical oxidants, POCP



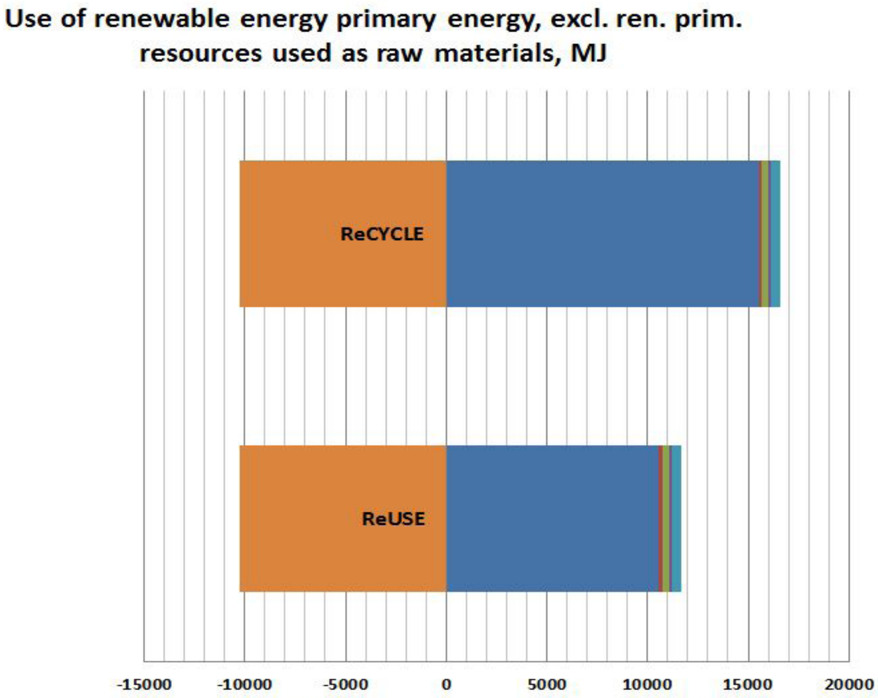
	ReUSE	ReCYCLE
Module D (D)	0.003	0.003
End of Life (C2-C4)	3.00E-03	0.003
End of Life (C1)	0.00E+00	0.00E+00
Use and Maintainance (B1,B7)	0.00E+00	0.00E+00
Construction (A4,A5)	2.002	6.00E+00
Product stage (A1,A2,A3)	-0.0045	-0.007395

Figure 6.15. Depletion of abiotic resources, elements



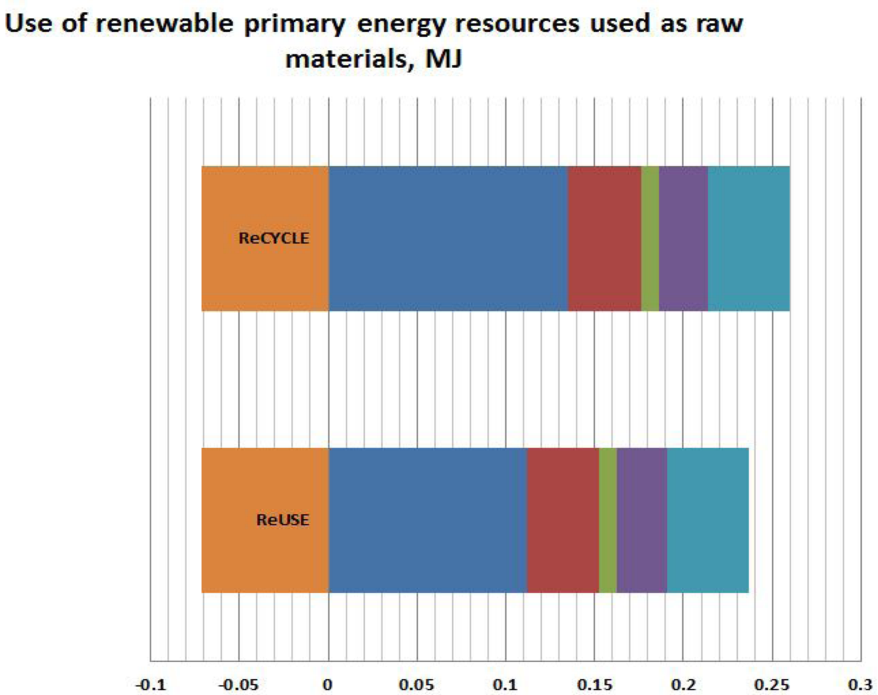
	ReUSE	ReCYCLE
Module D (D)	-304045.127	-304045.127
End of Life (C2-C4)	19449.805	19449.805
End of Life (C1)	24634.015	24634.015
Use and Maintainance (B1,B7)	10212.165	10212.165
Construction (A4,A5)	13654.884	13654.884
Product stage (A1,A2,A3)	305642.6345	404279.8991

Figure 6.16. Depletion of abiotic resources, fossil fuels



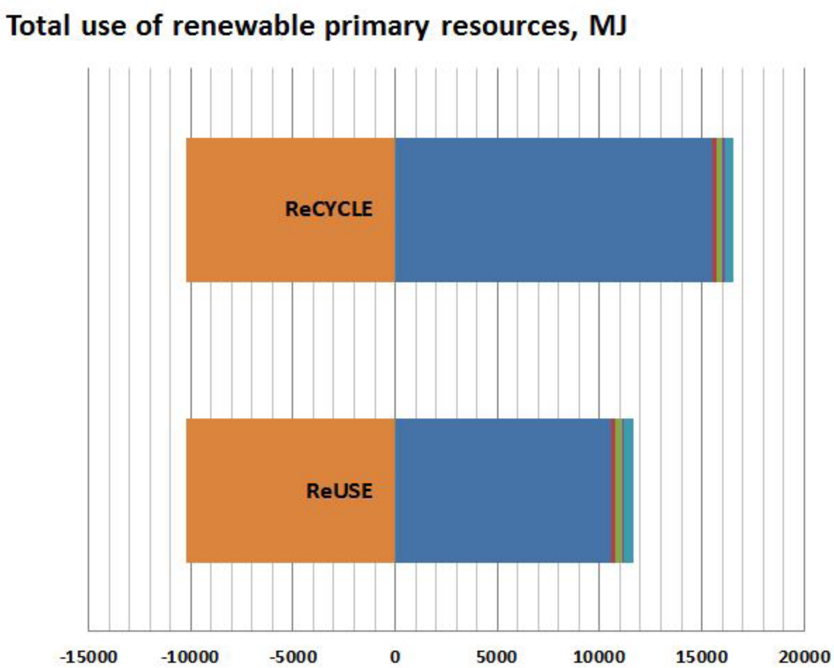
	ReUSE	ReCYCLE
Product stage (A1,A2,A3)	10572.3046	15504.46157
Construction (A4,A5)	179.336	179.336
Use and Maintainance (B1,B7)	338.657	338.657
End of Life (C1)	91.079	91.079
End of Life (C2-C4)	461.086	461.086
Module D (D)	-10235.898	-10235.898

Figure 6.17. Use of renewable energy primary energy, excl. ren. prim. resources used as raw materials



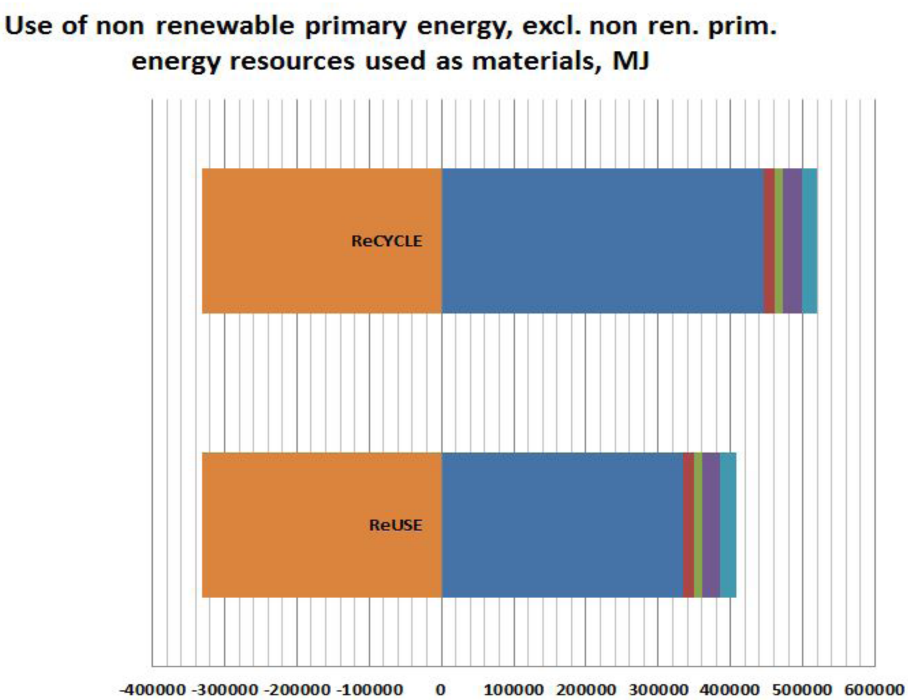
	ReUSE	ReCYCLE
Product stage (A1,A2,A3)	0.1117	0.135015
Construction (A4,A5)	0.041	0.041
Use and Maintainance (B1,B7)	0.01	0.01
End of Life (C1)	0.028	0.028
End of Life (C2-C4)	0.046	0.046
Module D (D)	-0.071	-0.071

Figure 6.18. Use of renewable primary energy resources used as raw materials



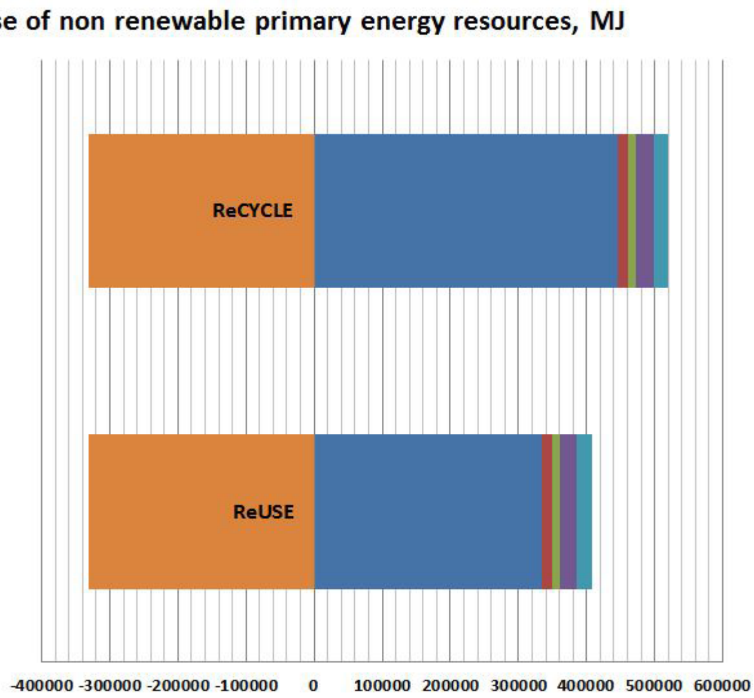
	ReUSE	ReCYCLE
Product stage (A1,A2,A3)	10572.3046	15504.46157
Construction (A4,A5)	179.336	179.336
Use and Maintainance (B1,B7)	338.657	338.657
End of Life (C1)	91.079	91.079
End of Life (C2-C4)	461.086	461.086
Module D (D)	-10235.898	-10235.898

Figure 6.19. Total use of renewable primary resources



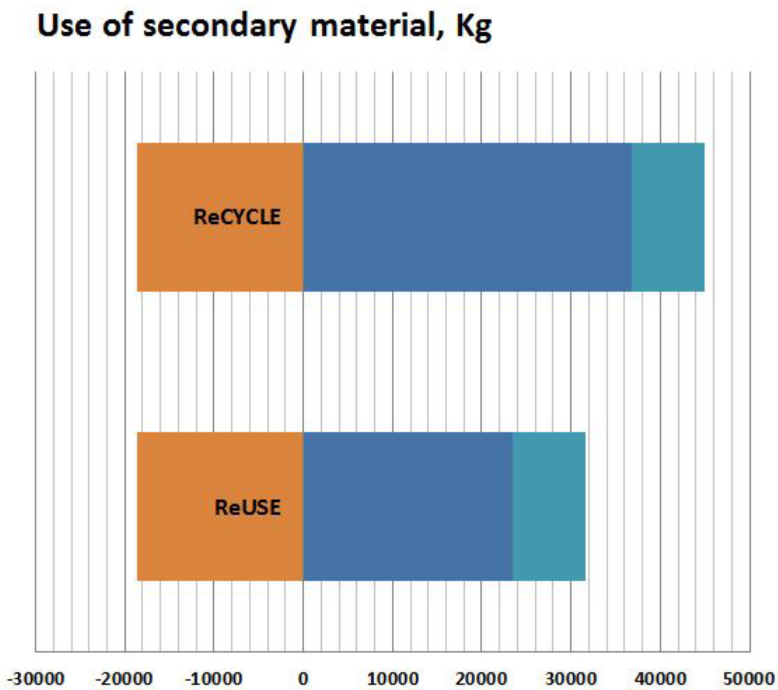
	ReUSE	ReCYCLE
Product stage (A1,A2,A3)	334276.8008	445985.352
Construction (A4,A5)	14447.298	14447.298
Use and Maintainance (B1,B7)	12253.619	12253.619
End of Life (C1)	25149.957	25149.957
End of Life (C2-C4)	20975.698	20975.698
Module D (D)	-331398.742	-331398.742

Figure 6.20. Use of non renewable primary energy, excl. non ren. prim. energy resources used as materials



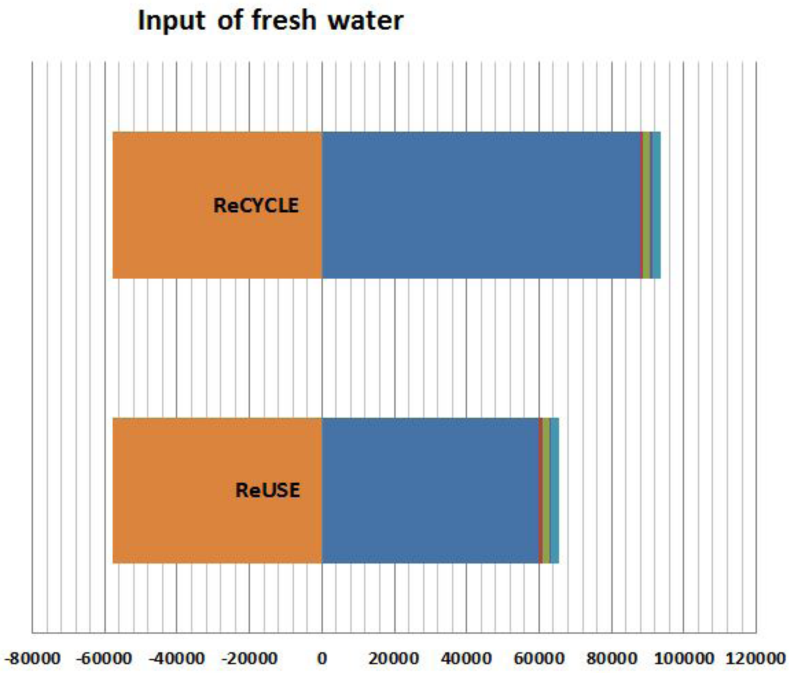
	ReUSE	ReCYCLE
Product stage (A1,A2,A3)	334278.4428	445987.7768
Construction (A4,A5)	14447.298	14447.298
Use and Maintainance (B1,B7)	12253.619	12253.619
End of Life (C1)	25149.957	25149.957
End of Life (C2-C4)	20975.698	20975.698
Module D (D)	-331400.348	-331400.348

Figure 6.21. Total use of non renewable primary energy resources



	ReUSE	ReCYCLE
Product stage (A1,A2,A3)	23417.09	36870.90496
Construction (A4,A5)	0	0
Use and Maintainance (B1,B7)	0	0
End of Life (C1)	0	0
End of Life (C2-C4)	8141.412	8141.412
Module D (D)	-18622.944	-18622.944

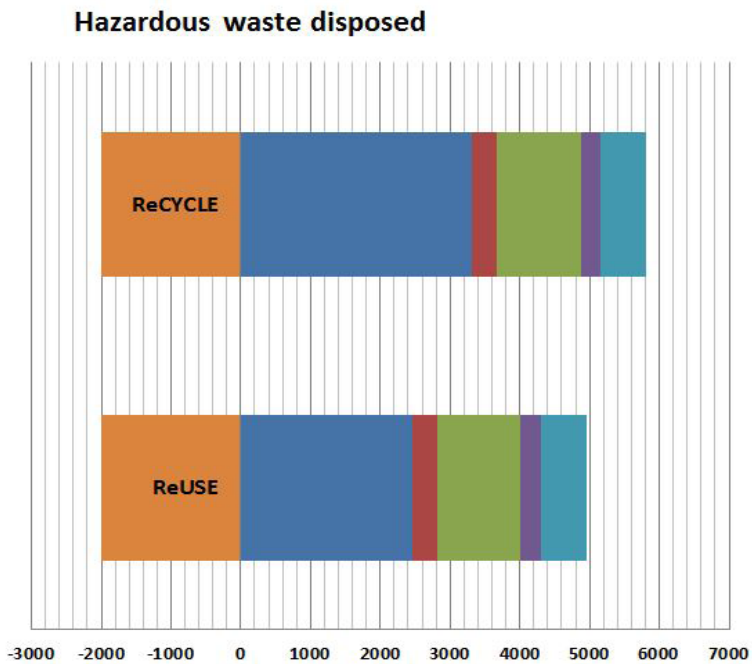
Figure 6.22. Use of secondary material



	ReUSE	ReCYCLE
Product stage (A1,A2,A3)	59870.4709	87804.55688
Construction (A4,A5)	1046.203	1046.203
Use and Maintainance (B1,B7)	1884.157	1884.157
End of Life (C1)	508.531	508.531
End of Life (C2-C4)	2227.562	2227.562
Module D (D)	-57983.232	-57983.232

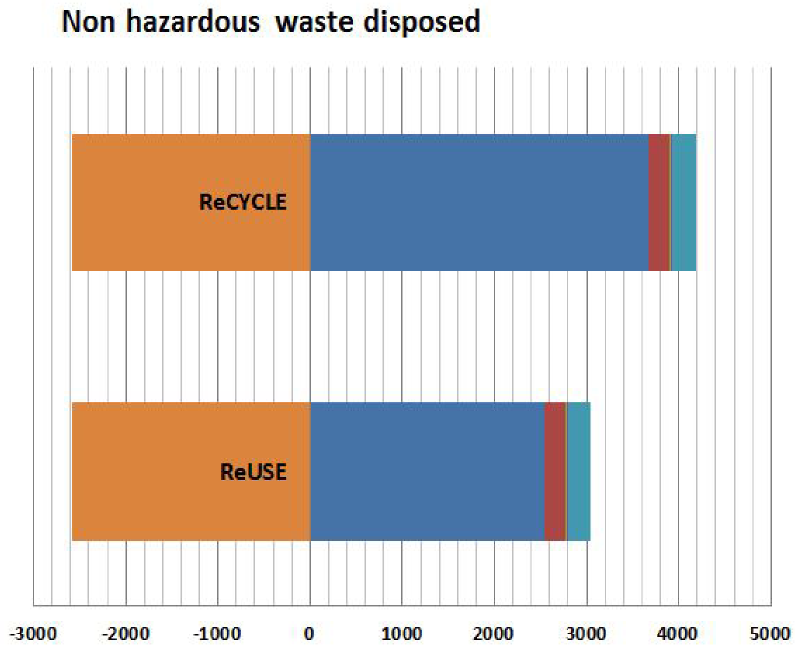
Figure 6.23. Input of fresh water

Waste Indicators



	ReUSE	ReCYCLE
Product stage (A1,A2,A3)	2458.4634	3316.975135
Construction (A4,A5)	352.514	352.514
Use and Maintainance (B1,B7)	1203.848	1203.848
End of Life (C1)	291.731	291.731
End of Life (C2-C4)	648.657	648.657
Module D (D)	-2009.039	-2009.039

Figure 6.24. Hazardous Waste disposed



	ReUSE	ReCYCLE
Product stage (A1,A2,A3)	2540.4637	3673.232215
Construction (A4,A5)	224.235	224.235
Use and Maintainance (B1,B7)	21.432	21.432
End of Life (C1)	14.283	14.283
End of Life (C2-C4)	251.382	251.382
Module D (D)	-2583.151	-2583.151

Figure 6.25. Non hazardous waste disposed

As one can notice from the diagrams above every indicator has a significant reduction for the Product and Construction stage of the life cycle of the building under assessment while for the rest of the stages the values for both scenarios remain the same. The fact that the Reuse scenario benefits the environmental burden of the potential new building in these life cycle stages can already be considered as an incentive in favour of the concept of Design for Deconstruction since the results from the initial EPD showed that the Product stage is the major contributor of the total environmental burden of the building.

Table 6.3 shows the resulted difference for the two scenarios. The results shown are only referring to the Product and Construction stage of the EPD as these are the only results affected within the two scenarios. The values are calculated by subtracting the values of the Reuse scenario from those of the Recycle. As one can observe the results for all the indicators have positive values indicating that for our case study the concept of deconstruction is beneficial from an environmental point of view.

2011 EPD Heavy Construction Products	Unit	Product stage	Construction (A4,A5)
Environmental Profile			
Global warming potential, GWP	kg CO2	6797,215005	465
Depletion potential of the stratospheric ozone layer, ODP	kg CFK-11	0,0005	0
Acidification potential of land and water resources, AP	kg SO2	9,343795	2
Eutrophication potential, EP [EN15804/prA1]	kg PO43-	3,02643	1
Formation potential of tropospheric ozone photochemical oxidants, POCP	kg ethyl	0,858225	1
Depletion of abiotic resources, elements	kg Sb	-0,002895	4
Depletion of abiotic resources, fossil fuels	MJ	98637,26456	0
Resource input			
Use of renewable energy primary energy, excl. ren. prim. resources used as raw materials	MJ (n.c.v)	4932,15697	0
Use of renewable primary energy resources used as raw materials	MJ (n.c.v)	0,023315	0
Total use of renewable primary resources	MJ (n.c.v)	4932,15697	0
Use of non renewable primary energy, excl. non ren. prim. energy resources used as materials	MJ (n.c.v)	111708,5512	0
Total use of non renewable primary energy resources	MJ (n.c.v)	111709,334	0
Use of secondary material	kg	13453,81496	0
Use of renewable secondary fuels	MJ	0	0
Use of non renewable secondary fuels	MJ	0	0
Input of fresh water	m3	27934,08598	0
Waste Categories			
Hazardous waste disposed	kg	858,511735	0
Non hazardous waste disposed	kg	1132,768515	0
Radioactive waste disposed	kg	0	0

Table 6.3 Difference between Reuse and Recycle scenario for the building under assessment

The inputs taken into account for the assessment between Reuse and Recycle scenario are presented in the table below.

	Transportation Impacts	
	Reuse	Recycle
Distance (km)	100	250
Lorry Type	>16tonnes	>16tonnes

	Deconstruction/Demolition Burden
Ratio	1.4
RSP/ReqSL	1

Table 6.4 Transportation Impacts values

These values were assumed as such because the Transportation distance for the Reuse scenario usually includes the transfer of the reclaimed elements from the deconstruction site to the new construction site while the Recycle scenario includes the transfer of the demolished material to the recycling facility,then to the manufacturer and finally to the new construction site. As such the required transportation distance for the Recycled scenario is expected to be at least twice the distance of the Reuse case. Finally the RSP/ReqSL ratio is equal to 1 as the new building is considered to serve another complete life cycle (see Section 3.4.2).

Step 4 - Embodied Energy and Embodied Carbon Assessment

The fourth step requires the assessment of the Embodied Energy and Embodied Carbon of the initial building and the two scenarios. The results from the QTO Analysis are again used from the EmbodiedEnergy component for the conduction of this assessment and the allocation process for the two scenarios is described in Section 3.3.1. Diagrams 6.1 and 6.2 present the results of this assessment.

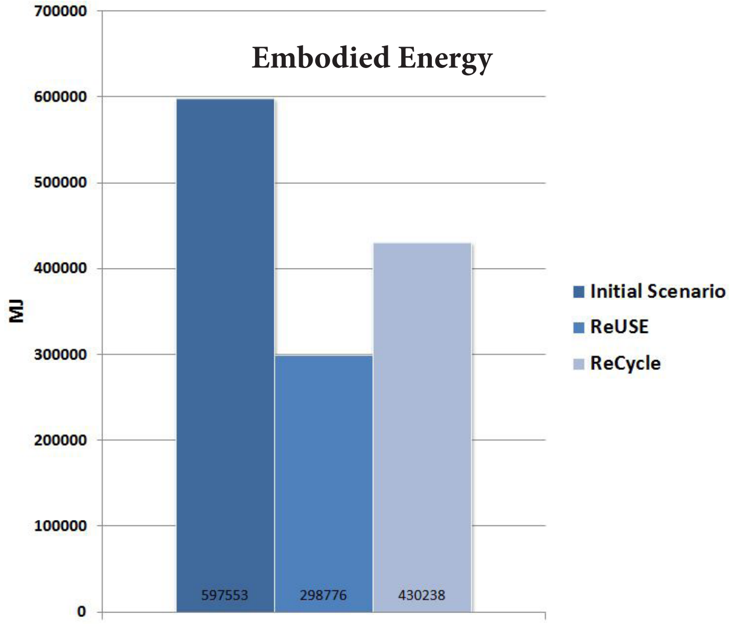


Diagram 6.1. Embodied Energy for the initial, Reuse and Recycle scenario

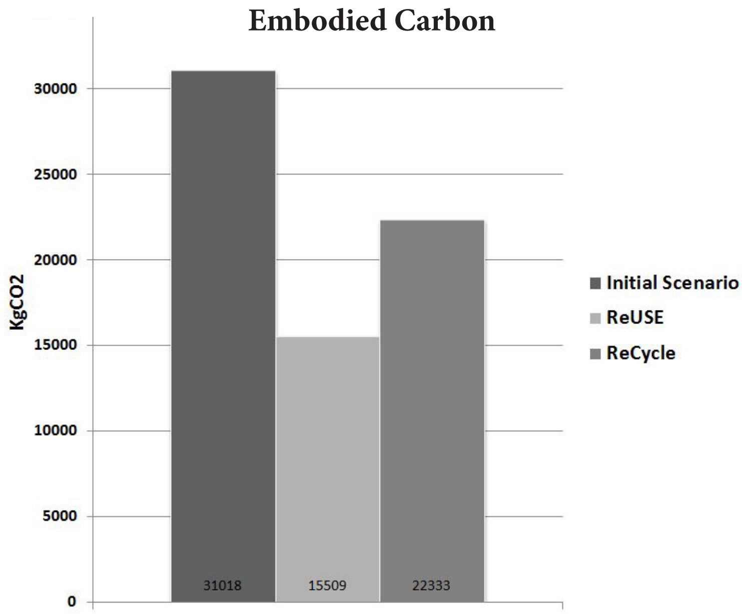


Diagram 6.2. Embodied Carbon for the initial, Reuse and Recycle scenario

The only question remaining is weather the concept of deconstruction will also be beneficial from a financial point of view.

Step 5 - Financial Assessment

For the financial Assessment of the two scenarios the assessment results from Step 3 were used. In first place a translation of the Product Stage results from the LCIA analysis and the transportation Impacts to Shadow costs is taking place. After the translation of the environmental Impacts to financial values, the results are inserted to the FinancialAssessment component. Along with these results a set of inputs is needed for the assessment to take place. The assumed values of these inputs for this case study are shown in Table 6.5.

	Values
Demolition Price/m²	20 Euros/m²
Deconstruction Price/m²	40 Euros/m²
Additional modification costs / element	15 Euros/element
New steel price / tonne	1400 Euros/tonne
Scrap steel price / tonne	280 Euros/tonne

Table 6.5 Financial Assessment values

The price for new is calculated as the average value from the prices provided by Staalprijzen (www.staalprijzen.nl) and the price for scrap steel is taken from European Steel Association: EUROFER (www.eurofer.org) and is reflecting the most recent registered scrap steel price (January 2013). The additional cost per element and the demolition and deconstruction prices are deriving from average prices found during the background research and are subject to change. The parametric nature of the toolbox allows such changes in an easy manner for further assessment. The demolition and deconstruction costs is advised to be set according to values provided by local contractors.

The results of the financial assessment are shown in Diagrams 6.3 - 6.5. The values are expressed in different forms in order to provide to the user a better understanding of the impacts of his/her design options in the final cost of the project.

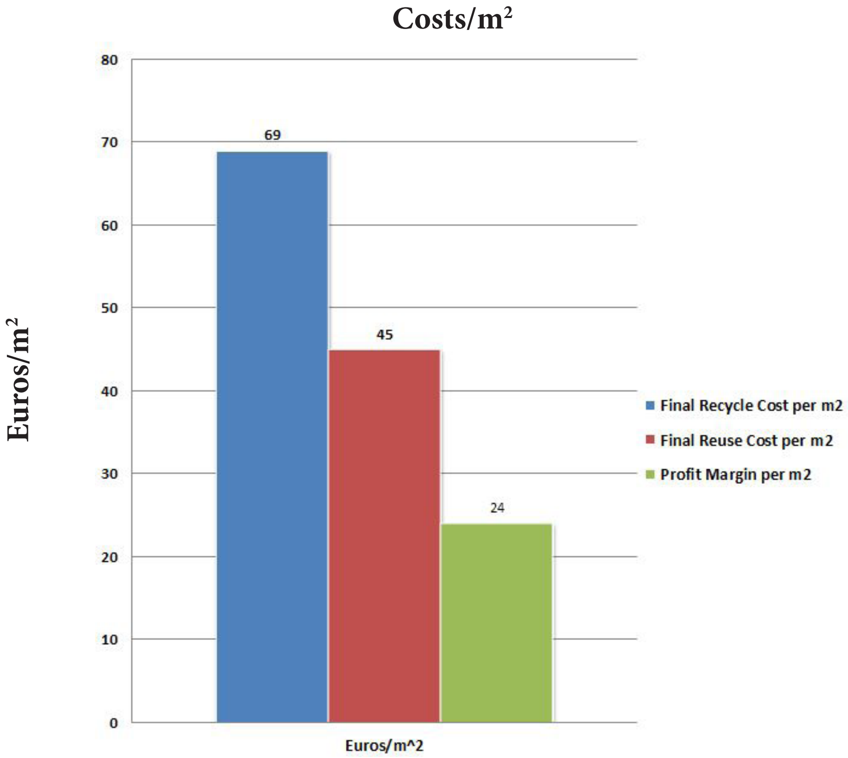


Diagram 6.3. Final costs per m² of the building under assessment

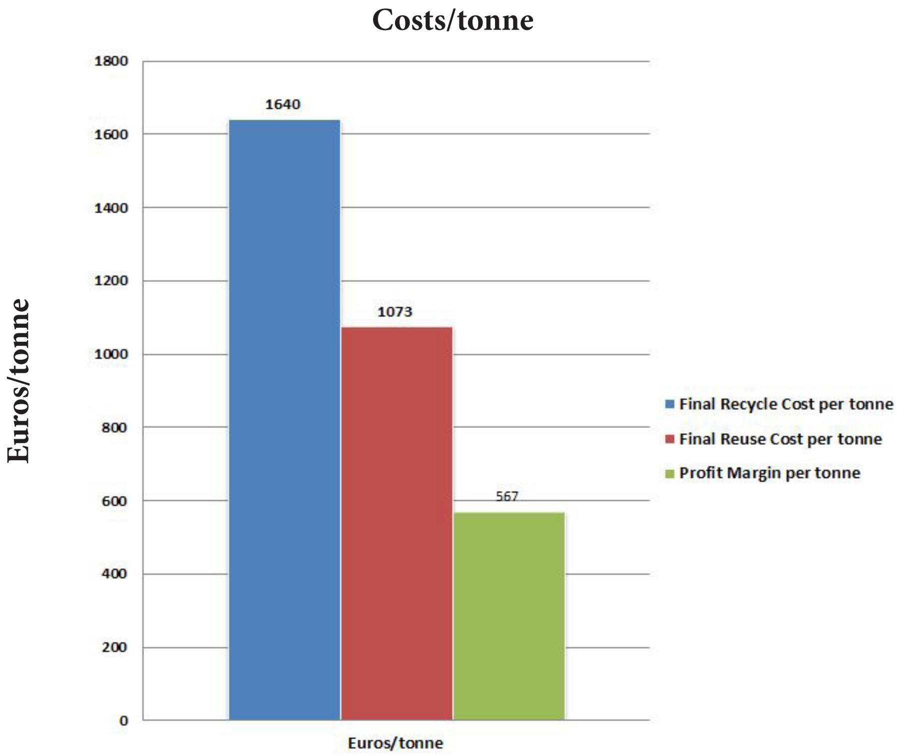


Diagram 6.4. Final costs per tonne of steel for the building under assessment

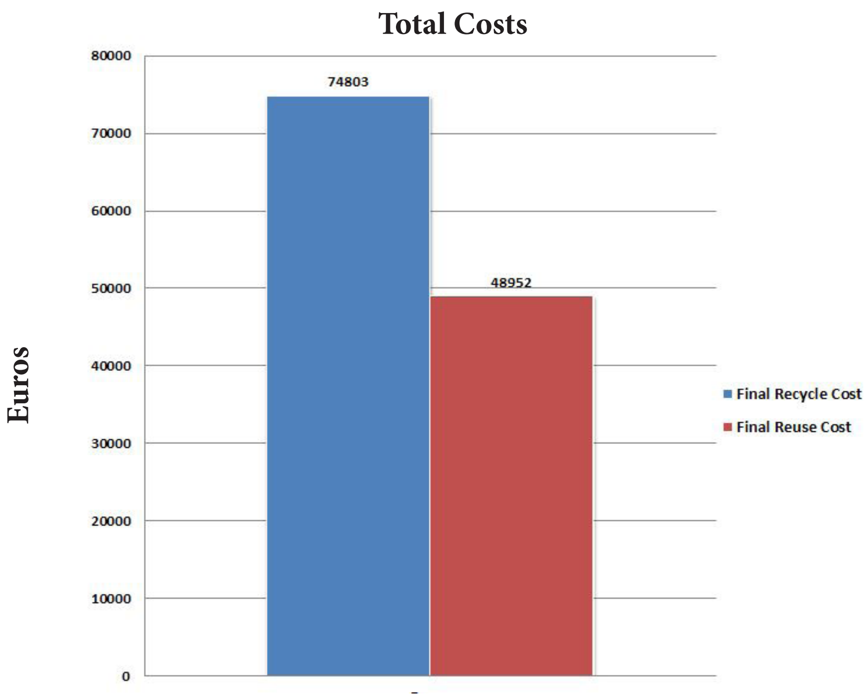


Diagram 6.5. Final total costs for Reuse and Recycle scenario for the building under assessment

As one can observe from the financial assessment results the ReCycle scenario costs are higher than those of the ReUse scenario and a positive profit margin is provided. These results are proving, for the given values, that the concept of Design for Deconstruction is bringing not only environmental benefits as expected but also benefits regarding the financial scope of a project. This aspect can be proven crucially favourable for the promotion of the concept as it provides a strong incentive to the stakeholders and the owner of the building in order to implement it to the project.

6.3. Validity of the case study approach and the proposed strategy

During the development of this Thesis topic the main requirement that came up was that of proposing a strategy that would efficiently assess and expose the potential benefits of the concept of deconstruction and reuse. The use of Environmental Product Declarations in a building level although it exists as a methodology it is not applied for allocation purpose as the developed strategy proposes. The case study was a key point for the assessment of the validity of the strategy as there are only few examples where EPDs are used as LCA analysis tools for buildings and the allocation process was under question. The approach followed in this case study though can also be found in the background research in the form of a report from “bauforumstahl” under the name “Life cycle assessment comparison of a typical storey building” (Siebers, Hauke, 2011). In this report a comparative assessment between four single storey building of identical geometries built with different construction material is conducted using EPDs. The first two buildings are composed by structural steel of different quality (S 235 and S 460), The third by reinforced concrete (C30/37) and the fourth by reinforced concrete (C30/37) and timber BS 16. During this study the foundations were also taken into account and the sstudy expanded beyond the structural system including a study for the Use and Maintenance stage of the EPD by comparing four different building envelopes and their impacts.

The comparison of the impacts of the four different structural systems was achieved by using the results from the Product stage of the EPD of each building and the potential benefits from reuse or recycling as exposed in the Module D of the according EPDs. For the purposes of comparison, even though the related directive (EN15978) prohibits the combination of the results of the different modules of a EPD, the authors summed up the results from Product stage and Module D. A process that is also proposed for the allocation methodology of the developed strategy.

Following the results of this research the authors note that there is not a safe conclusion regarding which of the four structural systems is more environmental friendly as the different indicators of the EPDs are varying among the chosen material. They conclude though that the structural steel frame with steel quality S460 seems to be the most recommendable.

6.4. Conclusions

For the case study

The building under study is a building highly suitable for deconstruction. It is designed for a short life time and the reuse of components with the current settings seems an ideal option regarding its environmental benefits and financial results. It is important to highlight though that due to the amount of parameters involved in the assessment and the nature of these parameters that are highly influenced by local conditions and market trends the current results can not be taken as granted for every building of this type. The parameters involved in the final environmental and financial assessments must be used after research from the user but can also act as niche indicators for the user in order to set his/her limits above which the concept of deconstruction will no longer be beneficial.

Regarding the environmental impacts of the two scenarios the results for the Product and Construction stage give a clear image of the benefits of the concept in these terms. Regarding the Produc stage the burden of the Deconstruction process that is allocated from the End - of - Life stage (Module C1) to the Product stage of the Reuse scenario is assumed 1.4 higher than the one of the Demolition process. Despite this difference though all the indicators of the EPD are resulting to lower values for the Reuse scenario. The root of this result is mainly caused from the fact that for the Recycle scenario a new set of identical components must be purchased adding a significant burden to the Product stage of the building, a burden that in case of Reuse is avoided as there is no further need for new elements. As for the Construction stage since the transportation costs are higher for the Recycle scenario the results are expected to be in favour of the Reuse scenario since the rest of the modules in Construction stage remain the same for the two scenarios.

Regarding the Financial impacts of the two scenarios, for the current case under study the results clearly show that the Reuse scenario is beneficial costing 24 euros per square meter of building area less than the Recycle scenario. Further investigation though regarding the exact prices and market conditions might give a more clear image of the final impacts of the process although in the early design process the current results are considered efficient for the promotion or not of the concept. Also the parametric nature of the tool provides the opportunity to the users to investigate the limits within which the concept of deconstruction will be beneficial if applied. It must be noticed though that for projects like the one under study in this chapter that have a short life time, meaning that the possible benefits of the concept may reflect directly to the contractors or the owners of the building ,the current assessment process can become a real motive to deploy the concept of deconstruction. If we compare the final costs between the two scenarios the difference is more than 25000 euros, an amount that can constitute a strong incentive to the owner and the stakeholders to deploy the concept in combination with the resulted environmental benefits that can add an extra commercial value to the project.

For the application of the tool

The parametric nature of the toolbox is giving the designers and involved parties the possibility to produce assessment results for different design choices. The application of the toolbox to the current case study provided us the freedom to evaluate different scenarios starting from the geometry of the building and ending to the given prices to quickly investigate the limits within which deconstruction can be proven beneficial. A process that otherwise would be time consuming and probably avoided as is the case till today. Some assumption and simplification during the development of the strategy implemented in the tool though may be critical for the final assessment of the design, as for example the exact deconstruction and demolition environmental and financial burdens. Although the current project is a proof of concept and can be further developed and enriched with values that can ensure the preciseness of the results. Finally the scenarios created for the Reuse and Recycle case are defined from the allocation process of the environmental impacts from the first to the second scenario. A process that is subject to further investigation and discussion as the nature of life cycle analyses till today are. The definition of the system boundaries and the input and output flows can differ for each case resulting to different assessment results. But if one considers the comparative nature of the provided assessment and the fact that the system boundaries are defined identically for the two scenarios then the results can be considered safe for comparison purposes in order to provide the user with a correct magnitude that can rely on to decide weather or not designing for deconstruction should be taken into account and to which extent.

7 Discussion

The current research focused on the development of a strategy for the evaluation of the concept of Design for Deconstruction and the implementation of this strategy into a parametric and associative design and analysis tool. The current chapter will focus on the initially formulated research objectives and the limitations of the toolbox in order to give a better understanding to potential developers of the areas where they can focus for further improvement of the toolbox.

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7.1. Reflection on the research objectives

As described in Paragraph 2.3, the main research objective of this Thesis was:

"To develop a strategy that will demonstrate the benefits of designing for deconstruction in comparison to a conventional design in an early design stage and to form a basis for the formation of a management system that will support the concept in a wider sense by exploiting the potentials of parametric and associative design".

In order to meet this objective a background research on the concept of deconstruction and the existing technics that can facilitate it was conducted. Also the current management systems that can facilitate efficiently the concept of deconstruction were identified. A background research on the quantification of the environmental impact assessment methods that can expose the impacts of a process in a composed level such as a building had also to be undertaken in order to identify the most efficient way that the results of such a process can be exposed. Furthermore a study on the suitability of steel structures for the concept of deconstruction and reuse and the parameters that can influence this suitability were undertaken to ensure that steel structures can constitute efficiently the scope of this research. Finally a study on the concept of parametric and associative design strategies and tools was carried to ensure their suitability for the purpose of the research. The results of the above mentioned research are provided in Chapters 2,3 and 4.

The strategy developed to implement the findings of the background research incorporates the advantages of parametric and associative design and responds to the key features that can expose the benefits of deconstruction and convince involved parties to adapt the strategy and exploit the already proven environmental benefits that can bring. The parametric modelling allows the generation of various design models and the quick response of the tool allows the setup and assessment of various models but the implemented strategy tackles the problem of defining and quantifying the basic parameters that encapsulate the broad concept of deconstruction.

Far from the extensive literature and the scarcity of successful examples the concept of Deconstruction is lacking of any software support stating the interpretation and implementation of even the basic principles of it almost restrictive. The developed strategy though is providing a solid framework that takes into account those basic parameters and expose the benefits of the concept in the early design stage something that is considered necessary for the proper implementation of the concept in a project. Far from that the strategy is also proposing an allocation method for the purposes of Reuse regarding environmental and financial benefits that can arise form the concept of deconstruction. A process that is yet not well defined by any impact assessment concept as the existing concepts are focusing only on "cradle to gate: or "cradle to cradle" scenarios leaving the case of reuse in a theoretical level.

The **second research objective** of this Thesis following the first was:

"Develop a software tool for the early design stage that will assess the benefits of Design for Deconstruction regarding its environmental impacts and costs and will support the formation of a management system that will facilitate the process."

The second objective was met by implementing the above mentioned developed strategy to a parametric and associative toolbox. In order to do so an investigation of existing tools facilitating the same purpose was carried resulting to none as stating a need to design from scratch an initial strategy for this purpose and implement it in solid steps into a tool. The steps undertaken are translated into components that are carrying out analysis and assessment processes as defined by the developed strategy in order to better encapsulate the concept of deconstruction and produce valuable results for the user. The toolbox is developed following the structure of SustainabiltyOpen framework and can be used by two different use cases as described in Paragraph 4.1.3 from which the main functional requirements were derived. The toolbox's intended user are the designers including architects and engineers but the framework and results of the toolbox are referring to all the involved parties. The results can be exported to Excel spreadsheets for further use and the reason for that is to facilitate the basic steps needed to build a solid framework that will support the concept of "Design for Deconstruction" not only in an engineering level but also in a management and supply chain level fitting the needs of the proposed management model as described in Paragraph 3.1.6.

Furthermore since the concept of deconstruction and its parameters are encapsulated in the toolbox the parametric and associative nature of it offers the possibility of interaction between designers, engineers, contractors and owners stating possible to set the limits within which the concept is beneficial and should be applied. These limits can be easily identified as they are provided as input parameters in the steps of the analysis and assessment that they influence accordingly.

7.2. Limitations

The 'Design for Deconstruction" toolbox is developed and provided as a proof of concept to the implemented assessment strategy for the early design stage of a project. The implementation of the toolbox into the SustainabilityOpen framework implies that the code behind the toolbox is provided in an open-source concept stating that the toolbox is open for further improvements and added functionality. The modular nature of the components give the option of deploying the toolbox for different purposes as for example for the production of an EPD report that could follow a building. As such the limitations and areas of improvement are highlighted below.

Development and use limitations

- The toolbox is designed to be used in the Grasshopper3d plug-in of Rino3d design platform. As such the intended user must have these applications. More specifically the custom components are build deriving properties from the latest library classes provided by the developers of the program and as such at least Rhino 5.0 and Grasshopper 0.9.0061 must be used.

- The toolbox is also built using C# programming language in the .NET framework and as such future extensions must be built in the same language.

Limitation of the toolbox

- The toolbox is designed to assess steel structures. This limitation implies to the fact that the two databases connected to the toolbox include data regarding steel section and the environmental impacts of Heavy Construction Products (such as steel structures). The strategy though can be applied to different construction materials if according data are associated through databases to the toolbox.

- The carried assessments are only focusing on the structural frame of steel structures and do not include any other layer of a building for the moment. The complexity and diversity of the extra layers of any building would not state feasible to develop a strategy that would take their influence and impact into account in the given time. The modularity of the components though and the open-source nature of the SustainabilityOpen concept provides the ground for further development in this direction.

- The assessment is not taking into account the material used for the connection of the structural components. Although the connections have probably the highest impact on the technical application of the concept of deconstruction their diversity and complexity were restrictive factors on taking them into account for the time given. Another reason was the proportionally small percentage on the total weight of the structure as weight was the main value used for the assessment of the structure.

- The allocation process followed for the assessment of the Reuse and Recycle scenarios are developed for the comparison of the two scenarios and validity of the results are not guaranteed. This implies that the produced EPDs for the scenarios under assessment are not intended to be used for external purposes since in this case the PCRs of the allocation processes must be provided for external review from third parties as described in Paragraph 3.4.2.

The above mentioned limitations can be considered as indicators for further research. Further elaboration on the limitations can be found in the next chapter.

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8 Conclusions & Recommendations

In this report a detailed description of the research process followed for the course of this MSc thesis along with the results of the research has been presented. The research results have led to the development of a strategy for the environmental and financial assessment of the concept of "Design for Deconstruction". The developed strategy has then been implemented into a tool implemented into Grasshopper3D's interface exploiting the benefits of parametric and associative design.

In the current chapter general conclusions drawn from the research, the development of the strategy and the development of the tool are presented followed by a series of recommendations that can enhance the current results and the functionality of the tool. The recommendations partially reflect the current limitations of the tool as briefly discussed in the previous chapter.

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8.1. Conclusions

This research has been developed and driven by specific research questions that have led to the development of a sound strategy used for the assessment of the environmental and financial impacts of the concept of “Design for Deconstruction”. The conclusions following from this research can be drawn as followed:

Conclusions regarding the proposed strategy

- Design for Deconstruction is a concept that is influenced by various parameters such as connection details, complexity of geometry and others (see Section 3.1.3). These parameters need to be taken into account in the early design of a project in order to form a design suitable for deconstruction. The proposed strategy does not assist any technical extend, it is intended though to be used in the early design stage of a project. It allows the users to evaluate the benefits of applying the concept of deconstruction in their design and in order to focus on these parameters in the early stage of their project. Thus, it is concluded that the proposed strategy saves additional time and costs from labour intensive modifications that might be needed later in the process in order to allow designers to deploy the concept.

- Design for deconstruction is also a concept that requires the engagement of all the different parties involved in the completion of a project including stakeholders and supply chain. (see Section 3.1.5). The research showed that the lack of infrastructure to support the process is a significant reason that makes deconstruction not feasible. The proposed strategy provides a scheme that exposes the potential benefits of deconstruction for those involved in the design process but also suggests a scheme for the support of the creation of a supply chain management system that will facilitate the concept. Therefore, it can be concluded that the proposed strategy will provide an incentive to the stakeholders to invest on the concept as it proves that a structured management system can be created for its support(see Section 3.1.6).

Conclusions regarding the implementation of the strategy in a computational modelling tool

- The concept of Design for Deconstruction can only be implemented if taken into account in the early design stage of a project. Therefore, the developed parametric and associative tool that is focused on the assessment of the concept in the early design stage is aligned to this requirement.

- The research results showed that the concept of DfD is not deployed from the construction industry also due to its complexity and the time intensive research that is required in order to quantify and assess its benefits on the proposed design. This concludes the provided toolbox is facilitating this need by providing a ready-to-use framework by implementing the proposed strategy.

- The efficiency of the deployment of the concept of Design for Deconstruction is influenced by various parameters and at different levels that is difficult to indicate and quantify. The proposed strategy takes into account these parameters as derived from the background research and the implementation of the strategy in a toolbox allows their translation into varying values. Therefore, it can be concluded that the developed toolbox acts as a platform for the communication of the research results to the users allowing them to understand the impact of these parameters on the efficiency of the concept of DfD in their design.

- The case study results showed DfD is beneficial for the environmental impacts of a building design. More specifically the results of the proposed strategy revealed a reduction on the environmental burden for all the environmental indicators of an EPD for the Product and Construction stage of a building. The results also revealed potential benefits for the final costs of a project when DfD is applied.

- The proposed strategy, based on the management scheme proposed by Fujita (Fujita et al, 2008), suggests the management of the data produced during the design stage, in order to promote the concept of deconstruction not only in the design level but also in a management and supply chain level(see Section 3.1.6). The implementation of the strategy in the toolbox allows the export of the produced data to Excel spreadsheets as a proof of concept. It can therefore be concluded that the creation of a management system can be addressed through the toolbox even during in the early design stage of a project overcoming the lack of the required infrastructure that would support the concept of DfD in this extent.

Conclusions regarding the toolbox

- A parametric and associative tool for the early design stage of a project must provide a user friendly handling, a direct feedback and an easily readable output. Within the developed tool the user can adjust the design and assessment parameters and get direct feedback on the various design options. The results of the assessment are exposed in Rhino3D's interface in forms of diagrams in order to provide direct feedback for further improvement of the initial design. Finally, these results can be exported to Excel spreadsheets in common EPD format and lists stating them easy to read. It can therefore be concluded that the developed toolbox meets the key requirements of a parametric and associative tool for the early design stage of a project.

- Regarding the development, the modularity of the toolbox offers the user the ability to use parts of the tool for different assessment options and does not limit the assessment to single results. Also, the implementation into SustainabilityOpen framework facilitates the development of further extensions that can enhance the functionality of the toolbox. It can thus be concluded that the toolbox can be modified or complemented by future extensions based on specific design requirements.

- The provided assessment results are following the form of an EPD. The results of an official EPD and the followed Product Category Rules (PCRs) must be reviewed by external parties (see EN 15804, Section 7), the implemented strategy though is drawn based on a system defined for the purposes of the comparative assessment (see Section 3.4). As such it can be concluded that the results are not intended to be used as part of an official EPD but only for internal comparison purposes.

8.2. Recommendations

The main goal of the development of the tool was to provide a toolbox that will assess the potential benefits of adapting the concept of deconstruction in the early design stage of a project. In this extent the toolbox is formed with a modular approach in order to provide assessment results for different parameters of the concept and various indicators. The assessment approach followed is divided in steps that are encapsulated in the different custom developed components providing a framework that is subject to further development that could state the toolbox more effective or part of a bigger assessment approach of a project. During the development of the tool there were various parameters and assessment options that were considered suitable to the concept and are forming the following recommendations.

- The first recommendation is regarding the structural assessment of the design before the assessment of the design in the concept of deconstruction. An initial structural assessment and a selection of suitable structural sections for the different design options would provide a more precise assessment as the user would have a feedback directly applied to the different proposed geometries.

- Another recommendation for further improvement of the assessment results is the further investigation of the environmental burden of the deconstruction and demolition process as the current strategy is implementing an allocation process using the EPD results and providing some extra components to input extra potential impacts such the impacts caused due to transportation of the elements but e precise definition and quantification of the impacts of these options is highly recommended.

- For the concept of deconstruction one bottleneck that derived from the background research is that many projects that are implementing the concept of deconstruction failed to deliver their purpose due to lack of potential future use of the reclaimed components. As such a set of components that will propose new potential designs based on the geometry of the initial design would enhance the concept further.

- Another recommendation is the implementation in the results of the connections used in the structure and their evaluation regarding their suitability for deconstruction or the proposition of different connection types that would benefit the process.

- Finally the export of the results to a database instead of Excel spreadsheets would facilitate even further the concept of deconstruction as it would act as a basis for the development of databank where designers could retrieve information regarding existing reclaimed stock and make design choices according to this stock. This would result in a well functioning infrastructure that would ensure the involved parties that in case they do not intend to reuse the reclaimed components themselves they have a market with the required capacity to absorb their stock and benefit from it.

- The last recommendation is focused on the problem of identification of the components of a building. The problem of unknown identity could be solve be implementing the data prepared for the above mentioned database to identification tags like RFID's or QRCodes that would in return be attached to every element. This would result into an easy identification process during deconstruction and would eliminate the risk of uncertainty promoting the concept of deconstruction even further. Finally this technology could provide serious benefits during construction and deconstruction process as the management of the components in the site especially in large scale projects is usually a problem for any construction site as currently is being done manually providing space for many mistakes and delays during these processes.

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BIBLIOGRAPHY

AMA Research, “CurrentPractices abd Future Potential in Modern Methods of Construction:”, Banury, UK : WRAP, 2007

Arena AP, de Rosa C.; Life cycle assessment of energy and environmental implications of the implementation of conservation technologies in school buildings in Mendoza–Argentina. Building & Environment; 38:359–68; Elsevier Ltd., 2003

Ayers R., “Products as service carriers: should we kill the messenger – or send it back?” Zero emissions forum, UNU; INSEAD, France, 1999

Basson, E., “Sustainable steel: at the core of a green economy”, Presentation to Rio +20 UN Conference on Sustainable Development, Rio, 19 June 2012. http://www.worldsteel.org/media-centre/speeches-and-presentations/basson-Rio--20.html

BRE, “Environmental Profiles 2013 Product Category Rules for Type iii environmental product declaration of construction products to EN 15804:2012”, BRE Ltd 2013

Brocklesby M., “The Environmental Impact of frame materials, an assessment of the embodied impacts for building frames in the UK construction industry.” Ph.D Thesis, The University of Sheffield, 1998

Bruyn d. S., Korteland M., Markowska A.,Davidson M., Jong d.F., Bles M., Sevenster M., “Shadow Prices Handbook, Valuation and weighting of emissions and environmental impacts’”, CE Delft, Delft, March 2010

Burry, Mark and Murray, Zolna, “Computer AIDED Architectural Design Using Parametric Variation And Associative Geometry”, eCAADe-15 Conference Proceedings, Vienna University of Technology, Bob Martens, Helena Linzer, Andreas Voigt(eds.), Österreichischer Kunst- und Kulturverlag, Vienna, 1997

CIBE., “Construction Waste Reduction around the World”, CIB Publication 364, Walford, UK, 2011

Coenders J., “Open source engineering and sustainability tools for the built environment”; Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2013 „BEYOND THE LIMITS OF MAN”, Wroclaw University of Technology, Poland, September 2013.

Coenders J., “SUSTAINABILITY-OPEN: WHY EVERY BUILDING WILL BE SUSTAINABLE IN THE FUTURE”, Design Modelling Symposium, Berlin 2013.

Coenders J., “NetworkedDesign next generation infrastructure for computational design”, Ph.D thesis, VSSD, Delft, The Netherlands, 2011

Davidson, Buick and Owens, Graham W., “Steel Designers’ Manual 6th Edition”, Oxford, UK: Stee; Construction Institute/Blackwel Publishing, 2003.

Dimoudi, A., & Tompa C., “Energy and Environmental Indicators Related to Construction of Office Buildings.” Resources, Conservation, and Recycling 53.1-2 (2008): 86-95. ScienceDirect. Web. 28 March 2010.

Durmisevic E., Transformable building structures, Design for disassembly as a way to introduce sustainable engineering to building design & construction", Cedris M&CC, Delft, 2006.

Durmisevic E. and Brouwer J., " Design Aspects of Decomposable Building Structures", Proceedings of the Deconstruction and Materials Reuse Conference, Karlsruhe, Germany, 2002.

Fujita M., Iwata M., "Reuse system of building steel structures', in: Structural and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance", Vol. 4, No. 3 (p.p 207-220), 2008

Fujita M., "Reuse System of Building Steel Structures - Structural performance of reusable members and practical examples", Key Engineering Materials Vol. 517 (pp 513-521), Transh Tech publications, Switcherland, 2012

Geyer R., Jackson T., Clift R., "Economic and environmental comparison between recycling and reuse of structural steel sections", Centre for Environmental Strategy, University of Surrey, UK; 2002.

Gorgolewski, M., "The Implications of reuse and recycling for the design of steel buildings.", Journal of Civil Engineering , 33 (4), p.p 489-496., 2006

Guy B., Shell S., Esherick & Homsey, *"Design for Deconstruction and Materials Reuse*", Center for Construction and Environment; Florida, Dodge & Davis Architecture, CA, 2003

Guy B., Ciarimboli N., Hendrickson K., "Design for Disassembly in the built environment: a guide to closed-loop design and building", Seattle, 2006

G8 Environmental Ministers Meeting, "Kobe 3R action Plan", 2008

HermanMiller Healthcare, "A Life Cycle Assessment: Comparing Fixed and Modular Structures", Herman Miller, Inc. Michigan, 2009

ISO 14040:2006, "Environmental management - Life cycle assessment - Principles and framework"', CEN, Brussels, 2006

ISO 14044:2006, "Environmental management - Life cycle assessment - Requirements and Guidelines"', CEN, Brussels, 2006

NEN-EN 15978, "Sustainability of construction works- Assessment of environmental performance of buildings - Calculation methos", CEN, Brussels 2011

NEN-EN ISO 15804:2012, "Environmental labels and declarations - Type III environmental declarations - Principles and procedures", CEN, Brussels, 2010

NEN-ISO 15686-1, "Buildings and constructed assets - Service life planning - Part 1 : General principles and framework", CEN, Brussels, 2011

Olson P., "DESIGN FOR DECONSTRUCTION AND MODULARITY IN A SUSTAINABLE BUILT ENVIRONMENT", Washington State University , 2010

Peeters T. , Tata Steel, "Hlsarna, a Revolution in Steelmaking", CEPS Meeting, Brussels, 2013.

Ramesh, T., Prakashm, R., & Shukkla, K. K., "Life cycle energy analysis of buildings: an overview. Energy and Buildings ", paper 42, p.p 1592-1600, 2010.

Siebers R., Hauke B., "Life cycle assessment comparison of a typical storey building" , bauforum-stahl e.V, Dusseldorf, 2011.

Stahel, W., "The product-life factor", Product-Life Institute, Geneva, 1982. http://www.product-life.org/en/major-publications/the-product-life-factor.(last visit: 06/2013)

Taylor J.M., Coady S.A., Chesser J., "Radio Frequency Identification and Building Information Modeling: Integrating the Lean Construction Process", in B.H.V. Topping, L.F. Costa Neves, R.C. Barros, (Editors), Proceedings of the "Twelfth International Conference on Civil, Structural and Environmental Engineering Computing", Civil-Comp Press, Stirlingshire, UK, Paper 90, 2009.

Tingley D., "Design for Deconstruction : An Appraisal", Ph.D Thesis, University of Sheffield, Oct 2012

UL, "Transparency and the Role of Environmental Product Declarations", PEInternational, 2011

Velamati S., "Feasibility benefits and challenges of modular construction in high rise development in the united states : A developer's perspective", MIT , September 2012

WellMet2050, "Novel Joining Techniques ti Promote Deconstruction of Buildings", University of Cambridge, July 2010.

WorldSteel Assosciation, "Steel's contribution to a low carbon future", World Steel Association Position Paper., 2012 [http://www.worldsteel.org/dms/internetDocumentList/downloads/publications/Climate-change-position-paper-A4/document/Climate%20change%20position%20paper%20A4.pdf (last visit: 06/2013)]

WorldSteel Assosciation, "FACT SHEET Raw materials", May 2011. [http://www.worldsteel.org/dms/internetDocumentList/fact-sheets/Fact-sheet_Raw-materials2011/document/Fact%20sheet_Raw%20materials2011.pdf (last visit: 01/2014)]

Worldsteel Association, "LIFE CYCLE ASSESSMENT METHODOLOGY REPORT: Life cycle inventory for steel products", World Steel Association 2011

Worldwide LCI Database from steel industry products. Technical Report. Available from the International Iron and Steel Institute, Brussels., April 1998

Yalinay Cinici S., Ozel Akipe F., Yazar T., "Computational Design, parametric modelling and architectural education", Arkitekt Temmuz - Augustos - Eylul- Ekim, 2008

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Appendicies

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I

Life Cycle Allocation Process

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I. Life cycle allocation processes

The Steel Construction Institute (SCI) has developed a formula to calculate the burden of recycling and reuse when this occurs for one or more cycles. The formula relates the environmental burden of each cycle of reuse or recycling to those associated with the primary production and previous cycles taking into account the recycling and/or reuse yield of the system. The system that the formula is applied on does not take into account the input in raw material and energy of BF and EAF route as it is assumed that the primary material is the basis for all recycled material. It does not also take into account the impact of the output of the system to other subsystems along with the intermediate processes of material transportation. It is only focused on the number of cycles dividing the future environmental impacts over them. Finally the only external input to the system is the amount of reused products that it might be added to the remanufactured product in every cycle.

The formula is expressed in global values meaning that it applies to any of the potential environmental burdens of the steel making, recycling and reuse process like embodied energy, embodied carbon, global worming potential e.t.c and its results are expressed in "per tonne of steel" unit. The scheme of the system is shown in the figure below and in the formula following formula.

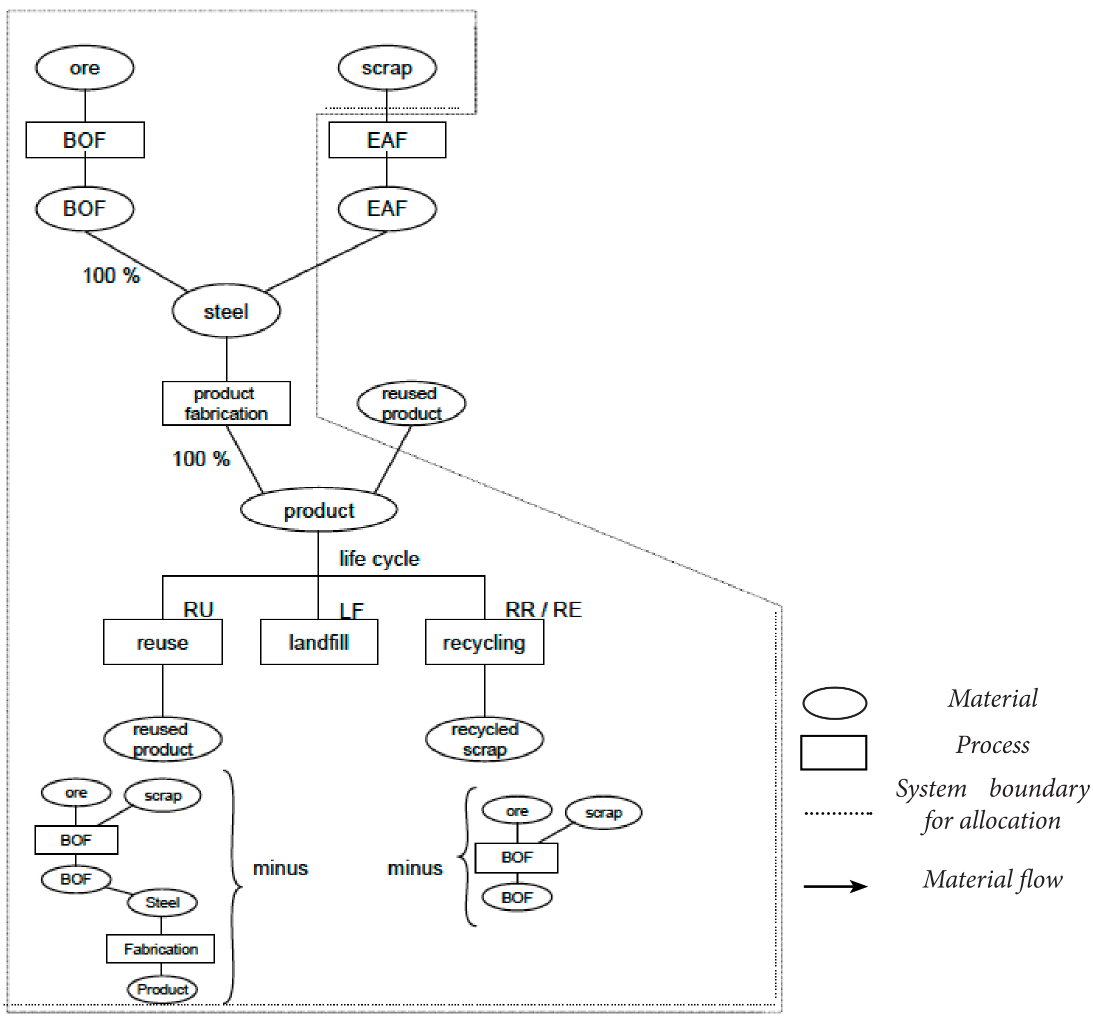

Diagram Ap.I.1 System scheme for recycling and reuse allocation processes over multiple cycles

$$X = \frac{X_{prim}}{1+(n-1)*(RR+RE)+(n'-1)*RU} + X_{Fabr} + X_{Tcmd} + (n-1)*\frac{(1-RR-RE)*Y*X_{prim}+(RR+RE)*Y*X_{\sec}}{2a} +$$

$$(n'-1)*\frac{(1-RU)*Y'*(X_{prim}+X_{Fabr})+RU*Y'*X_{reused}}{n'} + RR*X_{scrap} + RE*X_{\exp} + RLF*X_{LF}$$

Formula Ap.I.1 The SCI formula

Where

X	Environmental intervention (LCI figure)
Prim	Primary material (steel from ore)
Sec	Secondary material (recycled steel)
Reused	Reused product
Fabr	Fabrication of product
Tcmd	Transport to site, construction, maintenance & use, deconstruction
Scrap	Scrap arising at deconstruction
Steel	steel material, either primary or secondary
LF	landfill
Exp	Export of scrap and processing elsewhere
%	percentage input in product[1] under study
RR	Recycling Ratio after use of the product
RU	Ratio Reuse of the product after use
RE	Ratio export of the product after use
RRcBre	primary steel for recycling currently arising/primary steel manufactured (mass)
RcBre	secondary steel for recycling currently arising/secondary steel manufactured (mass)
RRuBre	primary steel for reuse currently arising/primary steel manufactured (mass)
RuBre	secondary steel for reuse currently arising/secondary steel manufactured (mass)
RLF	Ratio of landfill of the product after use
n	Number of recycling cycles, including 1st cycle (so minimum n = 1)
n'	Number of reuse cycles, including 1st cycle (so minimum n' = 1)
BOF	Blast Oxygen Furnace
EAF	Electric Arc Furnace
Y	metallic yield ratio at recycling proces (Y = 1,07 (IISI))
Y'	product yield ratio at reuse proces (if no information available, assume Y' = 1)
p	price

$X_{sec} = X_{EAF}$ (IISI data EAF) $n = 1 / (1\text{-}RR\text{-}RE)$

$X_{prim} = 1{,}08 * X_{BOF}$ [2] (IISI data BOF) $n' = 1 / (1\text{-}RU)$

$X_{reused} = X_{transport\ for\ reuse} + X_{processing\ reuse}$

$X_{scrap} = X_{transport\ scrap} + X_{processing\ scrap}$

$X_{export} = X_{transport\ scrap} + X_{processing\ scrap}$ [3]

In order to calculate the burden of recycling using this formula the factor of CO_2 emissions was used as one of the most common LCI flows. The data used are taken by the worldsteel LCI data collection as derived from the steel producers themselves and from the LCA Methodology report provided by worldsteel institute. The data coming from the steel producers will be marked with an "SP" label in front. It is important to be noted though that the calculation is taking place not to produce exact results but to predict a range of values and most important to demonstrate the effect of continuous recycling in a closed system in a long term situation. As such some assumptions that will not affect these results were made as will be explained in Table Ap.1.

Factor	Value	Unit	Consideration
Xprim	1,92	$KgCO_2$	
(SP) Xsec	0,386	$KgCO_2$	
Xreused	0		ny part of the product is assumed to be reused in the system instead the product is assumed to be recycled
X_{Fabr}	1,756	$KgCO_2$	as Fabrication method we assume the BOF route.
X tcmd	1		
Xscrap	0,1		this factor can always differ regarding the system under study but will always be positive so we assume a value of 1 that will be added to the formula.
X_{LF}	0		we assume that none of the products produce waste that is taken to landfill instead we assume that the total amount of the produces steel is returning back to the system
X_{Exp}	0		we assume a closed system with no output flows to secondary systems
RR	0,85		
RU	0		we assume that the entire produced steel is sent to recycle
RE	0		we assume that the entire produced steel is sent to recycle
RLF	0		the same reason as RE
n	X		number of cycles
n’	1		we only take into account the first use cycle of the product
(SP) Y	1,07		
Y’	1		we only take into account the first use cycle of the product

Table Ap.I.1 Values for the Steel Construction Institute formula

Using the these values the results are shown in the next diagram as a relation of the number of cycles and the burden that each cycle produce.

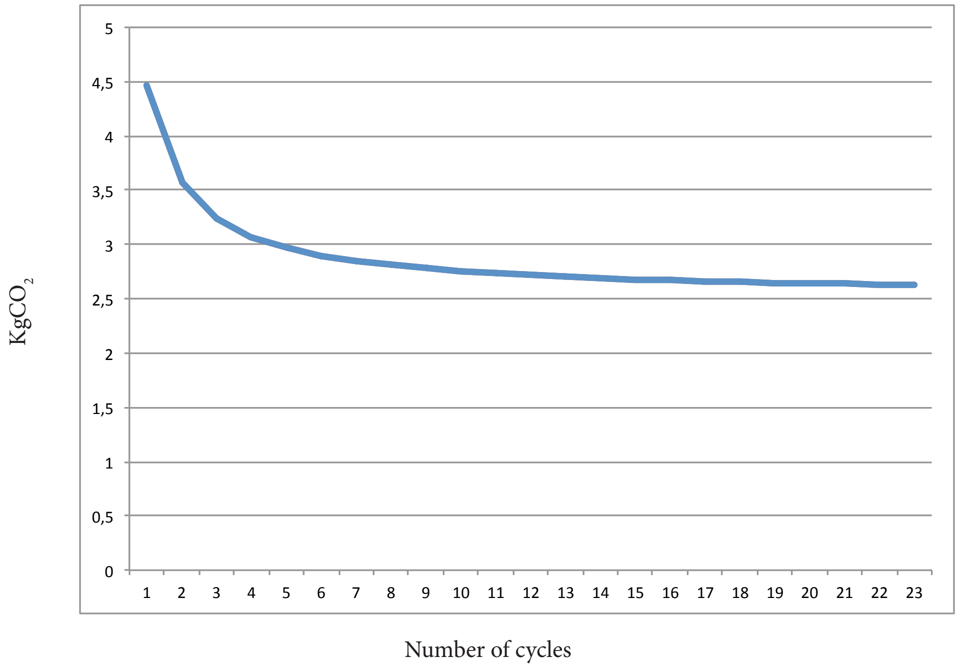

Diagram Ap.1 The environmental burden of recycle for each cycle of recycling

As one can notice the burden of each cycle is reduced although the curve has an asymptotic form meaning that the amount of reduction achieved in every cycle is gradually reduced. The relative reduction achieved for every cycle is shown in Table Ap.I.2. For the assessment of the Embdied energy and Carbon of the two proposed scenarior the reduction ratio of the second cycle that equals to 28% is used. The formula used to calculate the average change is calculated as the absolute difference of the initial value to the next one divided by the initial value and is expressed in percentages.

no. of Cycles	Burden	Average change (%)
1	5,08	
2	3,64	0,284
3	3,16	0,132
4	2,91	0,076
5	2,77	0,050
6	2,67	0,035
7	2,60	0,026
8	2,55	0,020
9	2,51	0,016
10	2,48	0,013
11	2,45	0,011
12	2,43	0,009
13	2,41	0,008
14	2,40	0,007
15	2,38	0,006
16	2,37	0,005
17	2,36	0,004
18	2,35	0,004
19	2,34	0,004
20	2,34	0,003
21	2,33	0,003
22	2,32	0,003
23	2,32	0,002

Figures Ap.I.2 Values and average difference as resulted from the SCI formula for 23 cycles

II

Toolbox Validation

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II.Toolbox validation

In this Appendix the results from the tool validation are presented in form of tables as these were produced manually from Excel spreadsheets and from the components of the toolbox.

Function	Designation	Area	Length	Volume	Weight	mass per meter	Section's Height	Section's Width	Web Thickness	Flange thickness	Root radius
		cm^2	m	m^3	tonnes	kg/m	mm	mm	mm	mm	mm
Column	HD 260 x 54.1	69,00	97,87	0,68	5,27	54,10	244,00	260,00	6,50	9,50	24,00
	HD 260 x 54.1	69,00	97,87	0,68	5,27	54,10	244,00	260,00	6,50	9,50	24,00
Beam	IPE A 160	16,200	97,867	0,159	1,237	12,700	157,000	82,000	4,000	5,900	9,000
	IPE A 160	16,200	97,867	0,159	1,237	12,700	157,000	82,000	4,000	5,900	9,000
Beam	HE 100 AA	15,600	97,867	0,153	1,191	12,200	91,000	100,000	4,200	5,500	12,000
	HE 100 AA	15,600	97,867	0,153	1,191	12,200	91,000	100,000	4,200	5,500	12,000

Function	Section height incl. rRadius hi	Web height	max dist. Between holes	min dist. Between holes	Side are per meter	Elastic Modulus Y	Plastic Modulus Y	Radious of Gyration Y
	mm	mm	mm	mm	cm^2/m	cm^3	cm^3	cm
Column	225,00	177,00	158,00	110,00	1,47	654,10	714,50	10,76
	225,00	177,00	158,00	110,00	1,47	654,10	714,50	10,76
Beam	145,200	127,200	0,000	0,000	0,619	87,800	99,100	6,530
	145,200	127,200	0,000	0,000	0,619	87,800	99,100	6,530
Beam	80,000	56,000	58,000	54,000	0,553	51,980	58,360	3,890
	80,000	56,000	58,000	54,000	0,553	51,980	58,360	3,890

Function	Shear force area	Moment of Interia About Y	Elastic Modulus Z	Plastic Modulus Z	radious of gyration Z	Moment of Interia About Z	Length of Stifness	Torsional Constant	Wraping Constant
	cm^2	cm^4	cm^	cm^3	cm	cm^4	mm	cm^4	cm^6
Column	24,75	7981,00	214,50	327,70	6,36	2788,00	53,62	30,31	382,60
	24,75	7981,00	214,50	327,70	6,36	2788,00	53,62	30,31	382,60
Beam	7,800	689,000	13,300	20,700	1,830	54,400	26,300	1,960	3,090
	7,800	689,000	13,300	20,700	1,830	54,400	26,300	1,960	3,090
Beam	6,150	236,500	18,410	28,440	2,430	92,060	29,260	2,510	1,680
	6,150	236,500	18,410	28,440	2,430	92,060	29,260	2,510	1,680

Table Ap.II.1 Sections produced by the ComponentDesigner_Component. In black is the properties as produced from the component while in red are the properties as provided by Arcelormittal

2011 EPD Heavy Construction Products	Unit	Product stage (A1,A2,A3)	Construction (A4,A5)	Use and Maintainance (B1,B7)
Environmental Profile				
Global warming potential, GWP [EN15804/prA1]	kg CO2	6992,397951	150,6086736	130,9997458
Depletion potential of the stratospheric ozone layer, ODP [EN15804/prA1]	kg CFK-11	0,00011935	0,000024948	0,000015708
Acidification potential of land and water resources, AP [EN15804/prA1]	kg SO2	9,83864651	0,793271787	0,71893169
Eutrophication potential, EP [EN15804/prA1]	kg PO43-	2,84467645	0,171929696	0,142575164
Formation potential of tropospheric ozone photochemical oxidants, POCP [EN15804/prA1]	kg ethyl	1,493161747	0,028592071	0,024670169
Depletion of abiotic resources, elements [EN15804/prA1]	kg Sb	-0,001512157	0,000041888	0,000016786
Depletion of abiotic resources, fossil fuels [EN15804/prA1]	MJ	91544,7456	2305,015251	1723,866375
Resource input				
Use of renewable energy primary energy, excl. ren. prim. resources used as raw materials	MJ (net calorific value)	3526,270748	30,27284645	57,16712232
Use of renewable primary energy resources used as raw materials	MJ (net calorific value)	0,024418463	0,00696686	0,001621635
Total use of renewable primary resources	MJ (net calorific value)	3526,270748	30,27284645	57,16712232
Use of non renewable primary energy, excl. non ren. prim. energy resources used as materials	MJ (net calorific value)	100968,0749	2438,778881	2068,474485
Total use of non renewable primary energy resources	MJ (net calorific value)	100968,6293	2438,778881	2068,474485
Use of secondary material	kg	7905,85257	0	0
Use of renewable secondary fuels	MJ	0	0	0
Use of non renewable secondary fuels	MJ	0	0	0
Input of fresh water	m3	19972,53258	176,6044665	318,0555301
Waste Categories				
Hazardous waste disposed	kg	692,1147041	59,50624962	203,2157839
Non hazardous waste disposed	kg	850,9360036	37,85196002	3,617890992
Radioactive waste disposed	kg	0	0	0

Total weight in tonnes	7,7

2011 EPD Heavy Construction Products	Unit	Product sfe (C1)	End of Life (C2-C4)	Module D (D)
Environmental Profile				
Global warming potential, GWP [EN15804/prA1]	kg CO2	310,5936218	217,5193251	-4158,049357
Depletion potential of the stratospheric ozone layer, ODP [EN15804/prA1]	kg CFK-11	0,000046277	0,00003003	-0,000058674
Acidification potential of land and water resources, AP [EN15804/prA1]	kg SO2	1,788826116	1,046504382	-4,909376703
Eutrophication potential, EP [EN15804/prA1]	kg PO43-	0,404246242	0,231587695	-1,401416478
Formation potential of tropospheric ozone photochemical oxidants, POCP [EN15804/prA1]	kg ethyl	0,058051902	0,036786742	-1,081153997
Depletion of abiotic resources, elements [EN15804/prA1]	kg Sb	0,000018095	0,00047971	0,00043813
Depletion of abiotic resources, fossil fuels [EN15804/prA1]	MJ	4158,34958	3283,227948	-51324,39466
Resource input				
Use of renewable energy primary energy, excl. ren. prim. resources used as raw materials	MJ (net calorific value)	15,37460232	77,8336251	-1727,872685
Use of renewable primary energy resources used as raw materials	MJ (net calorific value)	0,00480952	0,007829637	-0,011965045
Total use of renewable primary resources	MJ (net calorific value)	15,37460232	77,8336251	-1727,872685
Use of non renewable primary energy, excl. non ren. prim. energy resources used as materials	MJ (net calorific value)	4245,443125	3540,806577	-55941,82671
Total use of non renewable primary energy resources	MJ (net calorific value)	4245,443125	3540,806577	-55942,09775
Use of secondary material	kg	0	1374,312555	-3143,649586
Use of renewable secondary fuels	MJ	0	0	0
Use of non renewable secondary fuels	MJ	0	0	0
Input of fresh water	m3	85,8426646	376,0240869	-9787,8704
Waste Categories				
Hazardous waste disposed	kg	49,2456449	109,4965912	-339,1362064
Non hazardous waste disposed	kg	2,411039408	42,43464437	-436,0493701
Radioactive waste disposed	kg	0	0	0

Table Ap.II.2 EPD results as produced form the EPD components for their validation

2011 EPD Heavy Construction Products	Unit	Product stage (A1,A2,A3)	Construction (A4,A5)	Use and Maintainance (B1,B7)
Environmental Profile				
Global warming potential, GWP [EN15804/prA1]	kg CO2	6987,56	150,504	130,909
Depletion potential of the stratospheric ozone layer, ODP [EN15804/prA1]	kg CFK-11	0,00E+00	0,00E+00	0,00E+00
Acidification potential of land and water resources, AP [EN15804/prA1]	kg SO2	9,832	0,793	0,718
Eutrophication potential, EP [EN15804/prA1]	kg PO43-	2,843	0,172	0,142
Formation potential of tropospheric ozone photochemical oxidants, POCP [EN15804/prA1]	kg ethyl	1,492	0,029	0,025
Depletion of abiotic resources, elements [EN15804/prA1]	kg Sb	-0,002	0,00E+00	0,00E+00
Depletion of abiotic resources, fossil fuels [EN15804/prA1]	MJ	91481,409	2303,421	1722,674
Resource input				
Use of renewable energy primary energy, excl. ren. prim. resources used as raw materials	MJ (net calorific value)	3523,831	30,252	57,128
Use of renewable primary energy resources used as raw materials	MJ (net calorific value)	0,024	0,007	0,002
Total use of renewable primary resources	MJ (net calorific value)	3523,831	30,252	57,128
Use of non renewable primary energy, excl. non ren. prim. energy resources used as materials	MJ (net calorific value)	100898,219	2437,092	2067,043
Total use of non renewable primary energy resources	MJ (net calorific value)	100898,773	2437,092	2067,043
Use of secondary material	kg	7900,383	0	0
Use of renewable secondary fuels	MJ	0	0	0
Use of non renewable secondary fuels	MJ	0	0	0
Input of fresh water	m3	19958,714	176,482	317,835
Waste Categories				
Hazardous waste disposed	kg	691,636	59,465	203,075
Non hazardous waste disposed	kg	850,347	37,826	3,615
Radioactive waste disposed	kg	0	0	0

2011 EPD Heavy Construction Products	Unit	Product Life (C1)	End of Life (C2-C4)	Module D (D)
Environmental Profile				
Global warming potential, GWP [EN15804/prA1]	kg CO2	310,379	217,369	-4155,173
Depletion potential of the stratospheric ozone layer, ODP [EN15804/prA1]	kg CFK-11	0,00E+00	0,00E+00	0,00E+00
Acidification potential of land and water resources, AP [EN15804/prA1]	kg SO2	1,788	1,046	-4,906
Eutrophication potential, EP [EN15804/prA1]	kg PO43-	0,404	0,231	-1,4
Formation potential of tropospheric ozone photochemical oxidants, POCP [EN15804/prA1]	kg ethyl	0,058	0,037	-1,08
Depletion of abiotic resources, elements [EN15804/prA1]	kg Sb	0,00E+00	0	0
Depletion of abiotic resources, fossil fuels [EN15804/prA1]	MJ	4155,473	3280,956	-51288,885
Resource input				
Use of renewable energy primary energy, excl. ren. prim. resources used as raw materials	MJ (net calorific value)	15,364	77,78	-1726,677
Use of renewable primary energy resources used as raw materials	MJ (net calorific value)	0,005	0,008	-0,012
Total use of renewable primary resources	MJ (net calorific value)	15,364	77,78	-1726,677
Use of non renewable primary energy, excl. non ren. prim. energy resources used as materials	MJ (net calorific value)	4242,506	3538,357	-55903,123
Total use of non renewable primary energy resources	MJ (net calorific value)	4242,506	3538,357	-55903,394
Use of secondary material	kg	0	1373,362	-3141,475
Use of renewable secondary fuels	MJ	0	0	0
Use of non renewable secondary fuels	MJ	0	0	0
Input of fresh water	m3	85,783	375,764	-9781,099
Waste Categories				
Hazardous waste disposed	kg	49,212	109,421	-338,902
Non hazardous waste disposed	kg	2,409	42,405	-435,748
Radioactive waste disposed	kg	0	0	0

Table Ap.II.3 EPD results as produced manually through Excel for the validation of the EPD components

	2011 EPD Heavy Construction Products	Unit	Product stage (A1,A2,A3)		Construction (A4,A5)		Use and Maintainance (B1,B7)		End of Life (C1)		End of Life (C2-C4)		Module D (D)	
			ReUSE	ReCYCLE	ReUSE	ReCYCLE	ReUSE	ReCYCLE	ReUSE	ReCYCLE	ReUSE	ReCYCLE	ReUSE	ReCYCLE
	Environmental Profile													
LCIA ISO14025(7.2.2)	Global warming potential, GWP [EN15804/prA1]	kg CO2	3928,3106	5074,921445	412,504	359,504	130,909	130,909	310,379	310,379	217,369	217,369	-4155,173	-4155,173
	Depletion potential of the stratospheric ozone layer, ODP [EN15804/prA1]	kg CFK-11	0	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
	Acidification potential of land and water resources, AP [EN15804/prA1]	kg SO2	7,4192	8,99529	1,793	1,793	0,718	0,718	1,788	1,788	1,046	1,046	-4,906	-4,906
	Eutrophication potential, EP [EN15804/prA1]	kg PO43-	1,9871	2,498	0,172	0,172	0,142	0,142	0,404	0,404	0,231	0,231	-1,4	-1,4
	Formation potential of tropospheric ozone photochemical oxidants, POCP [EN15804/prA1]	kg ethyl	0,8272	0,9722	0,029	0,029	0,025	0,025	0,058	0,058	0,037	0,037	-1,08	-1,08
	Depletion of abiotic resources, elements [EN15804/prA1]	kg Sb	-0,001	-0,002	2	1,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0	0	0
	Depletion of abiotic resources, fossil fuels [EN15804/prA1]	MJ	51558,3667	68197,32853	2303,421	2303,421	1722,674	1722,674	4155,473	4155,473	3280,956	3280,956	-51288,885	-51288,885
	Resource input													
LCI ISO14025(7.2.2)	Use of renewable energy primary energy, excl. ren. prim. resources used as raw materials	MJ (net calorific value)	1783,4251	2615,422805	30,252	30,252	57,128	57,128	15,364	15,364	77,78	77,78	-1726,677	-1726,677
	Use of renewable primary energy resources used as raw materials	MJ (net calorific value)	0,019	0,02258	0,007	0,007	0,002	0,002	0,005	0,005	0,008	0,008	-0,012	-0,012
	Total use of renewable primary resources	MJ (net calorific value)	1783,4251	2615,422805	30,252	30,252	57,128	57,128	15,364	15,364	77,78	77,78	-1726,677	-1726,677
	Use of non renewable primary energy, excl. non ren. prim. energy resources used as materials	MJ (net calorific value)	56388,6179	75232,5542	2437,092	2437,092	2067,043	2067,043	4242,506	4242,506	3538,357	3538,357	-55903,123	-55903,123
	Total use of non renewable primary energy resources	MJ (net calorific value)	56388,8949	75232,96321	2437,092	2437,092	2067,043	2067,043	4242,506	4242,506	3538,357	3538,357	-55903,394	-55903,394
	Use of secondary material	kg	3950,1915	6219,693875	0	0	0	0	0	0	1373,362	1373,362	-3141,475	-3141,475
	Use of renewable secondary fuels	MJ	0	0	0	0	0	0	0	0	0	0	0	0
	Use of non renewable secondary fuels	MJ	0	0	0	0	0	0	0	0	0	0	0	0
	Input of fresh water	m3	10099,4532	14811,60904	176,482	176,482	317,835	317,835	85,783	85,783	375,764	375,764	-9781,099	-9781,099
	Waste Categories													
Other	Hazardous waste disposed	kg	414,7148	559,53543	59,465	59,465	203,075	203,075	49,212	49,212	109,421	109,421	-338,902	-338,902
	Non hazardous waste disposed	kg	428,5461	619,63082	37,826	37,826	3,615	3,615	2,409	2,409	42,405	42,405	-435,748	-435,748
	Radioactive waste	kg	0	0	0	0	0	0	0	0	0	0	0	0

Table Ap..II.4 Reuse vs. Recycle results as produced form the Grapher_Assessment Component for its validation

	2011 EPD Heavy Construction Products	Unit	Product stage (A1,A2,A3)		Construction (A4,A5)		Use and Maintainance (B1,B7)		End of Life (C1)		End of Life (C2-C4)		Module D (D)	
			ReUSE	ReCYCLE	ReUSE	ReCYCLE	ReUSE	ReCYCLE	ReUSE	ReCYCLE	ReUSE	ReCYCLE	ReUSE	ReCYCLE
	Environmental Profile													
LCIA ISO14025(7.2.2)	Global warming potential, GWP [EN15804/prA1]	kg CO2	3931,030046	4767,841545	412,6086736	359,6086736	130,9997458	130,9997458	310,5936218	310,5936218	217,5193251	217,5193251	-4158,049357	-4158,049357
	Depletion potential of the stratospheric ozone layer, ODP [EN15804/prA1]	kg CFK-11	0,000124463	8,79594E-05	0,000024948	0,000024948	0,000015708	0,000015708	0,000046277	0,000046277	0,00003003	0,00003003	-0,000058674	-0,000058674
	Acidification potential of land and water resources, AP [EN15804/prA1]	kg SO2	7,423679817	7,212129974	1,793271787	1,793271787	0,71893169	0,71893169	1,788826116	1,788826116	1,046504382	1,046504382	-4,909376703	-4,909376703
	Eutrophication potential, EP [EN15804/prA1]	kg PO43-	1,988282964	2,094918634	0,171929696	0,171929696	0,142575164	0,142575164	0,404246242	0,404246242	0,231587695	0,231587695	-1,401416478	-1,401416478
	Formation potential of tropospheric ozone photochemical oxidants, POCP [EN15804/prA1]	kg ethyl	0,827853536	0,914744359	0,028592071	0,028592071	0,024670169	0,024670169	0,058051902	0,058051902	0,036786742	0,036786742	-1,081153997	-1,081153997
	Depletion of abiotic resources, elements [EN15804/prA1]	kg Sb	-0,000730745	-0,001277757	2,00041888	1,00041888	0,000016786	0,000016786	0,000018095	0,000018095	0,00047971	0,00047971	0,00043813	0,00043813
	Depletion of abiotic resources, fossil fuels [EN15804/prA1]	MJ	51594,06221	64086,19446	2305,015251	2305,015251	1723,866375	1723,866375	4158,34958	4158,34958	3283,227948	3283,227948	-51324,39466	-51324,39466
	Resource input													
LCI ISO14025(7.2.2)	Use of renewable energy primary energy, excl. ren. prim. resources used as raw materials	MJ (net calorific value)	1784,659817	2601,858862	30,27284645	30,27284645	57,16712232	57,16712232	15,37460232	15,37460232	77,8336251	77,8336251	-1727,872685	-1727,872685
	Use of renewable primary energy resources used as raw materials	MJ (net calorific value)	0,01894256	0,018017164	0,00696686	0,00696686	0,001621635	0,001621635	0,00480952	0,00480952	0,007829637	0,007829637	-0,011965045	-0,011965045
	Total use of renewable primary resources	MJ (net calorific value)	1784,659817	2601,858862	30,27284645	30,27284645	57,16712232	57,16712232	15,37460232	15,37460232	77,8336251	77,8336251	-1727,872685	-1727,872685
	Use of non renewable primary energy, excl. non ren. prim. energy resources used as materials	MJ (net calorific value)	56427,65783	71039,19761	2438,778881	2438,778881	2068,474485	2068,474485	4245,443125	4245,443125	3540,806577	3540,806577	-55941,82671	-55941,82671
	Total use of non renewable primary energy resources	MJ (net calorific value)	56427,93503	71039,607	2438,778881	2438,778881	2068,474485	2068,474485	4245,443125	4245,443125	3540,806577	3540,806577	-55942,09775	-55942,09775
	Use of secondary material	kg	3952,926285	6224,000041	0	0	0	0	0	0	1374,312555	1374,312555	-3143,649586	-3143,649586
	Use of renewable secondary fuels	MJ	0	0	0	0	0	0	0	0	0	0	0	0
	Use of non renewable secondary fuels	MJ	0	0	0	0	0	0	0	0	0	0	0	0
	Input of fresh water	m3	10106,44602	14736,02192	176,6044665	176,6044665	318,0555301	318,0555301	85,8426646	85,8426646	376,0240869	376,0240869	-9787,8704	-9787,8704
	Waste Categories													
Other	Hazardous waste disposed	kg	415,0012549	510,6768337	59,50624962	59,50624962	203,2157839	203,2157839	49,2456449	49,2456449	109,4965912	109,4965912	-339,1362064	-339,1362064
	Non hazardous waste disposed	kg	428,843457	617,6495906	37,85196002	37,85196002	3,617890992	3,617890992	2,411039408	2,411039408	42,43464437	42,43464437	-436,0493701	-436,0493701
	Radioactive waste	kg	0	0	0	0	0	0	0	0	0	0	0	0

Table Ap.II.5 Reuse vs. Recycle results as produced manually for the validation of the Grapher_Assessment Component

Transportation Reuse	262
	0
	1
	0
	0
	2
	0

Transportation Recycle	209
	0
	1
	0
	0
	1
	0

Total weight in tonnes	7,7
Deconstruction / Demolition burdern	1,4
Reuse-Recycle potential	0,535

Table Ap.II.6 Extra parameters needed for the validation of the Grapher_Assessment component

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III Case study details

In this appendix the drawings of the case study building are presented along with the results from the assessment as produced from the developed toolbox.

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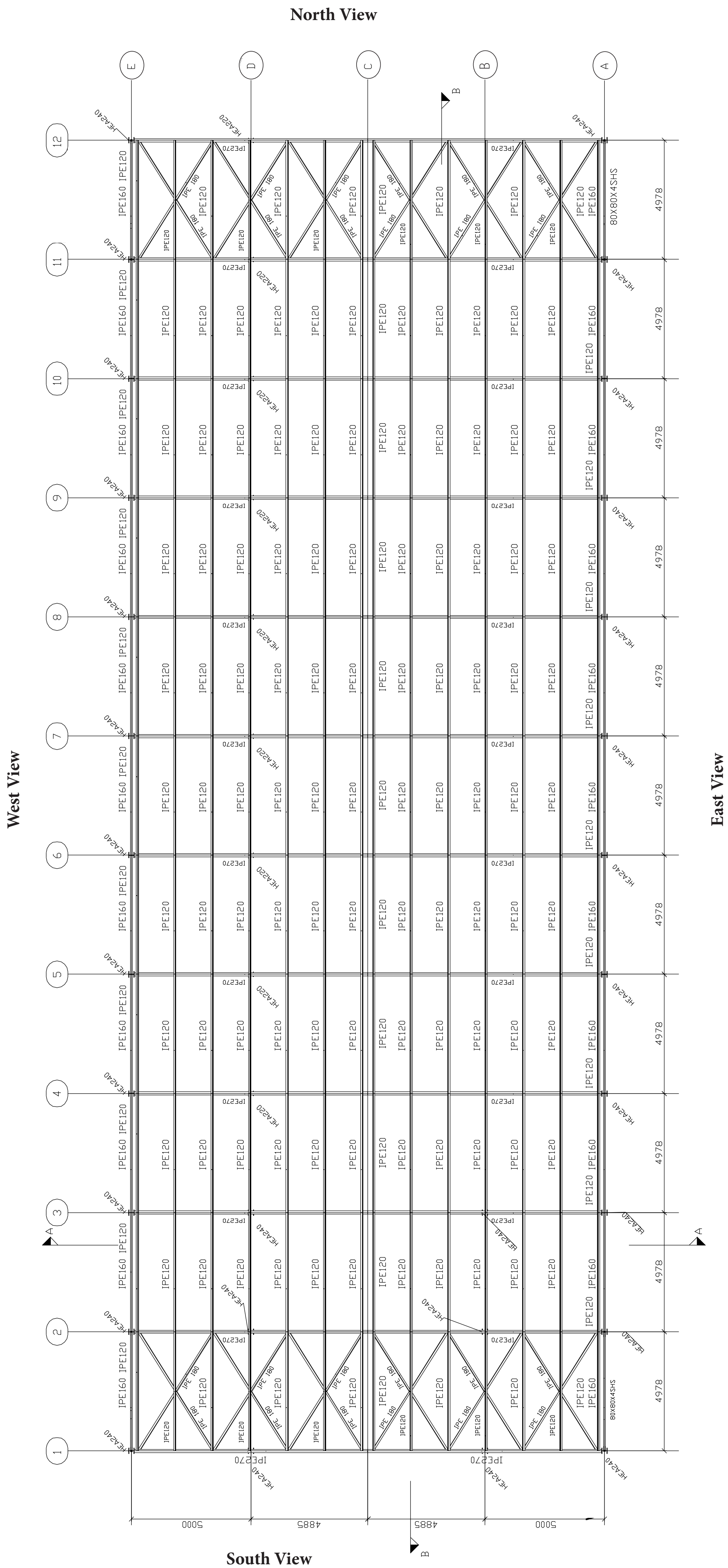
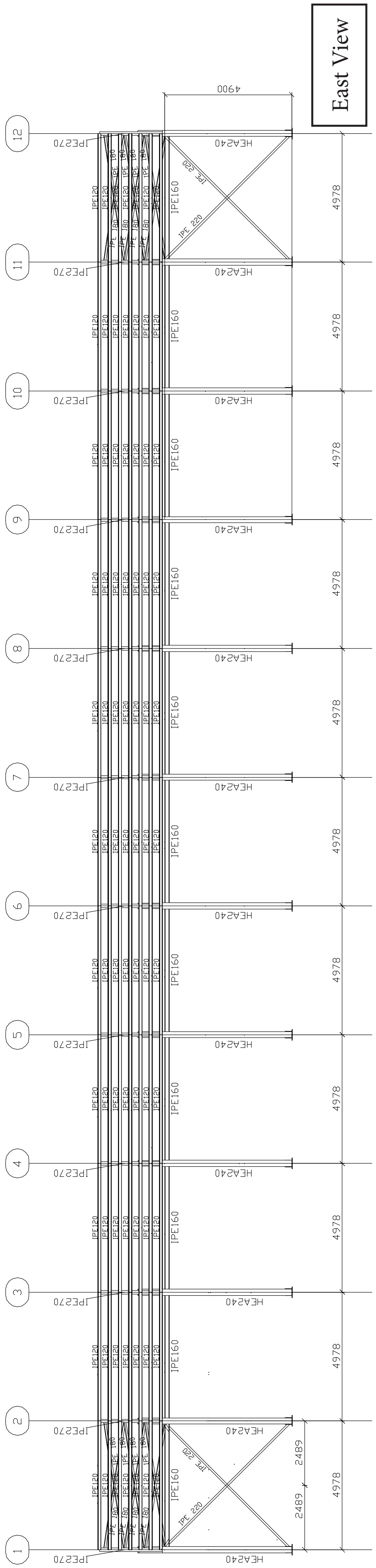
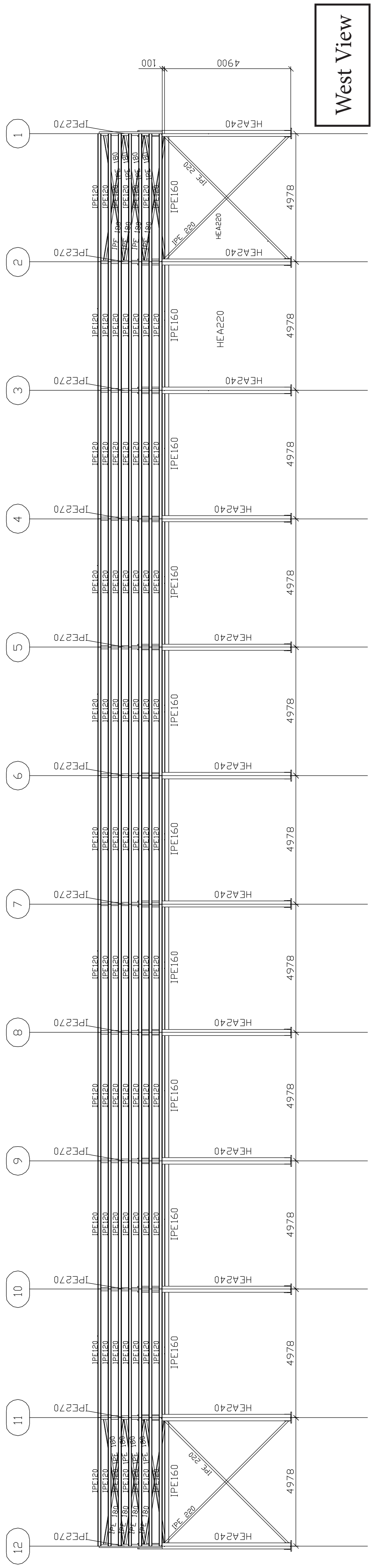
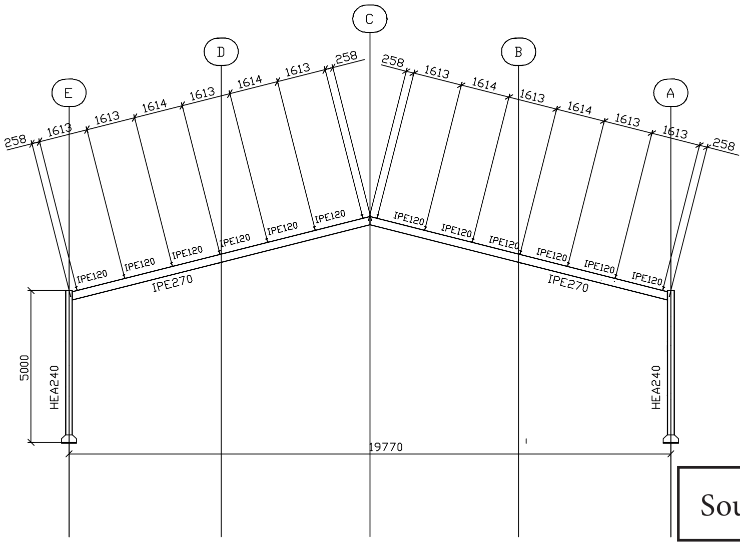

North View
South View
West View
East View
A
B
C
D
E
1
2
3
4
5
6
7
8
9
10
11
12
IPE120
IPE160
IPE180
IPE270
HEA220
HEA240
80X80X4SHS
4978
5000
4885

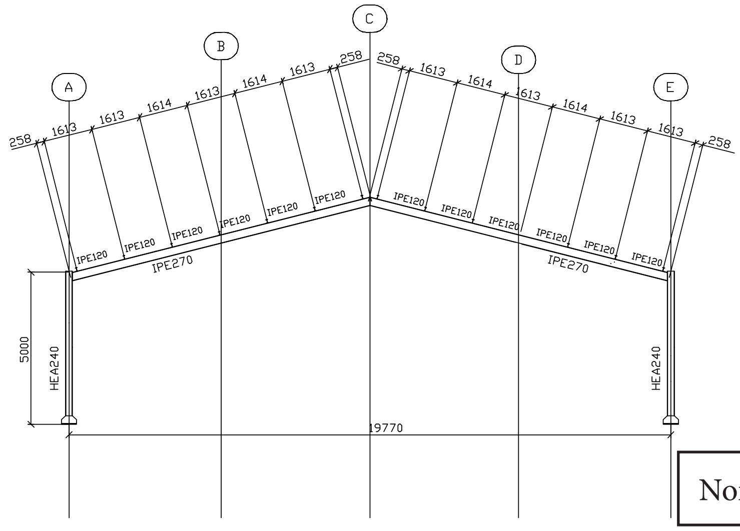
Top View


East View
4900
HEA240
IPE 220
IPE160
IPE120
IPE 180
IPE270
4978
2489

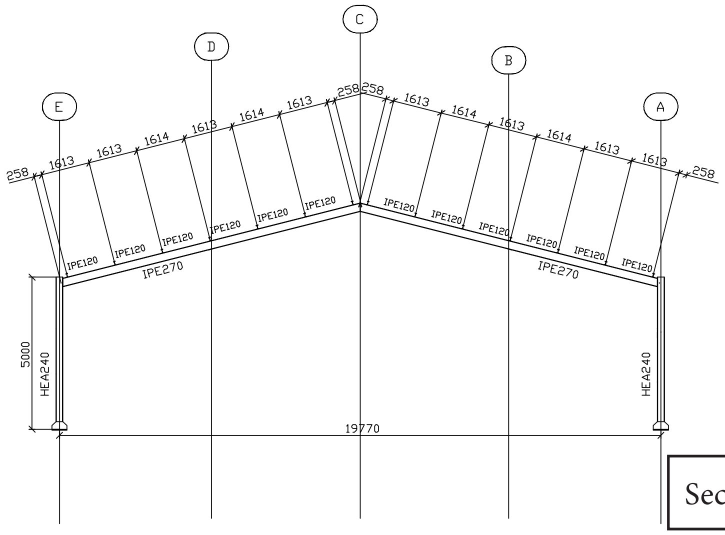

West View
100
4900
HEA240
HEA220
IPE 220
IPE160
IPE120
IPE 180
IPE270
4978



South View



North View



Section A-A’

			CaseStudy_EPDResults					
	2011 EPD Heavy Construction Products	Unit	Product stage (A1,A2,A3)	Construction (A4,A5)	Use and Maintainance (B1,B7)	End of Life (C1)	End of Life (C2-C4)	Module D (D)
	Environmental Profile							
	Global warming potential, GWP [EN15804/prA1]	kg CO2	101265,169	2181,142	1897,162	4498,073	3150,154	-60217,621
	Depletion potential of the stratospheric ozone layer, ODP [EN15804/prA1]	kg CFK-11	2,00E-03	0,00E+00	0,00E+00	1,00E-03	0,00E+00	-1,00E-03
LCIA	Acidification potential of land and water resources, AP [EN15804/prA1]	kg SO2	142,485	11,488	10,412	25,906	15,156	-71,098
ISO14025(	Eutrophication potential, EP [EN15804/prA1]	kg PO43-	41,197	2,49	2,065	5,854	3,354	-20,296
7.2.2)	Formation potential of tropospheric ozone photochemical oxidants, POCP [EN15804/prA1]	kg ethyl	21,624	0,414	0,357	0,841	0,533	-15,657
	Depletion of abiotic resources, elements [EN15804/prA1]	kg Sb	-0,022	6,00E-03	0,00E+00	0,00E+00	0,007	0,006
	Depletion of abiotic resources, fossil fuels [EN15804/prA1]	MJ	1325767,521	33381,647	24965,344	60221,969	47548,299	-743289,143
	Resource input							
	Use of renewable energy primary energy, excl. ren. prim. resources used as raw materials	MJ (net calorific value)	51068,089	438,417	827,905	222,658	1127,201	-25023,364
	Use of renewable primary energy resources used as raw materials	MJ (net calorific value)	0,354	0,101	0,023	0,07	0,113	-0,173
	Total use of renewable primary resources	MJ (net calorific value)	51068,089	438,417	827,905	222,658	1127,201	-25023,364
LCI	Use of non renewable primary energy, excl. non ren. prim. energy resources used as materials	MJ (net calorific value)	1462237,876	35318,836	29956,021	61483,273	51278,6	-810159,627
ISO14025(	Total use of non renewable primary energy resources	MJ (net calorific value)	1462245,905	35318,836	29956,021	61483,273	51278,6	-810163,552
7.2.2)	Use of secondary material	kg	114493,983	0	0	0	19903,042	-45526,9
	Use of renewable secondary fuels	MJ	0	0	0	0	0	0
	Use of non renewable secondary fuels	MJ	0	0	0	0	0	0
	Input of fresh water	m3	289245,82	2557,618	4606,138	1243,189	5445,649	-141749,705
	Waste Categories							
	Hazardous waste disposed	kg	10023,33	861,78	2943,008	713,184	1585,749	-4911,432
Other	Non hazardous waste disposed	kg	12323,409	548,179	52,395	34,917	614,546	-6314,946
	Radioactive waste disposed	kg	0	0	0	0	0	0

Table Ap.III.7 EPD results as produced form the EPD components for the case building under assessment

Reuse vs Recycle scenario results

The tables below show the results from the Reuse/Recycle scenario assessment as produced from the Grapher_Assessment, FinancialAssessment and EmdodiedEnergy component and exported to Excel from the ExcelWriter component. The diagrams produced from these results are presented in the Case study chapter. Along with these results all three of these assessment components generate graphs for that are visualised through Rhino3D's interface and are also presented below.

	Unit	Product stage (A1,A2,A3)		Construction (A4,A5)		Use and Maintainance (B1,B7)	
2011 EPD Heavy Construction Products		ReUSE	ReCYCLE	ReUSE	ReCYCLE	ReUSE	ReCYCLE
Environmental Profile							
Global warming potential, GWP	kg CO2	23287,3772	30084,59221	1202,204	1667,204	776,041	776,041
Depletion potential of the stratospheric ozone layer, ODP	kg CFK-11	0,0005	1,00E-03	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Acidification potential of land and water resources, AP	kg SO2	43,9778	53,321595	6,699	8,699	4,259	4,259
Eutrophication potential, EP	kg PO43-	11,779	14,80543	1,019	2,019	0,845	0,845
Formation potential of tropospheric ozone photochemical oxidants, POCP	kg ethyl	4,9041	5,762325	0,169	1,169	0,146	0,146
Depletion of abiotic resources, elements	kg Sb	-0,0045	-0,007395	2,002	6,00E+00	0,00E+00	0,00E+00
Depletion of abiotic resources, fossil fuels	MJ	305642,6345	404279,8991	13654,884	13654,884	10212,165	10212,165
Resource input							
Use of renewable energy primary energy, excl. ren. prim. resources used as raw materials	MJ (net calorific value)	10572,3046	15504,46157	179,336	179,336	338,657	338,657
Use of renewable primary energy resources used as raw materials	MJ (net calorific value)	0,1117	0,135015	0,041	0,041	0,01	0,01
Total use of renewable primary resources	MJ (net calorific value)	10572,3046	15504,46157	179,336	179,336	338,657	338,657
Use of non renewable primary energy, excl. non ren. prim. energy resources used as materials	MJ (net calorific value)	334276,8008	445985,352	14447,298	14447,298	12253,619	12253,619
Total use of non renewable primary energy resources	MJ (net calorific value)	334278,4428	445987,7768	14447,298	14447,298	12253,619	12253,619
Use of secondary material	kg	23417,09	36870,90496	0	0	0	0
Use of renewable secondary fuels	MJ	0	0	0	0	0	0
Use of non renewable secondary fuels	MJ	0	0	0	0	0	0
Input of fresh water	m3	59870,4709	87804,55688	1046,203	1046,203	1884,157	1884,157
Waste Categories							
Hazardous waste disposed	kg	2458,4634	3316,975135	352,514	352,514	1203,848	1203,848
Non hazardous waste disposed	kg	2540,4637	3673,232215	224,235	224,235	21,432	21,432
Radioactive waste	kg	0	0	0	0	0	0

	Unit	End of Life (C1)		End of Life (C2-C4)		Module D (D)	
2011 EPD Heavy Construction Products		ReUSE	ReCYCLE	ReUSE	ReCYCLE	ReUSE	ReCYCLE
Environmental Profile							
Global warming potential, GWP	kg CO2	1839,953	1839,953	1288,582	1288,582	-24632,237	-24632,237
Depletion potential of the stratospheric ozone layer, ODP	kg CFK-11	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Acidification potential of land and water resources, AP	kg SO2	10,597	10,597	6,199	6,199	-29,083	-29,083
Eutrophication potential, EP	kg PO43-	2,395	2,395	1,372	1,372	-8,302	-8,302
Formation potential of tropospheric ozone photochemical oxidants, POCP	kg ethyl	0,344	0,344	0,218	0,218	-6,405	-6,405
Depletion of abiotic resources, elements	kg Sb	0,00E+00	0,00E+00	3,00E-03	0,003	0,003	0,003
Depletion of abiotic resources, fossil fuels	MJ	24634,015	24634,015	19449,805	19449,805	-304045,127	-304045,127
Resource input							
Use of renewable energy primary energy, excl. ren. prim. resources used as raw materials	MJ (net calorific value)	91,079	91,079	461,086	461,086	-10235,898	-10235,898
Use of renewable primary energy resources used as raw materials	MJ (net calorific value)	0,028	0,028	0,046	0,046	-0,071	-0,071
Total use of renewable primary resources	MJ (net calorific value)	91,079	91,079	461,086	461,086	-10235,898	-10235,898
Use of non renewable primary energy, excl. non ren. prim. energy resources used as materials	MJ (net calorific value)	25149,957	25149,957	20975,698	20975,698	-331398,742	-331398,742
Total use of non renewable primary energy resources	MJ (net calorific value)	25149,957	25149,957	20975,698	20975,698	-331400,348	-331400,348
Use of secondary material	kg	0	0	8141,412	8141,412	-18622,944	-18622,944
Use of renewable secondary fuels	MJ	0	0	0	0	0	0
Use of non renewable secondary fuels	MJ	0	0	0	0	0	0
Input of fresh water	m3	508,531	508,531	2227,562	2227,562	-57983,232	-57983,232
Waste Categories							
Hazardous waste disposed	kg	291,731	291,731	648,657	648,657	-2009,039	-2009,039
Non hazardous waste disposed	kg	14,283	14,283	251,382	251,382	-2583,151	-2583,151
Radioactive waste	kg	0	0	0	0	0	0

Table Ap.III.8 Reuse/Recycle results as produced by Grapher_Assessment component for the case study

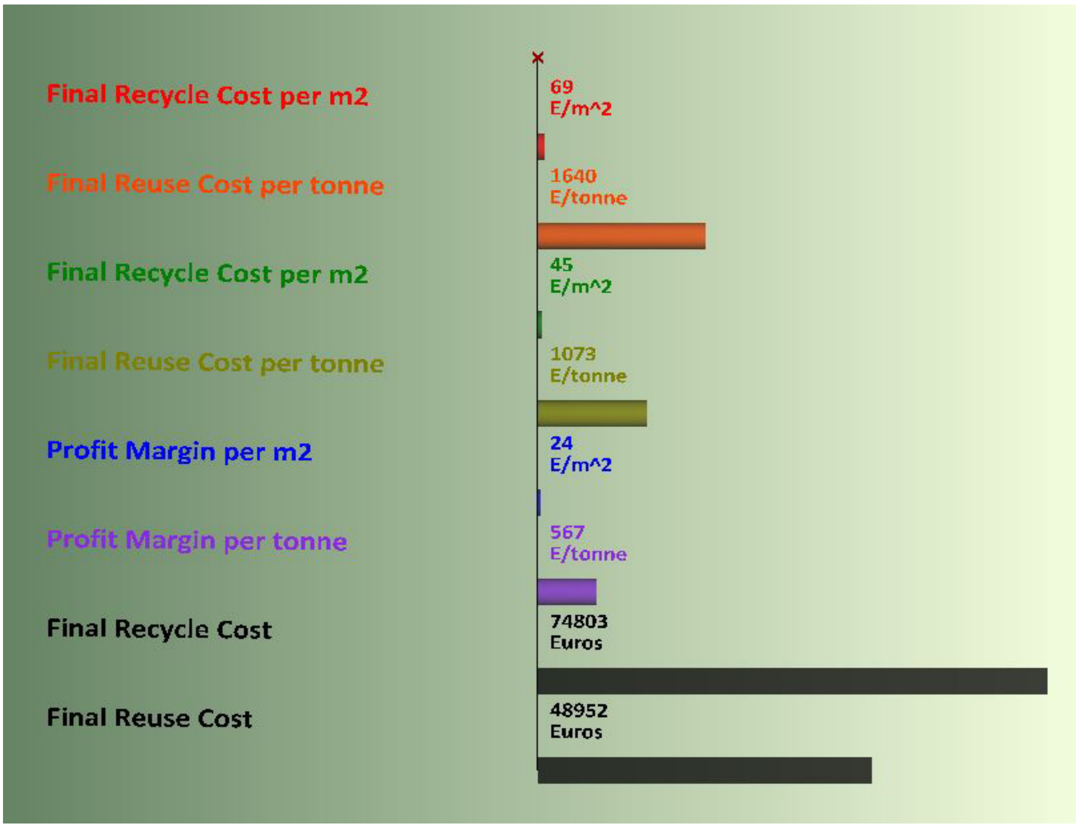
Final Project Costs	
Final Recycle Cost per m2	Final Recycle Cost per tonne
Euros/m^2	Euros/tonne
69	1640

Final Reuse Cost per m2	Final Reuse Cost per tonne
Euros/m^2	Euros/tonne
45	1073

Profit Margin per m2	Profit Margin per tonne
Euros/m^2	Euros/tonne
24	567

Final Recycle Cost	Final Reuse Cost
Euros	Euros
74803	48952

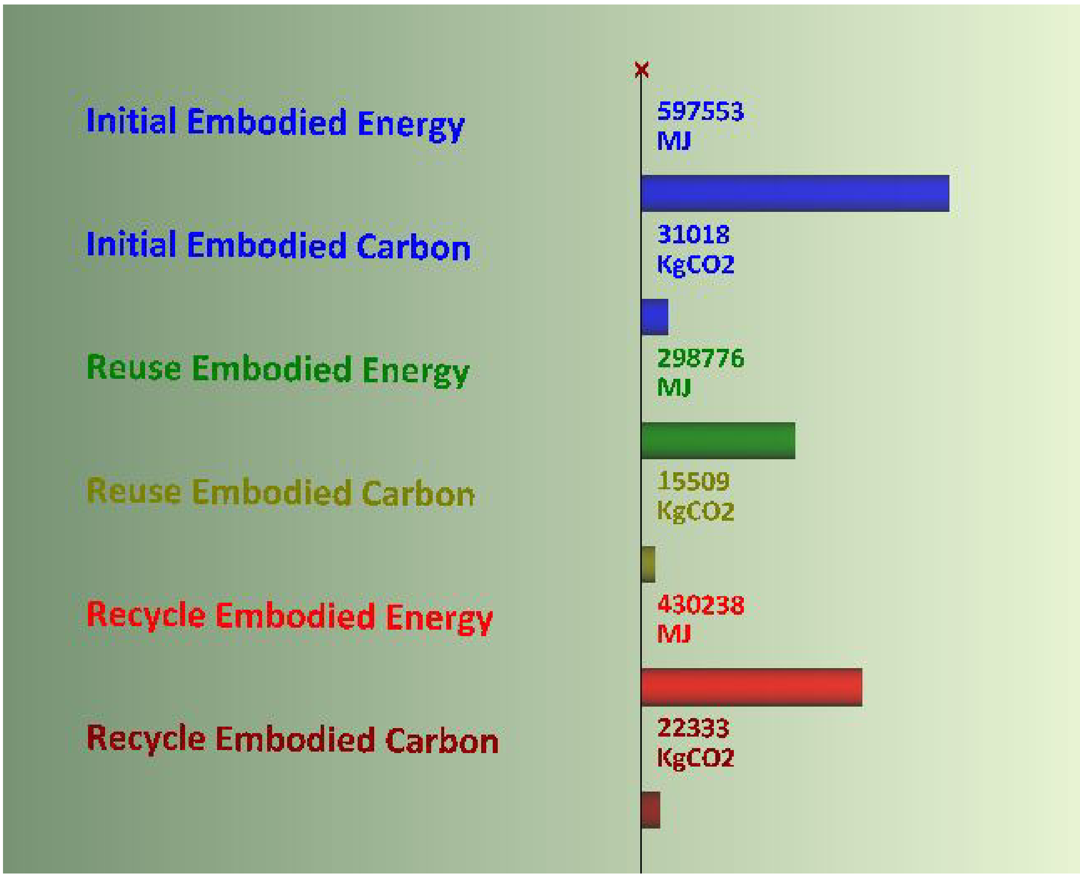
Table Ap.III.9 Financial assessment results as produced by the FinancialAssessment component



Figures Ap.III.1 Financial assessment results as visualized in Rhino3D's environment by the Financial-Assessment component

	Embodied Energy (MJ)		Embodied Carbon (KgCO2)	
Initial Scenario	597553		31018	
	ReUSE	ReCycle	ReUSE	ReCycle
Reuse/Recycle Scenario	298776	430238	15509	22333

Table Ap.III.10 Embodied energy and Embodied Carbon assessment results as produced by the EmbodiedEbergy component



Figures Ap.III.2 Embodied Energy and Carbon assessment results as visualized in Rhino3D's environment by the EmbodiedEnergy component

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IV

Component Overview

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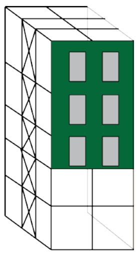
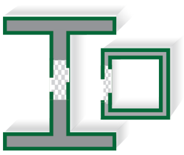
I.Component overview

In this Appendix chapter an overview of all the custom developed components is given. The components are grouped into three main categories following the logic that was followed during the development of the tool: Design, Analysis, Assessment plus an additional category for the extra components that were developed for the support of the functionality of the toolbox named Utilities. The overview is presented in form of tables where the icon of each component is presented along with a short description of its functionality and an overview of the input and output parameters that appear in the interface.

DESIGN

Icon	Component	Functionality	Input/Output
	BuildingGeometry	• Creates a basic building geometry with columns, beams and girders placed automatically close to the middle spans of the building	• IN: – No. of Floors (integer) – Floor height (double) – Bay length (double) – Bay width (double) – No. of bays (integer) – Orientation (double) – Perimeter (double) – Net Gross Ratio (double) – Floor span (double) – Stability system (String) – Origin (Point3d) • OUT: – Columns (Rhino Curve) – Beams (Rhino Curve) – Braces (Rhino Curve) – Total Area (double)
	ComponentDesigner	• Translates a Rhino geometry(Curve) into a structural steel section	• IN: – Designer (SODesigner) – Section function (integer) – Curve to Component (Rhino Curve) – Type of Section (integer) – Section Type (String) – Steel Quality (integer) • OUT: – Designer (SODesigner) – Sections (GH_Param. SOSection_Param) – Weight (double)

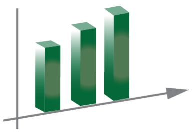
ANALYSIS

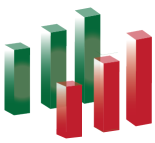
Icon	Component	Functionality	Input/Output
	QTOAnalysis	• Calculates the total amount of steel (in tonnes) used in the building	• IN: – Designers (SODesigner) – Analysis (SOAnalusis) • OUT: – Anaysis (SOAnalysis) – Analysis results(SOAnalysis)
	ComponentCol-lector	• Collects all the pro-duced sections and calculates the total weight (tonnes of steel) of the structure	• IN: – Columns (GH_Param. SOSection_Param) – Beams (GH_Param. SOSection_Param) – Girders (GH_Param. SOSection_Param) – Braces (GH_Param.SO-Section_Param) • OUT: – Sections (GH_Param. SOSection_Param) – Weight (double)

<table>
<tr><th>Icon</th><th>Component</th><th>Functionality</th><th>Input/Output</th></tr>
<tr><td></td><td>MainIndicators</td><td>• Runs an LCIA as part of the EPD for the design under study</td><td>• IN:
– Designers (SODesign)
– Analyses (SOAnalysis)
– Assessment (SOAssessment)

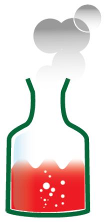
• OUT:
– Assessments (SOAssessment)
– Product Stage (GH_Param.MainIndicatorsParam)
– Construct Stage (GH_Param.MainIndicatorsParam)
– Use&Maintenance Stage (GH_Param.MainIndicatorsParam)
– EoL1 Stage (GH_Param.MainIndicatorsParam)
– EoL2 Stage (GH_Param.MainIndicatorsParam)
– Module D Stage (GH_Param.MainIndicatorsParam)</td></tr>
<tr><td></td><td>ResourceInputIndicators</td><td>• Runs an LCI as part of the EPD for the design under study</td><td>• IN:
– Designers (SODesign)
– Analyses (SOAnalysis)
– Assessment (SOAssessment)

• OUT:
– Assessments (SOAssessment)
– Product Stage (GH_Param.ResourceInputIndicatorsParam)
– Construct Stage(GH_Param.ResourceInputIndicatorsParam)
– Use&Maintenance Stage (GH_Param.ResourceInputIndicatorsParam)
– EoL1 Stage (GH_Param.ResourceInputIndicatorsParam)
– EoL2 Stage(GH_Param.ResourceInputIndicatorsParam)
– Module D Stage (GH_Param.ResourceInputIndicatorsParam)</td></tr>
</table>

Icon	Component	Functionality	Input/Output
	WasteIndicators	• Runs a Waste production analysis as part of the EPD for the design under study	• IN: – Designers (SODesign) – Analyses (SOAnalysis) – Assessment (SOAssessment) • OUT: – Assessments (SOAssessment) – Product Stage (GH_Param.WasteIndicatorsParam) – Construct Stage(GH_Param.WasteIndicatorsParam – Use&Maintenance Stage (GH_Param.WasteIndicatorsParam) – EoL1 Stage ((GH_Param.WasteIndicatorsParam)) – EoL2 Stage(GH_Param.WasteIndicatorsParam) – Module D Stage (GH_Param.WasteIndicatorsParam)
	GrapherEPD	• Visualize the results of the EPD assessment	• IN: – Assessments (SOAssessment) – Product Stage (GenericParam) – Construct Stage(GenericParam) – Use&Maintenance Stage (GenericParam) – EoL1 Stage (GenericParam) – EoL2 Stage(GenericParam) – Module D Stage(GenericParam) – RSP/ReqSL (Double) – Insert Point (Point3d) – Scale Factor (double) – Image Capture (Boolean) • OUT: – Visual Rhino output
	TransportationImpacts	• Calculates the potential Transportation impacts for the Reuse and Recycle scenario	• IN: – LorryType (integer) – Distance (double) – Total weight (double) • OUT: – Environmentla Imapcts (List<double>)

Icon	Component	Functionality	Input/Output
	ShadowCosts	• Translates the Product stage reuse and recycle values and the transportation impacts to shadow costs using shadow prices	• IN: – Product stage (LCIA) values (GH_Param.MainIndicatorsParam) – Reuse Trtansportation Impacts (List<double>) – Recycle Trtansportation Impacts (List<double>) – BOF/EAF ratio (double) • OUT: – Final Reuse shadow costs (List<double>) – Final Recycle Shadow Costs (List<double>)
	Grapher_Assessment	• Runs the core assessment for the two proposed scenarios using the results from the EPD assessment	• IN: – Product Stage (GenericParam) – Construct Stage(GenericParam) – Use&Maintenance Stage (GenericParam) – EoL1 Stage (GenericParam) – EoL2 Stage(GenericParam) – Module D Stage(GenericParam) – RSP/RewSL (double) – Reuse tranportation Impacts (List<double>) – Recycle transportation Impacts (List<double>) – Deconstruction/Demolition ratio (double) – Insert Point (Point3d) – Scale factor (double) – Image capture(boolean) • OUT: – Product Stage (GH_Tree) – Construct Stage (GH_Tree) – Use&Maintenance Stage(GH_Tree) – EoL1 Stage (GH_Tree) – EoL2 Stage(GH_Tree) – Module D Stage((GH_Tree)

Icon	Component	Functionality	Input/Output
	FinancialAssess- ment	• Runs a financial assessment taking into account the results of the QTOAnalysis and Shadow costs assessment.	• IN: – Deigners (SODesigners) – Analyses (SOAnalysis) – Assessment (SOAssessment) – Demolition Price/ m^2(double) – Deconstruction Price/ m^2(Double) – Add. Modification costs/ element (double) – New steel price (double) – Scrap steel price (double) – Shadow costs reuse (List<double>) – Shadow costs Recycle (List<double>) – Total building area (double) – Sections (GH_Param.SOSections_Param) – Insert Point (Point3d) – Scale factor (double) – Image capture (boolean) • OUT: – Assessment (SOAssessment) – Final Recycle cost/ m^2(double) – Final Recycle Cost/ tonne(double) – Final Reuse cost/ m^2(double) – Final Reuse Cost/ tonne(double) – Profit Margin/m^2 (double) – Profit margin /tonne (double) – Final Recycle cost (double) – Final Reuse Cost (double) – Final Cossts to export (List<double>)

Icon	Component	Functionality	Input/Output
	EmbodiedEnergy & EmbodiedCarbon assessment	• Runs an Embodied Energy and Embodied Carbon assessment on the initial design and on the potential new designs for the Reuse and Recycle scenarios	• IN: – Deigners (SODesigners) – Analyses (SOAnalysis) – Assessment (SOAssessment) – Sections (GH_Param.SOSections_Param) – Insert point (Point3d) – Scale factor (double) – Image capture (boolean) • OUT: – Assessment (SOAssessment) – Embodied energy (double) – Embodied carbon(double) – Reuse Embodied energy (double) – Reuse Embodied carbon (double) – Recycle Embodied energy (double) – Recycle Embodied carbon (double) – Values to export (List<double>) – Structure (Rhino Curves)

UTILITIES

Icon	Component	Funcionality	Input/Output
	EPDtoExcel	• Export the results of the EPD assessment to Excel spreadsheets	• IN: – Product Stage (GenericParam) – Construct Stage(GenericParam) – Use&Maintenance Stage (GenericParam) – EoL1 Stage (GenericParam) – EoL2 Stage(GenericParam) – Module D Stage(GenericParam) – ExporttoExcel (Boolean)

Icon	Component	Funcionality	Input/Output
	ExcelWriter	• Expots the results from the Reuse/Recycle assessment, the Financial assessment, the Embodied energy and Carbon assessment and the Sections' details to Excel Spreadsheets	• IN: – Product Stage (GH_Tree) – Construct Stage (GH_Tree) – Use&Maintenance Stage(GH_Tree) – EoL1 Stage (GH_Tree) – EoL2 Stage(GH_Tree) – Module D Stage((GH_Tree) – Sections (GH_Param.SOSections_Param) – Final costs (List<double>) – Embodied Energy & Carbonvalues (List<double>) – Write to Excel (Boolean)

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