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STUDENT REPORT

BIM AS A TOOL TO IMPLEMENT CIRCULAR ECONOMY INTO CONSTRUCTION PROJECTS' LIFE-CYCLE

4. Semester – Management in the Building Industry

Jakub Groh, Pavol Dubik

Aalborg University, Student Project

Department of Civil Engineering

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Project place:
Aalborg University, The Faculty of Engineering and Science
Aalborg 9220, Denmark

Supervisors:
Ekaterina Aleksandrova Petrova
Kjeld Svidt

Project group:
Jakub Groh
Pavol Dubík

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Authors:

Jakub Groh

Pavol Dubík

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“One man's trash is another man's treasure.”

Abstract

This report is a case study of the EU construction market and its connection to a generation of the construction and demolition waste. The project group, from the beginning of the process, aimed to understand specifics of the problem and to analyse, if the concept of the circular economy can provide a solution. The research is based on the extensive literature review of topics which lie in the interest of the project group. These are the circular economy, the design for disassembly, material passports and the building information modelling. For the purpose of the initial analysis, the project group adopted initial four steps of the logical framework approach. This was done in order to analyse and fully understand the situation in a connection to the EU construction market and CDW generation. Results of the initial analysis were used for a creation of the problem tree, which serves as basis for the problem formulation. Further created objective tree served as a basis for literature review topics in the theory chapter. Findings of the literature review were further compared with the project group members' knowledge and served as a basis to discussion chapters. Finally, the suggestion of the implementation of the circular economy through the building information modelling is formulated in order to solve or decrease the problem with increasing construction and demolition waste and presented as a part of the conclusion.

Preface

This report represents the master thesis of both members of the project group. It is a mandatory part of the last, 4th semester of the study programme, Management in the Building industry. The report aims to solve the problem connected to the generation of construction and demolition waste, which, according to the project group, has a significant impact on the environment. This is done by a discussion about topics of the circular economy, the design for disassembly, material passports and the building information modelling. These topics were chosen as they lie in the area of the interest of the project group. While the result of the report is globally applicable, the focus of the project group is on the area of EU, as this report represents the instrumental case study. During the process of the report writing, the project group collected and analysed data, connected to both the focal problem of poor design in terms of CDW management and topics of the interest. This was done in order to gain a better understanding and to allow the project group members to develop and present their solution. The solution of the problem presented by the project group is the concept of BIM as a tool to implement the circular economy into construction projects' life-cycle. This concept consists of the theoretical part connected to the circular economy, the design for disassembly and material passports, and the practical part of the concept about the implementation of material passports by the building information modelling. During the period of this semester, both members of the project group improved their skills in connection to a teamwork, writing of academical reports and conducting of a research.

Reader's manual

This manual is presented to help the reader to better understand the anatomy of the report and processes which the group members experienced and went through to create this report. The manual should help the reader to get the basic understanding as what to expect in the following pages and to ease the orientation throughout the reading.

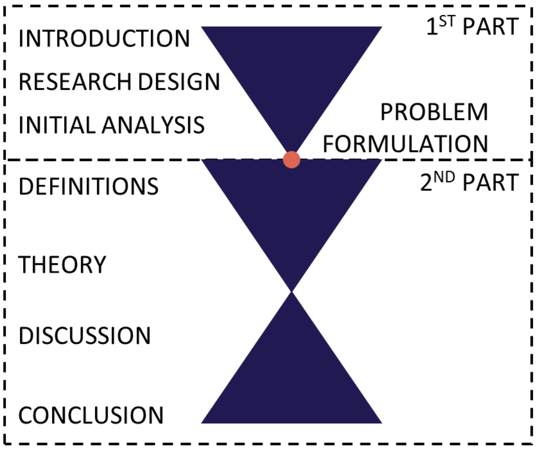


Figure 1 – The anatomy of the report

As it can be seen from the Figure 1, the anatomy of the report is inspired in a structure of a scientific article, especially the 2nd part. The 1st part consists mainly of initial analysis, during which initially wide topic of construction and demolition waste is narrowed down to a specific area of the problem formulation. The research area in the beginning of the 2nd part widens once again, as rather specific problem is now connected with more topics. This is then narrowed down through the theory chapter, which start wide at first and go into more particular areas of the interest. At the end of the theory chapter, the scope of the information is the narrowest of the 2nd part and ready for the discussion chapter, in which the theory chapter is combined to a proposal of a solution in form of a suggestion to the problem formulation and open up to new possibilities in a form of further research.

The process of the report creation follows the sequence illustrated in the Figure 2:

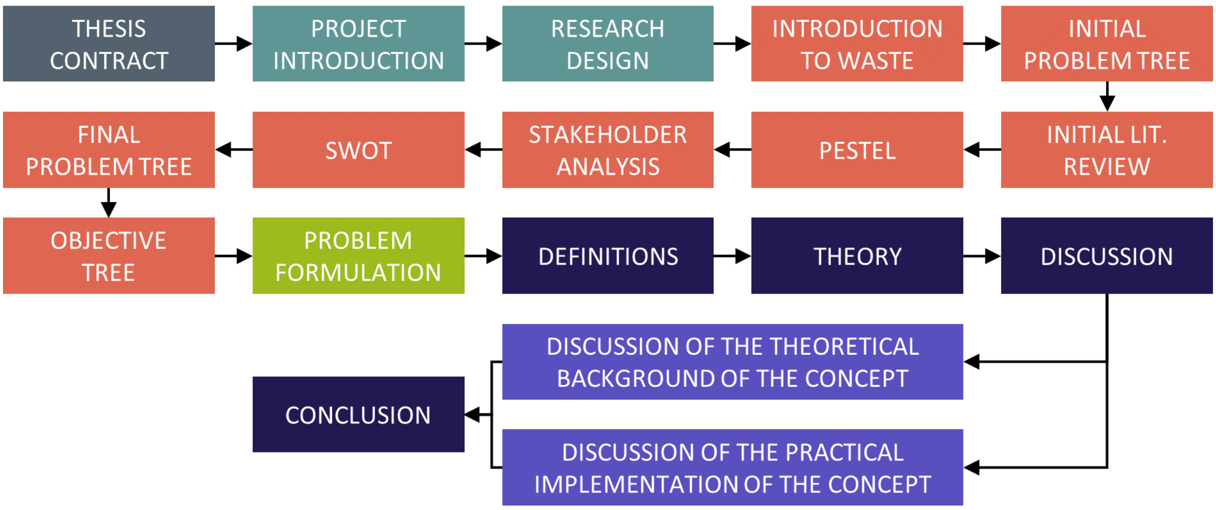


Figure 2 – The process diagram of the report

The entire process was initiated by a short description of the group members' intentions, which formed a thesis contract. This description, in some way, forms the basis for the rest of the report. The actual process of the report writing started by a project introduction and research design, which defined the way the research is executed. The initial analysis (in flamingo) was undertaken in order to narrow the scope of the case study and ultimately, to create a problem formulation. Main areas of the interest that were identified during initial analyses are explained in the definitions chapter, to make sure that both the reader and the group members have the same understanding of the topics. The topics that are part of the problem area are then further researched through literature review in the theory chapter, during which potential areas to solve the problem formulation are identified and become a basis for the discussion chapter. The discussion chapter is divided into two parts – discussion of the theoretical background of the concept and discussion of the practical implementation of the concept. Both of these parts are then, finally, combined in the conclusion, in which the report is summarised together with its suggestions and results.

Limitations

During the conduct of this thesis, the project group experienced and was limited by some aspects, that, in some way, influenced the process of the execution. Like every written report, there will always be something that could have been done better – no one is perfect. What is the most important, though, is to be able to identify the limitations so they can be taken into consideration when reading this thesis, as well as for the purpose of the further research.

This thesis is written as an obligatory part of the final semester of the master programme, which comes with limitations to time duration. The entire research has to fit into the timeframe between 3rd of September 2018 until 10th of January 2019. This, logically, comes with the limitation to the scope of the report, as all the methods utilised in thesis must be done on time. One of the main drawbacks that the time limitation affected is the lack of time to contact relevant stakeholders in order to gain their opinion about the proposed solution. The answers from the construction stakeholders could provide both new ideas and obstacles to overcome.

It should be noted, that neither of the group members is a native English speaker. Both group members have attended bachelor and master programmes with English spoken courses, but the teachers were not English speakers either. Therefore, it is possible that some grammatical errors might be part of the thesis, as well as some sentences being less sharp as they should be. However, both group members have done their best to deliver the result as good as possible. All the text was proof-read and corrected by the group members to make sure it makes sense at least internally. As part of this thesis is the defence of it, it is expected to clarify any remaining confusing parts in person.

Both of the group members live and conducted their parts apart from each other. This came both with limitations, but also some possible advantages. The main limitation was the inability for an immediate feedback, as the group members were used to work next to each other during previous projects. However, most of the processes that the group members learnt during collaboration during previous studies were still put in place – just most of them were executed remotely. Most of group meetings were conducted over phone and internet. Proof-reading and feedback were put together weekly with the help of a cloud-storage connected with comments in PDFs. Online tool, Trello, was used for the planning part of the thesis, allowing the group members to see the progress on the report. When needing a visual representation, online tools such as Google Docs, draw.io, or a desktop sharing were utilised. The only time the group members were meeting in person was during some of the supervisors' meetings. This limitation affected the thesis in some way, but whether the thesis was affected positively or negatively is a question. On the one hand, it was not possible for the group members to collaborate as much as they were used to – in some parts of the thesis, the connections between various topics could have been connected better. On the other hand, this allowed the group members to work more independently – which allowed to research topics which would have been left out otherwise and are now solid parts of the thesis. Nevertheless, it is something to consider when reading the thesis.

The content of the thesis is affected by the previous education of the group members. The education of both group members is the same - Architectural Technology and Construction Management. This might affect the objectivity of the thesis and the choice of the topic. Both of the group members have already worked on study projects together, both during bachelor programme and master programme. This affects the way of collaboration and methods used for the execution of the thesis.

In previous projects in which the group members have contributed, the objectivity of the report was usually assured through exhaustive literature review of peer-reviewed articles and established theories. However, in this case, this was not always possible, as the result of the report is a proposal of a concept, which has been researched only minimally in the circles of academia. In general, most of the topics in this thesis have started to be researched in the last few years, thus, there are not too many research articles to source and use as a basis to support the objectivity of the report. On top of that, most of the topics in this thesis are too recent, that there are missing studies of the implementation of the theories. In many cases, the group members include subjective explanations and comments of the findings from various sources – but the best effort was always made to not change the meanings of other sources and be objective towards the construction industry practices.

During the stakeholder’s analysis, it will be introduced that most of the stakeholders of construction industry are connected in some way to the problem of CDW generation. However, due to the limitation of the scope of the thesis, this thesis is primarily targeted towards clients of the construction industry. This is mostly due to the lack of regulations which would force someone other than a client to follow principles of circular economy. Therefore, most of the suggestions are presented and defended in a way to persuade clients to take a step forward towards circular economy. However, since CDW generation is so interconnected with all of the stakeholders, suggestions for other stakeholders are part of this report as well, just not so prioritised, yet they all can benefit and get inspired in this thesis. Nevertheless, in order to successfully implement circular economy into construction industry, every stakeholder needs to undertake some actions.

Lastly, it should be noted that the group members possess only limited ability to code in a programming language. This has affected the discussion chapter about proposed concept – there is no functional concept developed, instead, proposals of the functionality and the graphical interface are presented, supported with many figures explaining the relationships between responsibilities, stakeholders and technological tools.

Table of Content

1. Introduction

The current level of waste generation is unsustainable and is enormously harmful towards both the environment and the society. Every year, there is between seven to ten billion tonnes of waste generated. Most of the waste is generated by so-called high-income countries. European Union is solely responsible for up to three billion tonnes of waste generated every year. Construction industry is considered to be one of the biggest polluters, and the amount of waste generated annually is increasing. In European Union (EU), approximately 25-30% of waste generated is construction and demolition waste (CDW). Thus, decreasing the amount of CDW is expected to lead towards significant decrease of waste in total, working towards more sustainable and healthier environment.

Construction and demolition waste in European Union are predominantly controlled by two directives. These are *Waste Framework Directive* from 2008 and *Landfill Directive* from 1999. Each member of European Economic Area (EEA) is responsible to transpose this into national law and implement strategy to reach goals set in the directives. There are large differences in the percentage of CDW to total waste in EEA, ranging from as low as below 10% to as high as above 70%. The overall goal is to recycle at least 70% of construction and demolition waste in EEA by 2020. However, the results between separate member countries vary greatly as well. Individual countries usually employ financial penalties for landfill of materials, but as the fines are not high enough, the motivation is missing. The incentives for support of approaches such as waste minimisation design or CDW management implementation are not common. Newly presented EU circular package shows the intentions of the EU to move towards circularity.

The potential to reuse/recycle materials in construction that are treated as waste at the moment is enormous. The proposed solution is inspired in circular economy, which is further supported by the idea of EU to become the recycling society, thus be less dependent on import of scarce materials. The proposed solution aims to unite this traditionally fragmented industry through universal tool allowing all the relevant stakeholders to handle material properties throughout the entire projects' life-cycle. This is done through implementation of circular economy principles into the BIM environment, which allows for timely circular analyses to be performed by the project's stakeholders. This is complemented with a comprehensive documentation of used materials, allowing for easier waste management in the future.

In this case study, the group members attempt to combine the principles of circular economy with BIM through material passports. To fully cover entire life-cycle of a building and make it easily accessible for all the stakeholders, the group members propose a solution relying on big and open BIM, which is accessible through a web-based application. To avoid scalability and interoperability issues known to exist for open BIM models, which are even escalated by the fragmentation of the industry, the group members explain various steps as how to avoid these issues and make the collaboration smoother. Since both circular economy and material passports are new to construction industry, proposal for gradual implementation is included as part of the solution.

In the first part of the thesis, the reader can expect a logical sequence of subsequent processes leading towards the identification of the focal problem – concluding the first part of the report. In the second part of the report, this problem is further researched through a literature review. Topics like circular economy, design for disassembly, BIM and material passports are scrutinised individually and possible solution is identified and discussed. These topics are then combined together, resulting both in proposal of new theory and a concept explaining the functionalities of the proposal both from the stakeholders' perspective, but also the technological needs behind it.

2. Research design

2.1 Research strategy and design

Business research strategies by Bryman & Bell (2011) served as a basis for a creation of the research design for the purpose of this report. In order to provide the reader with easier understanding of finding the research problem, this chapter is structured in the same way as Bryman & Bell's book.

The theory direction

In their book, Bryman & Bell are focused mostly on the two main directions which can be followed during the research. One of them is inductive and other is deductive direction. While they are both focused on hypothesis, it is how researchers work around them, what makes these directions different. In the case of inductive theory, a research group starts with a specific, narrow area of research. Based on their observations of the area they finish research by forming a hypothesis, so called generic theory. In case of deductive direction of theory, the scope of the research is exactly opposite. A project group starts with wider area of research based on the already existing hypothesis. Based on the research conducted for the purpose of deductive research, a project group finalise a report by confirming or rejecting a theory.

This report follows the inductive approach. The reason for that is that the project group started by researching a narrow area of interest around the waste. By the further analysing the project area the research group was able to formalise the problem tree and specify the focal problem. With further literature review, the project group analyse the focal problem which leaded to the creation of the theory. These processes, together with result of theory creation is implying that inductive theory direction is followed in this report.

Another reason for the project group focus on inductive is time constrain. The project group is limited by time of the semester. As the deductive theory is focused on confirming or rejecting the theory, it is necessary that a project group will collect reliable data in order to validate the theory. This process requires eminent amount of time. Therefore, the project group restrain from following deductive theory and is rather focused on the inductive direction.

Epistemological consideration

The way how the knowledge of the research is seen is determined by epistemology. Epistemology is trying to answer the question if the natural and social sciences can be researched in the same way or it is necessary to take different approach to both of them.

While there are more epistemological directions known to the world, Bryman & Bell are focused primarily on two. First of them is positivism which is focused on the explanation and the other is interpretivism, which if focused on the understanding.

For the purposes of this report, the epistemological consideration is interpretivist. The reason for that is that the main goal of this report is for the group to understand a social phenomenon of the construction and demolition waste generation. This is done by collecting the literature focused on the specific problem which often offer different opinions of the researchers. Collected data are further discussed by the individual members of the project group. They offer their subjective view of the problem, based on the theory and offer their suggestions how the implementation of circular economy (CE) via BIM, can be done, as there is no other specific research conducted about the same topic. The result might be affected by subjective way how researchers see the world. It is not possible to conduct this report with positivist epistemological consideration, as this require objectivity of the report. Most of the data collected for the purposes of this report are further discussed by the project group members and together with their subjective understanding of the social phenomena. Based on the subjectivity of the results in the final suggestions for the implementation of circular economy, the epistemological consideration of this report is interpretivist.

Ontological consideration

The ontological consideration is focused on the form and nature of the reality. Bryman & Bell differentiate two different ontological consideration, based on their interpretation of reality. These are objectivism and constructivism. While objectivists believe in pure nature where the social phenomena are independent of the social factors, the constructivists believe that social factors have high impact and are constantly affecting development of that social phenomena.

This report is based on constructivist view. This is closely connected to the both group members' decision to pursue a master's degree in a construction project management. Before starting the master education, both members of the project group gained bachelor's degree in the Architectural technology and construction management (ATCM). With such study, the project group members were able to see the world in objectivist view, as they were ready to become other part of the work force, focused solely on fulfilling the tasks with no consideration or reasoning behind it. However, with the decision to become project manager, it became impossible to see the world from objectivist point of view. This is due to the manner of the project manager's tasks. With decisions and responsibilities given to the project manager it is impossible to neither neglect social factors affecting the social phenomena, nor avoid affecting this phenomenon by decisions taken by individual project managers.

This is clearly visible in the process of this report, as the result of the report is to develop the process of implementation of the circular economy into the construction industry via BIM. The project group believes that this process might solve the focal problem of continually increasing generation of construction and demolition waste. By implementation of CE the project group is intending to switch construction market from linear production into the closed loops. This means that group intention is to affect existing construction market and to start further development.

Choice of paradigm

Based on the epistemological and ontological consideration the project group chose the paradigm for this research paper. The paradigm selection is based on *Sociological Paradigms and Organisational Analysis* by Burrell & Morgan (1979) which was adopted by Bryman & Bell. To simplify the process of the paradigm selection, Bryman & Bell works with a limited options of paradigm. First selection of paradigm is between subjectivist and objectivist, both are specified by the way of data collection and the nature of the organisation. Second option is connected to function and purpose of research result, this can be even regulatory or radical.

Based on the ontological understanding of the both group members, epistemological consideration and the nature of this research, subjectivist view on the report was adopted by the project group.

As the main goal of this report is to actively decrease the construction and demolition waste production, it is necessary to take a radical step. Result of this report is the project group's idea to completely shift the way how the construction industry operates. While the group is cautious and careful in regard to suggestions, the report is considered to be radical by its purpose.

Based on the group choices connected to the paradigm, this report represents subjectivist radical report.

Research strategy

As the result of the choices made in the theory direction, epistemological, and ontological orientations, the research strategy is created. While these choices are not strictly related to the research strategy, they tend to follow the differences presented in the table below:

Fundamental differences between quantitative and qualitative research strategies

	Quantitative	Qualitative
Principal orientation to the role of theory in relation to research	Deductive; testing theory	Inductive; generation of theory
Epistemological orientation	Natural science model, in particular positivism	Interpretivism
Ontological orientation	Objectivism	Constructionism

Table 1 - Fundamental differences between quantitative and qualitative research strategies (Bryman & Bell, 2011)

Topics researched for the purpose of this study are closely connected to social studies of business strategy, market development, information technology and others. While most of the data collected presents valid literature for the following topics, their selection and presentation were done based on the subjective selection of the group members. This represents one of the reasons why this research is considered as qualitative rather than quantitative. Another reason is connected to the manner of the data collected. While some of the data presented in this report can be quantifiable, it is mostly representing subjective expectations of researchers as no real result of case studies are available yet. The project group is also focused mostly on the soft topics which are affecting a focal problem in order to offer the solution. Therefore, research strategy for this report is qualitative.

The research paper is inductive as it started with the problem formulation build around a focal problem and resulted in the project group's suggestion how this problem can be solved. From the epistemological view, while the group members collected data from the valid literature, they were presented in the subjective way by the project group members in order to allow them to develop their own theory. The project group was primarily focused on the soft topics of the social environment and while the project group tries to research the problem, it is not trying to find explanation for it, but rather understand it in order to find suitable solution. Based on above mentioned reasons the epistemological orientation of the report is interpretivist. Based on the education pursuing by the project group members and their understanding of social factors affecting the society, the nature of the reality for this report is constructivist.

Therefore, the research strategy of this research paper is qualitative, based on interpretative paradigm.

Research design

The project group did not work with a specific company assigned for the purpose of this project. However, the project group decided to focus on the specific area where the problem occurred. Therefore, the project group situated the problem in the area of the EU. Due to this constrains the study is focused specifically on this area, in case the other areas are covered by the report, it is in order to gain better understanding of the problem localised in the chosen area.

The choice of case based on the purpose of the study is an instrumental case. The project group decided to focus this research paper on the geographical location of EU. This is due to the group background as both members of the group are coming from the area. This allows the project group an easier understanding of the social aspects connected to the case. However, an instrumental nature of the case allows the project group to challenge the generalisability of the research. This is suitable for the report as the model of the CE together with the BIM is not specifically designed for the research area and therefore allows option for generalisability.

Research criteria

Research criteria commonly presented in the research papers are reliability, replication and validity. These according to the Bryman & Bell are not valid for the purposes of qualitative research and they tend to be ignored. Therefore, the project group decided to focus on the criteria presented by the Lincoln and Guba (1985). In their work they proposed two criteria of trustworthiness and authenticity. In order to better understand the criteria of trustworthiness, it is broken down into the following four criteria of credibility (internal validity), transferability (external validity), dependability (reliability) and confirmability (objectivity). All these research criteria will be discussed in the further text.

While the credibility of the report is not validated specifically, the project group members commonly validate text used for the purpose of this report. All the text went through the proof-reading done by other group member in order to discuss topics and avoid presentation of unclear or inaccurate data. Most of the text presented in this report was also briefly validated by the project group supervisors assigned for this semester.

In depth analysis of the specific case of EU together with deep understanding of topics connected to the final suggestion allows the transferability of the research. Base on the nature of this report and research of globally used models allow the possibility to transfer the finding of this study into another case.

In regards to dependability, all the data and knowledge gained for the purpose of this report were commonly shared between the individual members of the project group. All the literature was stored on web-based storage, in order to allow all the project group members to access it in any situation.

While the confirmability of the data collected for the purpose of this research is assured by the data collected primarily from the peer-reviewed articles. It is a presentation of these data by the individual members of the project group, what threats the confirmability. However, the research group tried to be honest and unbiased in the way how they present and discussed gained data.

Lastly the criterion of authenticity of the report. The authenticity of the report can be assured by five categories of fairness, ontological, educational, catalytic and tactical authenticity. For the purpose of this report the fairness stands most as criterion assuring the authenticity of the report. This is due to the complexity of the research where the project group was not only interested into the one stakeholder point of view. However, the project group took more holistic approach where all stakeholder and data connected to them were gained in order to assure better understanding of the problem and assure more suitable suggestion.

2.2 Methodology

This part of the report lists and describes the methods that were used for the creation of this thesis. Each method explanation comes with a simplified description of the method itself, the reference followed to carry out the method, the reasoning as why the method was used and, in some cases, the alternations from the original procedure.

LOGICAL FRAMEWORK APPROACH

Logical Framework Approach (LFA) is used in the 1st part of the report (as identified in the Figure 1 in Reader's manual). The final outcome of LFA for this thesis is the problem formulation, but LFA also serves as a structural aspect of the initial analysis. The entire method of LFA is based on Örtengren (2004). LFA was developed during the 1960s and the widespread of the approach happened in 1970s. LFA is in instrument for objective-oriented planning of projects. This means, that the problems are first identified, after that, objectives are acknowledged and then, finally, it is possible to choose relevant activities. It is emphasised, that it is necessary to analyse problems and objectives first, before making a plan of activities. LFA is usually used for analysis, follow-up and evaluation of the projects. It is used to improve planning, implementation, monitoring and evaluation of a development intervention. In this case, LFA is used for the analysis part, as it comes with a logical structure, which is easy to follow and proved to be supportive in the past projects.

LFA consists of nine following steps: (1) Analysis of the project's context, (2) Stakeholder Analysis, (3) Problem Analysis, (4) Objective Analysis, (5) Plan of Activities, (6) Resource Planning, (7) Indicators/Measurements of Objectives, (8) Risk Analysis and Risk Management, and (9) Analysis of the Assumptions.
For the purpose of this thesis, steps 1 to 4 are executed, this is, mostly, due to the limitations of this report. The result of problem analysis is reflected in the problem formulation. As it is emphasised by Örtengren (2004), LFA is a flexible method. It is advised to adapt the analysis and all the steps to given situation. This recommendation is followed in this thesis, as there is one problem tree executed before stakeholder analysis, not strictly following the recommended sequence of the steps, as well as the analysis of the project's context, which is done throughout entire initial analysis. The reason behind this decision and the rest of the individual steps will be discussed below:

(1) Analysis of the project's context

This analysis is performed to capture the state of the environment and to gain background information. As CDW is quite a complex issue, it is necessary to perform numerous analyses until holistic understanding of the problem is reached. The analysis of the project's context starts with the introduction to global waste and construction waste part of the initial analysis chapter. It serves as the initial investigation of the problem, without going into depth. It also serves as a basis to initial problem tree, sorting the obvious problems of the CDW. Initial literature review is used to get in-depth understanding of the problem. PESTEL analysis is used to gain holistic understanding of CDW in the macro-environment. SWOT analysis concludes the results of the initial analysis. The methods used to execute the literature review, PESTEL and SWOT analyses are described further in this chapter.

(3) Problem Analysis – Initial problem tree

Problem analysis in the form of problem tree is a framework to identify negative aspects of a certain situation. The problem is identified as focal problem. Focal problem is caused by causes, which are analysed to find reasons for the focal problem. The negative nature of effects of the problem tree are the arguments for the need of the problem solution. As the causes below the focal problem lead to effects above the focal problem, the problem tree is always read from bottom up.

Contrary to recommended sequence, initial problem tree is completed right after completion of introduction to global waste and construction waste part of the initial analysis. This means, that it is completed with limited knowledge about the topic. This process was decided based on previous experiences, during which opinions on given topic changed after literature review. Capturing of problem tree in the beginning of the research assures objectivity of the initial problem tree. The initial problem tree is created separately by each group member and completed with the help of Delphi method.

(2) Stakeholder Analysis

The purpose of stakeholder analysis is to identify stakeholders, who directly or indirectly have an effect or are affected by the effect of CDW. Literature review and general understanding of the industry are used as data for the analysis. The analysis itself is inspired in stakeholders' card introduced by Kousholt (2012). Stakeholders are assessed based on the amount of the influence they possess and whether they affect the issue of CDW directly or indirectly.

(3) Problem Analysis – Problem tree

This problem tree follows the recommended logical sequence of LFA. It is completed at the end of the initial analysis. Thus, the problems are refined compared to initial problem tree.

(4) Objective Analysis

The purpose of objective analysis is to reverse the negative problems which are identified in the problem analysis to positive objectives. Focal objective is the project undertaken to reach the goals set. Focal objective is reached by activities which are below the focal objective. These activities, through completion of focal objective, should lead towards desirable objectives. Desirable objectives are the main arguments to proceed with the project, as they illustrate the positives that go together with the implementation of the activities and the focal objective.

The final outcome of the problem analysis is the problem formulation. Areas to research in the theory chapter are based on the objective analysis. However, as it was already mentioned in the analysis of the project's context, LFA is not used solely to analyse the problem of CDW generation, as it is supported by supplementary methods which are introduced below:

Delphi method:

This method was used to supplement the process of creation of the initial problem tree, the problem tree and the objective tree. This process was inspired by the Delphi method as introduced by Helmer (1967) and Dalkey (1969). The Delphi method is suited for moments, during which a group of people needs to reach a consensus in an objective way. In Delphi method, this is assured through independent and anonymous answering – usually of a questionnaire. The method consists of as many rounds, as are necessary to reach a satisfactory consensus. After each round, the answers are evaluated by a facilitator and used for further rounds.

In the case of this thesis, the basis of this method was used to create every tree in the initial analysis. The group members would create each tree individually – without the contact of the other group member. When both group members finished, the similar answers were combined, and dissimilar answers were discussed, and a decision was made whether they are relevant to the problem or not, resulting in the final version of a given tree. Since there are only two members in this group, the role of a facilitator was not put in play. Since the answers were usually similar, it took only one round per each tree to reach a consensus, but the principles of the method were helpful for the creation of the trees without one group member taking a leading role, which could affect the objectivity of the result.

Literature review:

The process of literature review was used twice during the report. It was used during the initial analysis to research problems identified in the initial problem tree – getting a better idea about the problem in general. The following literature review was executed for a theory chapter, researching topics necessary to answer the problem formulation.
The method behind the literature reviews is based on Bryman & Bell, (2011). The main reason to conduct a literature review is to explore what is already known about the area of the interest, to simply not reinvent the wheel. Literature review allows for the extension of the original problem, as there are often found new questions, connections to other topics and related topics which could be overlooked otherwise.
Bryman & Bell suggest that there are two major approaches to conducting a literature review. These are systematic review and narrative review. The choice of the review is mostly affected by the choices made in the research strategy. As the outcome of this thesis is a new theory (inductive), it would be near impossible to create a systematic review – it is problematic to define scope, focus and limitations of the review as it is unknown when the literature review is initiated. As other choices identified in the research design lead towards qualitative research, narrative review is better suited. It does not limit the group members in the scope of the review and does not have to be as focused as systematic review.
The choice of the narrative review prooved to be suitable for this thesis. This is predominantly captured in the theory chapter, in which many areas of interest are reviewed as they become relevant to previously researched topics. This allowed the group member to build a concept and propose suggestions (and create theory) by a combination of many not directly connected theories in the discussion chapter. If a narrative review was used instead, this result would be impossible, as the area of interest would be too narrow to make such wide literature review in scope.
The source for literature reviews were mostly peer-review articles from databases such as ASCE Library, ScienceDirect, or Web of Science to name a few. To broaden the scope of the area of interest of a given article, the project group also followed references of the article to research more of a relevant literature. Apart from research articles, the project group used books as a source and few documents accessible only through internet websites.

PESTEL analysis:

PESTEL analysis was employed as the group members discovered that the CDW generation is in many aspects connected with the macro-environment. For the purpose of this thesis, a method introduced by Johnson, et al., (2017), is applied. This method allowed the group to analyse the macro-environment connected with the generation of CDW. The environment is analysed from the focus areas of Politics, Economy, Social, Technology, Environment and Legislation. This analysis allowed the group members to form a more comprehensive and more importantly, holistic understanding of the CDW generation problem. The findings of PESTEL analysis influenced the rest of the report, as it was possible to see the issues not only from the point of view of the directly involved stakeholders, but also holistically.
The group members aknowledge the desirability to source all the data in the PESTEL analysis,

but unfortunately, this was not possible due to the time constraint limitation of the thesis. However, the group members tried their best to provide generally known and accepted aspects of this analysis, to assure that both the reader and the group members have the same understanding of the given macro-environmental topics.

SWOT analysis:
This analysis is applied, mostly, to summarise the findings which occurred during the initial analysis. This analysis is inspired in the method introduced by Kousholt (2012) and Johnson, et al., (2017). All of these authors recommend to use this analysis to summarise and compare the internal capabilities of the company with the external aspects affecting the company. In the case of this thesis, there is no company in the focus, instead, it is the analysis of the issue of CDW generation. However, the SWOT analysis became a great tool to summarise all the data collected throughout the intial analysis and served as a basis to problem and objective analysis – bringing the group members a step further towards the creation of the problem formulation.

3. Initial analysis

In order to fully understand the specifics of EU construction market and its position in regards to the generation of construction and demolition waste, the project group adopts first four steps of logical framework approach (as it can be seen in the Figure 2 in the Reader's manual). The process of initial analysis starts with broad introductions in the form of a background into waste in general and specifically CDW. This is done in order to assure that both the reader and members of the project group share common understanding of the topic and current status in regard to waste. As it was already stated, the project group adopted the LFA in order to better analyse current situation. Therefore, as LFA allows, the project group updates the method according to their needs. The project group also conducts the initial literature review in order to better understand topics in close connection to CDW which are identified in the initial problem tree. These topics are public procurement, legal side of CDW, awareness of CDW, waste generation in design phase and waste sorting on construction site. In order to fully understand the situation, the project group uses different tools and models in order to gather information necessary for understanding the situation and localising the focal problem. The project group conducts PESTEL and stakeholder analysis and concludes them in a form of SWOT analysis. While SWOT analysis can be seen as unnecessary tool at first, in this situation, it presents a valuable part of the initial analysis. This is due to the ability of SWOT analysis to conclude multiple information into a simple diagram and to allow group members to organise their findings. Lastly, the initial analysis results in the final problem tree and the objective tree. While the problem tree serves as a tool to find focal problem and further formalise the problem formulation, the objective tree helps the project group to localise the desirable objective of the problem formulation.

3.1 Introduction to waste

The first part of this thesis (as illustrated in the Figure 1 in Reader's manual) is mostly about problems connected to the generation of construction and demolition waste (CDW).

Therefore, the definition of CDW is introduced in this part of the report already, to make sure both the reader and the project group have the same understanding. Remaining definitions are positioned in the corresponding chapter – Definitions, since these will become important for the theory chapter and succeeding chapters. This part of the initial analysis, apart from the definition, contains background to global waste and to construction waste. These background topics are the first part of the first step of LFA – the analysis of the project's context. This information serves as a basis to initial problem tree and following parts of the initial analysis. Mostly, this information served the group members to gain general understanding of the problem and to understand the problem in the same way, which is, also a goal of this this part of the initial analysis chapter for the reader.

Definition of construction and demolition waste

Waste, in general, is everywhere around us. It is generated by most of the processes connected to life on the planet. Waste can have physical form of trash, unused materials, or particles coming from processes; or be in abstract form of wasted time, finances and other. However, for the purpose of this report, the project group will be concerned only by the physical type of the waste in connection to the construction industry which will be referred as construction and demolition waste (CDW).

According to Lu, et al., (2016) CDW can be defined as:

"(…) material waste from all construction activities without confining to a certain stage of construction, renovation, or demolition."

One of the ways of categorising waste is presented by the European Waste Catalogue (Environmental Protection Agency, 2002) where CDW is categorised into 8 different categories according to materials. These categories are: (1) Concrete, bricks, tiles and ceramics; (2) Wood, glass and plastic; (3) Bituminous mixtures, coal tar and tarred products; (4) Metals; (5) Soil, stones and dredging spoil; (6) Insulation materials and asbestos-containing construction materials; (7) Gypsum based construction material; (8) Other construction and demolition waste.

For the purpose of this report, construction and demolition waste is defined as:

"Construction and demolition waste are all forms of material waste occurring from activities connected to construction in all stages of a project's life-cycle."

The alternation of the definition was done in order to cover the entire life-cycle of the projects. The definition presented by Lu, et al., is restrained only to construction, renovation and demolition. However, this is not sufficient for the purpose of this thesis, as phases such as design, production, maintenance etc. are not included.

Background to global waste

Waste has enormous impact on the environment and it affects all of us (EC, 2010). It is estimated, that there are seven to ten billion tonnes of waste generated every year, while around half of the waste is accounted to the traditionally high-income countries (Wilson, et al., 2015). The members of European Union are accounted for generation of up to three billion tonnes of waste annually. Environmentally, waste is connected to pollution, climate change caused by greenhouse gas emissions and to material losses. Material losses are rather important issue connected to waste for European Union, as EU is highly dependent on imported raw materials. (EC, 2010)

The resources that are available globally are not indefinite, indeed, they are finite. Yet they are depleted due to current establishment of how the economy and markets are set up. In the current thinking of linear economy, which is based on the principle of take-make-use-dispose, this is rational economic behaviour. (Portney, 2015) Current economy is driven by the need of continuous creation of products. (Andrews, 2015) However, such behaviour is well explained in *The Tragedy of the Commons* by Garrett, (1968): There is a pasture open to all herdsmen, and everyone is allowed to keep as many cattle as possible. Rational logic of each herdsman is to increase his herd to maximum to increase his wealth. However, once, there comes a moment, when the pasture reaches its limits, and the system collapses. It is this economic behaviour, which drives people to be self-interested towards their own good while ignoring the issues of the society and the environment.

During most of the 20th century, waste was looked at as an inevitable by-product of the modern times, as waste was necessarily associated with the economic development. The problems associated with the waste were only addressed as they appeared. It became clear at the end of the 20th century, that this growth is unsustainable and would result into irreparable damage to the environment. (Letcher & Vallero, 2011) Waste stored in landfills produces and releases greenhouse gases, such as methane. In addition to greenhouse gases, landfills are also prone to release heavy metals and chemicals in the form of leachate, which is a hazardous liquid, that can pollute soil and waters. On top of that, whether the waste is re-used, recycled, incinerated or landfilled, waste comes at both financial and environmental cost. It must be collected, sorted, transported and treated, which is expensive and results in greenhouse emissions and pollution of air, soils and water. (EC, 2010)

The majority of global population has started to realise, that nature cannot absorb the waste forever and that the resources are finite (Letcher & Vallero, 2011). The response by European Union is the *Landfill Directive* from 1999, which introduced new waste hierarchy of waste prevention, re-use, recycling and recovery and seeks to avoid landfilling (European Environment Agency, 2009). This is to ensure resource efficiency and sustainable growth of European economies, decreasing the dependency on supply of raw resources from outside European Union. This directive aims to provide European industries with supply of recovered materials to make new products. (EC, 2010)

Nevertheless, the current trend is to design as to not generate waste, because waste produced as by-product equals to missed opportunities to cut costs and to improve performance. In UK, waste typically costs companies 4% of their turnover in landfill costs. (Letcher & Vallero, 2011) The ignorance of waste management is costly both to the companies, but more importantly to the society and its economy. The goal is to move the thinking from waste management towards resource management, like the aphorism says: “One man's trash is another man's treasure”. (Wilson, et al., 2015) Or in this case, and as one of the fundamentals of circular economy, one man’s waste is another man’s resource.

Background to waste in construction industry

The construction industry is considered to be one of the biggest waste producers globally. Some of the researchers go that far to state that it actually produces the largest volume of waste across the globe (Osmani, et al., 2008). Amount of waste produced by construction industry is increasing annually, mostly due to the construction and renovation activities connected with the growth and transformation of the urban areas (Jailon & Poon, 2017), (Yang, et al., 2017).

The construction and demolition waste (CDW) is not only produced during the phases when construction of the project is carried out, but also during the whole life-cycle of the project. It is including design phase, construction phase, occupation & maintenance phase and demolition phase (Kozlovska & Spisakova, 2013). However, some of the researchers seem to agree that most waste is created due to the poor design decisions during the design phase (Magalhães, et al., 2017), (Akinade, et al., 2018).

Globally, most of the CDW is landfilled without any further treatment and therefore presents a significant problem (Bovea & Powell, 2016). In order to sustain natural resources and reduce costs connected to landfilling, it is necessary to ensure the possibility of recycling and reusing of construction materials with aim to decrease demand on landfills (Akinade, et al., 2018). Due to awareness of landfill problems, many countries tend to implement construction scheme disposal charging schemes (CWDCS) in order to decrease the amount of waste disposed into landfills and increase recycling rate (Lu, et al., 2015).

Based on the statistic of OECD (OECD, 2018), it is possible to rank CDW as the top source of the waste in whole area. According to statistics of the European Commission, approximately 25-30 % of the total waste in the European Union is consisting of construction and demolition waste (EC, 2018a). However, this number differentiates between the individual countries of the EU as it can be seen in the Figure 3:

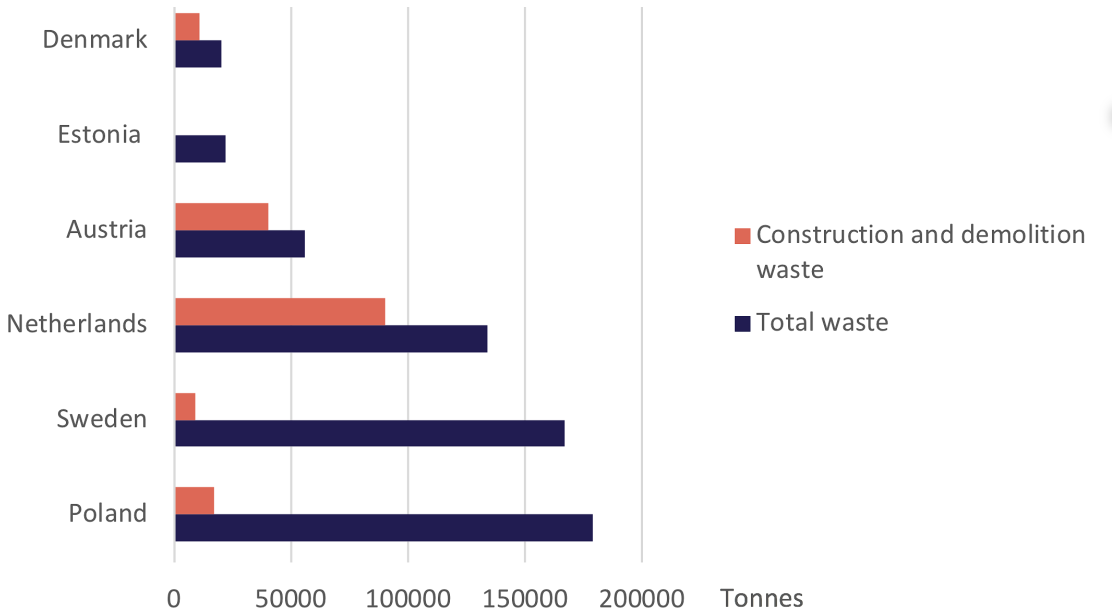


Figure 3 – Construction and demolition waste produced by countries compared to total waste production. Data based on OECD (2018)

Countries like Estonia, Sweden or Poland with their level of CDW below 10% of the total country waste suggest that there must be some sort of the solution to this global problem, others like Denmark (52,6%), Netherlands (67,3%) and Austria (72,1%) show how alarming the situation currently is. However, it can be stated that EU represents one of the better examples for the dealing with CDW. This is due to the environmental awareness of the member countries which agreed to set the target to recycle at least 70% of construction waste before 2020 (EC, 2010).

In Denmark, the situation regarding construction waste might seem optimistic. The country is fighting strongly against the waste disposal in the landfill. This is done by implementing one of the highest landfill taxes in the whole area (590kr per ton) and landfill ban for recyclable or combustible waste (CEWEP, 2017). Most of the waste in the country is recycled – 68% of total waste generated in Denmark is recycled. However, in case of CDW presented in the Figure 4, numbers are higher as up to 87% of construction waste is recycled and only 6% is incinerated and the same number is placed into a landfill. Historically, Denmark did even better when around 2000s recycled over 95% of the CDW, however, this number was lowered due to recent awareness of some hazardous materials (Miljøstyrelsen, 2017).

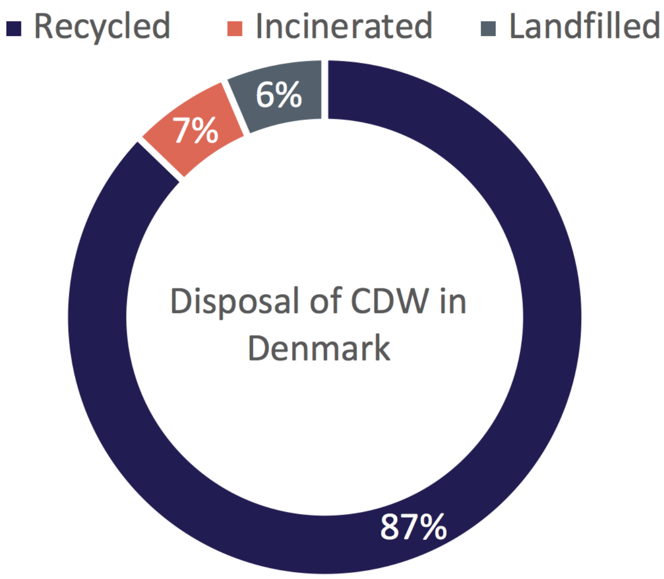


Figure 4 – Treatment of CDW in Denmark. Data based on Miljøstyrelsen (2017)

It might look like Denmark can be considered as the leader of a waste disposal, however, compared to the other countries like Sweden, statistics are less positive. This is due to Denmark constantly increasing amount of annually produced waste while their neighbours manage to slowly decrease this amount. Statistics are even more alarming as Denmark is still the biggest waste producer per capita in the whole EU (European Environment Agency, 2009).

3.2 Initial problem tree

Problem tree is, traditionally, the third step of the Logical Framework Approach (LFA). In this case, it was decided to begin the analysis with an initial problem tree, which was put together right after the preliminary information about waste got summarised into background parts of the initial analysis chapter of global waste and CDW. The final problem tree will be introduced at the end of the initial analysis. The initial problem tree was primarily conducted to make sure that both of the group members have the same understanding of the CDW generation problem. This problem tree is in the Figure 5 on the following page.

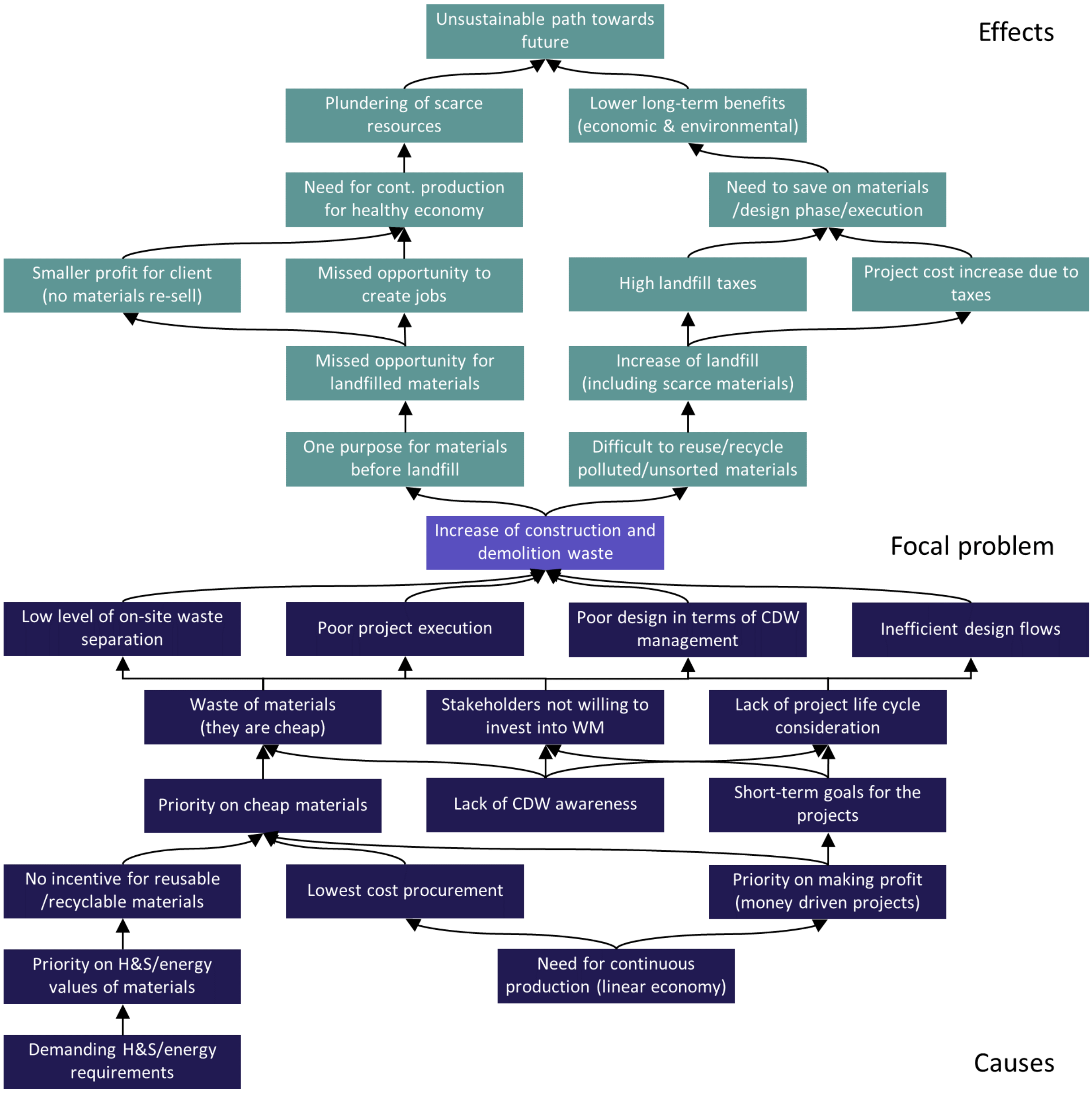


Figure 5 – Initial problem tree

In the following part of the initial analysis, many topics inspired in the causes of this problem tree are examined through initial literature review. Due to the lack of a literature base for some topics, they had to be altered, but that is explained in individual topics.
Although problem tree should follow after stakeholder analysis in LFA, initial problem tree served greatly to localise some of CDW issues.

3.3 Initial literature review

The purpose of the initial literature review is to explore causes identified in the initial problem tree and to continue in the first step of LFA, the analysis of the project's context. Causes, that will be introduced in this part of the initial analysis are: Awareness of construction and demolition waste; The connection between procurement and waste generation; Legal side of construction and demolition waste; Waste generation in design phase; and Waste sorting on construction site.

Awareness of construction and demolition waste

In the construction industry, there is only little awareness of saving resources and protecting the environment through waste management for both managers and contractors. They see waste management more as increase of the project cost, which results in lower profits. Instead of waste management, they tend to focus on cost, quality and timely delivery of their projects. However, the increasing level of awareness about construction and demolition waste (CDW) and issues it brings to the economy, environment and society is one of the main factors to minimise the generation of waste. (Lu & Yuan, 2010), (Osmani, et al., 2008) The top priority of European Union's Environment Action Plan is waste management throughout the entire project life-cycle (EC, 2010). This importance of the issue is emphasised by Gálvez-Martos, et al., (2018), who state, that new waste reduction approaches, which would take entire value chain into consideration are urgently required. There are many challenges connected to circular economy in the construction industry at the moment. These challenges, sorted according to importance of the perceived issue, are: (1) lack of interest, (2) awareness and (3) knowledge of circular economy (Adams, et al., 2017).

At first, increased awareness of harmful impact of CDW has led to the development of waste management as a function of construction project management. The increasing awareness of both CDW management and circular economy was captured through literature review, as both of the topics show linear growth in the number of articles published (Yuan & Shen, 2011), (Ghisellini, et al., 2018). The contribution to this research is mostly by developed countries, but developing countries, such as China and Malaysia begin to contribute more and more (Yuan & Shen, 2011).

During initial analysis into the topic of awareness about CDW in the construction industry, it was rather difficult to capture the overall state of the industry, mostly due to the fragmentation into various stakeholders, such as designers, managers, contractors, construction workers and so on.

Osmani, et al., (2008) during their research, came into findings, that designers believe, that waste management is not a priority in the design phase and that waste is mainly produced during site operations. However, architects are the ones who should explain the importance of waste reduction to their clients. The indications are, that the lack of engagement of architects is due to lack of understanding of good design to minimise waste and to a believe that waste is a priority of a contractor.

Unfamiliarity and the lack of commitment are two main factors for lack of implementation of waste management by contractors (Nobe, 2009).

Based on findings of Lu & Yuan (2010), neither managers nor constructors are sufficiently

aware of saving resources and protecting the environment. While managers are concerned with the cost of implementation of waste management (Tam, et al., 2017), (Lu & Yuan, 2010), the construction workers see the waste as an inevitable by-product, yet their attitude towards waste management is not negative, they are rather pragmatic due to managers' "commitment" towards waste management (Teo & Loosemore, 2001).
All the above-mentioned research proves how fragmented the industry really is, as there is clearly no agreement who actually is responsible for waste management.

The increasing awareness about CDW is a lengthy process. It requires vocational training of the practitioners by educated persons – it is being incorporated into courses in universities and research & governmental institution in order to convince the practitioners about the importance of CDW management. The awareness might also be enhanced by government policies, development of CDW management programmes inside companies and recognition of the importance of CDW management by the clients and public in general (Lu & Yuan, 2010), as there seems to be lack of will in the companies to implement CDW management (Tam, et al., 2017). This could be solved by either financial-based incentives or penalties for waste generation, but Mahpour & Mortaheb (2018) found that financial-based incentives provide better results. It was discovered, that students who have experience in construction industry from before they attend school, seem to put low priority on CDW management. They are undermined by their experience of lack of CDW inside the companies and might find it not applicable in the real world (Nobe, 2009).

However, spreading of the awareness might be promising way to reduce the amount of CDW generated. One of the successful cases of increasing CDW awareness to reduce waste generation was held by Jones, et al., (2012). They, during a period of two years, introduced staff training in environmental management, use of environmental teams and use of visual materials/aids (such as posters). Many of the construction workers were sceptical to the idea at first, employees delegated as environmental support were even made fun of by other employees in the beginning for pointing out how others can improve. Quiet absurdly, one of the most useful incentive were posters located by toilets, which received the highest attention. In the end, the incentive to increase the awareness of CDW resulted in decrease of waste generation and increase of materials recycled. (Jones, et al., 2012)

The connection between procurement and waste generation

The initial idea behind this topic was to examine whether bids tendered by lowest cost criterion result in generation of more waste than other bidding procurement types. However, this was not possible to examine due to lack of literature exploring such topic. The only article found close to the initial idea is about influence of various types of procurement methods on rework costs. The research, by Love (2002), concludes, that there are only minimal differences between various procurement methods, thus the differences are not relevant.

Instead, it was decided to shift the focus towards similar topics in this area. In research by Tam, et al., (2007) the authors assessed whether the material waste levels are affected by sub-contracting relationship. They examined three different sub-contracting arrangements, which are direct labour, labour only and labour and material arrangement, which are further explained in the Table 2.

Sub-contracting arrangements	Responsibility in material wastage
Direct labour	Main contractors provide their in-house staff to purchase materials directly. Hence, main contractors directly control and pay for the wastage.
Labour only	Main contractors purchase materials and sub-contractors provide labour force only. Hence, main contractors directly pay for the wastage.
Labour and material	Sub-contractors purchase materials and hire labour. But the main contractor indirectly pays for wastage through higher sub-contract prices.

Table 2 - Types of sub-contracting arrangements and their relationships to waste generation (Tam, et al., 2007)

The result is, that subcontractors hired only for labour generate most of the waste. The reason behind this is, that they neither pay for material, nor for waste. Since they do not pay for the waste generated, they are not interested in lowering of the CDW generation. The generation of CDW is lower both in direct labour and labour and material arrangement in comparison to labour only arrangement. In direct labour, main contractor has direct control over the payment for waste. In labour and material arrangement, main contractor pays for waste indirectly in the calculated price by subcontractor, thus, subcontractor's interest is to decrease the costs connected to the waste treatment to maximise his profits. (Tam, et al., 2007)

Most of the research on whether procurement might affect the level of waste generation is about procurement of materials, yet even this area was for long time widely neglected and was re-assessed only recently, so there are many more research questions to consider (Ajayi & Oyedele, 2018). It is estimated, that building materials wastage contributes to cost overruns by 21-30% (Ameh & Itodo, 2013). There are various reasons for material wastage, and although it seems like most of it happens during the construction process, large part is based on poor design and materials procurement (Ajayi & Oyedele, 2018). This is further supported by Gavilan & Bernold, (1994) and Formoso, et al., (2002). They see the root issue in procurement and managerial issues resulting in over-shipment, under-shipment or mis-shipment. Vrijhoef & Koskela, (2000) blame the waste generation on the uniqueness of construction projects, where a one-off approach is prevalent resulting in large quantities of waste. The proposed solutions are dedication and commitment to low waste measures and management by the stakeholders, effective materials delivery management and accurate materials take-offs. (Ajayi & Oyedele, 2018) Improvements in material wastage could enhance the construction industry's performance and bring cost-saving benefits (Ameh & Itodo, 2013).

Legal side of construction and demolition waste

One of the long-lasting debates in CDW management seems to be, whether it is more effective to minimise the waste through penalising or incentivising of the polluters (Mahpour & Mortaheb, 2018). As it can be expected, there are two sides to answer this question both having its own cons and pros. In this part, first, fiscal and legislative measures are examined, followed by incentivising to answer both sides of the question.

Government plays important role in developing policies to minimise CDW generation (Lu & Yuan, 2010), (Udawatta, et al., 2015). The key drivers of sustainability in construction industry are legislation and fiscal policies. In European union, construction waste is mainly targeted through two legislations, first is the *Waste Framework Directive* (WFD) from 2008 and the second is the *Landfill Directive* from 1999. (Ajayi & Oyedele, 2017) Since these are directives, it is down to each member of European economic area to transpose them into their national legislation. If the targets are set, and the directions are followed, it is down to each country to set their own rules how to reach the target of the directive. There are many crucial aspects of WFD which are relevant to construction industry, such as obligation to re-use or recycle minimum of 70% of non-hazardous CDW, excluding naturally occurring materials by 2020; sorting of materials for re-use and recycling; ban on mixing hazardous waste with other waste; control of hazardous waste; and in general, to move European towards recycling society. (Sáez, et al., 2011), (EC, 2008) Landfill directive sets rules to create and control existing and new landfills (EC, 1999). However, it is down to each country, whether they decide to penalise or incentivise the polluters.

In many nations, “Pay as you Throw” principle proved to be successful to reduce landfill volumes (Ajayi, et al., 2015). Under this principle, the polluter pays depending on the quantity of waste landfilled, which could be further graded based on the contamination of hazardous instances.
One of the countries to first deploy this principle is United Kingdom with its *Landfill Tax* (Ajayi & Oyedele, 2018). It reduces landfill disposal, and part of the funds collected is used to promote sustainable waste management. The implementation of the landfill tax was the much-needed change to increase the awareness of waste disposal and proved to be successful in reducing disposal of waste. (Morris & Read, 2001) Countries with high recycling rate often deploy high price penalties for waste disposal. In countries with low landfill prices and small or non-existing penalties for breach of the rules, there is missing incentive to recycle (Sáez, et al., 2011).

It was not until 2017 till first research touched the idea that construction industry practitioners should be part of waste management policies development (Ajayi & Oyedele, 2017). This has sparked the interest of other authors leading to a different viewpoint as how to reduce waste through legislation. The experts recommend providing financial incentives and tax breaks to good waste performers (Ajayi & Oyedele, 2017). Experts prefer financial-based incentives to fees and fines, as based on the results, financial incentives have better results than penalising. (Mahpour & Mortaheb, 2018) However, it seems that in construction industry, financial incentives do not function solely. Even experts, among other recommendations, suggest increasing fines for poor waste management (Ajayi & Oyedele, 2017). As most of the decisions in construction industry are based on the profit generated, the commercial reality behind the project is still the main determining factor. Project participants (clients, designers, subcontractors, etc.) generally do not support waste management, due to the profit-driven industry and price competitiveness of the market. It is suggested, that it is necessary to enforce waste management legislation across the entire supply chain. (Udawatta, et al., 2015) This might be done, for example, by companies including CDW management into their policy to change the attitude of project managers towards waste management (Yuan, et al., 2018).

Waste generation in design phase

Due to the design, phase planning, and analysing of a construction project ahead of time, waste minimisation design is often considered to be critical for lowering of CDW. (Baldwin, et al., 2009). Many researchers tend to see a reason for the high amount of construction and demolition waste in the improper design (Ding, et al., 2018). Therefore, an increased number of studies look at the problem of a design impact on the construction waste. However, with many different phases of a construction project, where construction waste management (CWM) was implemented, the design phase still stays the one with a limited implementation of waste minimisation (Dickerson, 2016). On the one hand, most of the studies in the field of waste minimisation focus on practical steps of lowering waste generation and an increase of material reuse on site in the construction phase. On the other hand, studies of impact on CDW during design phase are based more on theory. This is due to a designer’s attitudes towards waste reduction, constraints of waste minimisation or new waste reduction technologies (Wang, et al., 2014), (Ding, et al., 2016), (Ding, et al., 2018). However, according to Ding, et al., both of these topics are closely connected, as changes in design can have a severe impact on the construction and, therefore, they should be also analysed in close connection (Ding, et al., 2018).

In their study, (Wang, et al., 2014) tried to analyse and find the most significant success factors (SF) for minimisation of CDW. Based on the results of their study they ranked the six most important SF necessary to decrease generation of CDW. These are: (1) Usage of large panel metal formworks, (2) Usage of prefabricated components, (3) Limited or no design modification, (4) Modular design, (5) Waste reduction investment, (6) Economic incentive.

Based on the information found, it can be stated that generation of construction waste in the design phase is seen as a vital problem of many construction projects. Therefore, this subject is worth to be considered and further developed by the project group for the purpose of this semester project.

Waste sorting on construction site

As it is described in the definition of construction and demolition waste, CDW is consisting of various materials with different properties. Unfortunately, only on rare occasions, this waste occurs in a separated form. More often, these individual materials are mixed together. Therefore, waste should be sorted to assure the further possibility of recycling these materials. However, the nature of these materials often makes this process to be difficult and resource consuming (Wang, et al., 2010).

Nevertheless, even in situations where contractors are aware of the benefits from sorting of construction waste, they are still reluctant to do so due to difficulties connected to the on-site sorting of CDW. These were mostly represented by limited site space, low management efforts, labour and cost necessary for effective on-site sorting and interference with everyday activities on site. (Poon, et al., 2001) Other reasons for reluctant stand towards on-site sorting were an inability to sort some materials, lack of best practices and negative attitude towards sorting (Wang, et al., 2010).

On-site sorting of CDW presents clear benefits in comparison to off-site sorting. As often some materials found during on-site sorting can be repurposed and reused during the process of construction and, therefore, it can minimise the need for transportation and waste disposal (Poon, et al., 2001).

Based on the findings, the project group found that waste sorting on-site still represents a problem on some of the construction sites. However, due to the legislation and environmental awareness, it cannot be considered as a vital problem.

3.4 PESTEL

As a part of the initial analysis, the project group decided to conduct a PESTEL analysis as a part of the first step of LFA – the analysis of the project's context. In this analysis, individual focus areas of Politics, Economy, Social aspect, Technology, Environment and Legislation were researched in order to gain a holistic understanding of construction and demolition waste as a problem in a macro-environment. This was done based on the literature review aimed at six aspects of PESTEL analysis together with a common knowledge of the group members in connection to CDW problem and its environment. However, due to the time and resource constraint of this report, it was not possible for the group to conduct an intensive study in order to validate results of PESTEL analysis, therefore results provide only insight to project group understanding of the problem with connection to existing literature and other materials.

Political

As the main goal of a political aspect in PESTEL analysis is to understand the impact of the political situation on the existing problem (Johnson, et al., 2017). The project group analysed different political movements which are affecting situation connected to CDW or waste in general. Project group mainly focused on the area of the European Union as this is related to this case study. However, other areas of interest were also considered in order to understand possible future trends.

It is obvious in the policy of the European Union that the member states are fully aware of problems connected with the generation of the waste. This impacted also a creation of different directives which are trying to slowly decrease this acute problem. One of the most significant is the Landfill directive which was created in 1999 and implemented in 2001. This directive sets a goal to member states to slowly decrease usage of landfills (EC, 1999). Another significant document is the Waste Framework Directive (WFD) from 2008. This presents one of the most crucial goals, which are currently set for CDW in the area of EU. The goal is to recycle 70% of non-hazardous construction waste by 2020. WFD also promotes general sorting, control and recycling of construction waste (EC, 2008). Lastly, at the beginning of 2018, EU presented its new political programme called Circular economy package. This is currently focused mostly on the communal and packaging waste. It is focused on the way how products are designed, produced, used, recycled and a product life-cycle in general (EC, 2018b). Based on these initiatives of European Union, it can be stated, that political organisations are fully aware of the need to take steps in order to decrease waste production. While European Circular economy package is not fully focused on the construction industry in the present, it shows the trend and, therefore, it is only a matter of time when some sort of similar directive will be fully focused on the construction industry, as it is the biggest waste producer in general.

However, directives are representing only general goals for the countries and it is up to member states, how these goals are achieved. In the case of Denmark, it can be considered as one of the better countries in regard to CDW management, as sorting facilities for CDW are currently forced on construction sites by law (The Danish Ministry of Economic and Business Affairs. Danish Enterprise and Construction Authority, 2010). It is also banned to landfill all materials suitable for incineration or recycling (CEWEP, 2017), and individual municipalities are supporting projects for recycling waste. The proof of that is new state of art waste sorting facility which is currently built in the city of Copenhagen. Facility is focused on supporting circular economy, where different types of waste can be handed for recycling and repairing process. As a way of supporting the idea of recycling, at least 50% of the construction is going to be made from recycled materials (COWI, 2018).

Political decision and pressure are most commonly transferred onto society by legislation and taxation. These are considered to be one of the most important drivers on a way to waste minimisation (Osmani, 2012).

Economical

It is hard to establish what is the economic impact of the current level of CDW generation. This is due relatively still relatively new environmental movement in the construction industry, offering a limited amount of statistics and varying classification of waste by the members of EU.

One of the certain impacts of the construction and demolition waste on the economy is through the landfill tax. Landfill tax is a tax implemented in order to decrease waste accumulation in landfills. It is paid by every tone of waste placed in the landfill. Landfill tax is currently implemented in nearly every member state of EU and many other countries. In Denmark, the current tax presents price of 600 DKK per tonne of landfilled waste. This represents third highest tax in the whole EU after Austria and Belgium (CEWEP, 2017). According to statistics in 2014, the construction industry in Denmark generated 9,4 mil. tonnes of construction waste (OECD, 2018). Around 6% of this waste was landfilled (Miljøstyrelsen, 2017). That means, that in 2014, there was around 339 mil. DKK paid on landfill taxes in Denmark. That represents 0,15% of total turnover for the whole construction industry in the country which represents 221 billion DKK (Danmarks Statistiks, 2014).

While 0,15% represents a small percentage, according to different researches, savings provided by more ecological ways of constructing with low waste production can be significant. According to the case study conducted by Waste & Resources Action Programme, it is possible to save around 0,77% of total construction cost by reducing waste generation in construction (Waste & Resources Action Programme, 2015).

Another step further in creating an economic advantage in regards to CDW might be implementing of the circular economy into the process. Based on the research conducted by Sobotka & Sagan (2016), the savings connected to the full adaption of the circular economy are notable. These savings are mostly connected to the savings in regards to the further processing of a CDW (Sobotka & Sagan, 2016).

Based on the economic aspect of CDW on the environment, the project group found a significant impact of CDW on the total cost of construction. While percental share might sound small, 339 mil. DKK paid only on landfill tax annually shows how big the problem actually is.

Social

Construction and demolition waste presents a problem not only for governmental agencies but also for the wide public as there is an increasing concern in regards to CDW (Osmani, 2012). There is a visible increase in the pressure for decreasing our environmental footprint on this planet. This is also closely connected with the generation of the waste. This public pressure is standing behind many new movements which are occurring in EU but also globally. Zero waste lifestyle or implementation of the circular economy are becoming more and more popular. This is also transferred to the legal policies implemented by the government.

In Denmark, situation in regard to social awareness is closely connected to the program *Denmark without a waste I and II*. With its two different stages, the program is growing public awareness of waste as a big problem in Denmark (The Danish Government, 2013).

With this change in general public understanding of waste as a problem, comes impact on the industry sector. Companies are well aware of a possibility to increase their position on the market through building a better name by waste minimisation (Gangolells, et al., 2014). Another proof is companies' willingness to pay for waste minimisation. Research conducted by Lu, et al., (2015) showed that most of the stakeholders participating in construction projects are willing to pay more for waste sorting and recycling that they are actually paying.

Based on the increasing popularity of environmentally friendly lifestyle of people and companies willing to invest into the waste reduction, it can be said that current social aspect of the environment is hungry for minimisation of waste in general and, therefore, also CDW.

Technology

In regard to technological standards, possibilities to recycle waste are better and European states are recycling more than any time before. The statistics are getting better and better every year. This is valid not only for general public waste but also for construction and demolition waste (European Environment Agency, 2017).

Currently, Denmark is able to recycle around 87% of CDW. This number is considered to be very high, however, around the year 2000, Denmark was able to recycle over 95% of CDW. The reason for lowered amount of recycled waste are negative effects on environment from recycling of some hazardous materials (Miljøstyrelsen, 2017). Therefore, it can be stated that while technologies for recycling are nowadays better than ever before, we are still unable all the materials.

Recycling is one of the ways of reducing the CDW footprint on the environment, however, other possibility is to lower production of waste in general. While Denmark is increasing amount of waste produced by country on annual basis, Sweden is showing the possibility to decrease these numbers every year. While both countries are trying to be environmentally friendly, both took a different stand on the way how to deal with the waste (OECD, 2018).

Lastly, new systems or styles of recycling become more and more popular. One of them is implementing a circular economy. While by itself, the circular economy is not providing technology, it is taking advantage of technologies which are currently accessible. Circular economy adopted the idea of repurposing materials and products at the end of their life-cycle. This is especially valid for the construction industry, where, many of the materials have a varying lifespan and therefore can serve long after building demolition. One of the leaders in the implementation of the circular economy is construction company Balfour Beatty, which is implementing circular economy into most of their construction projects. Construction project of St. James Market can be considered as one of the best examples of Balfour Beatty's attempt to implement circular economy into construction process. During the demolition phase, contractor managed to highly increase the recycling rate of demolished material with over 98 % of it reused. The company is also participating in different projects where they try to decrease waste generation through repurposing and recycling most of CDW. (Toyne, 2016)

Environmental

Our planet is currently struggling in regard to its environment. Increase in awareness of global problems is visible from all sides. Recently UN and its organisation Intergovernmental Panel on Climate Change (IPCC) published the *Special report about global warming*. The main goal of the report is to bring higher focus on decreasing human footprint on the planet. This is due to the catastrophic expectations of scientists if the status quo is kept (IPCC, 2018).

However, UN is not the only organisation which is concerned about the environment. EU is standing behind different directives and packages in order to decrease the ecological footprint of the population. Waste, in general, is one of the biggest concerns in regards to environmental issues. Only EU is responsible for an annual generation of up to three billion tonnes of waste. This is closely connected to the pollution, the greenhouse effect and loss of raw materials. (EC, 2010).

Regarding waste generation, the construction industry is considered to be the biggest producer of waste globally (Osmani, et al., 2008). While many other industries are slowly decreasing waste generation, construction is going in the other direction with annual growth of waste production. This is, mostly, due to constantly growing population and cities (Jailon & Poon, 2017), (Yang, et al., 2017).

Globally, most of the CDW is landfilled (Bovea & Powell, 2016). This is considered to be one of the worst options in regard to dealing with waste. The reason is the higher risk of soil and groundwater contamination with landfilled waste. Another reason is a space consumption of the land by landfills as some of the areas might offer limited space (Lu, et al., 2015).

With increased awareness of landfill problems, countries are implementing policies to stop landfilling of waste. In the case of Denmark, there is a general ban on landfilling of all waste which can be incinerated. This leads to another popular way of dealing with all types of waste – incineration (Miljøstyrelsen, 2017). While this method is not raising so much of concern in regards to soil and water contamination, incineration process emits a significant amount of greenhouse gases which impact global warming. This is even more worrying as the incineration rate is increasing globally along with raising number of waste generated annually (Hwang, et al., 2017). Another impact of incineration is on human health. This is due to polluting particles generated during the process of incineration, which present a significant risk in regard to human health (Health, EOWIC, Board, OESAT, & National, RCS 2000, 2000).

Based on the findings it can be said that the planet environment is currently in the worst state ever. Environmental catastrophe might seem inevitable and, therefore, there is a strong need to decrease the global footprint of humans in order to minimise our impact on the environment.

Legal

The legal part of PESTEL is strongly connected to political aspect. This is due to the government being a political body of a country, responsible for the creation of legislative. As it was already mentioned, public bodies are clearly aware of the current bad situation in regards to waste as the environmental problem.

One of the biggest legal movements is visible in the area of EU. This is represented mostly by directives which were agreed by the majority of member state countries and, therefore, become the backbone of EU movement to lower waste future. One of the most important ones is the Landfill directive from 1999 (EC, 1999). The main goal of this directive is raising awareness of problems closely connected to waste landfilling and collectively work on minimisation of this problem. However, as EU directive has no legal power in individual member states, it is up to states to find out a way of directive implementation into the state's legislative. Up today, most of the 28-member states of EU implemented landfill taxes in numerous levels together with strict landfill bans for various types of waste. Denmark's stand represents strong position with a general ban on landfill for all waste which can be incinerated and 3rd highest landfill tax in the area of EU (CEWEP, 2017).

Another significant directive signed by EU member states is the Waste Framework Directive from 2008. This directive is also concerned about the specific problem of construction and demolition waste. It is setting a goal to increase the recycling rate of CDW up to 70% before 2020. It is also promoting waste sorting and recycling of the materials on the site (EC, 2008).

Additionally, CDW is regulated by legislation by the obligation of waste sorting on the construction site. Danish Building Regulations 2010 already stated the need to have individual sorting facilities placed on the construction site (The Danish Ministry of Economic and Business Affairs. Danish Enterprise and Construction Authority, 2010).

Currently, EU presented a new circular economy package. A new movement of the EU is currently not promoting any specific legislation which should be implemented by member states, however, it is only a matter of the time when countries become more and more interested in new ways of forcing better waste disposal schemes (EC, 2018b).

PESTEL Conclusion

Based on all of the six aspects of the PESTEL analysis, the project group came up with findings in regards to the connection of macro-environment and CDW. Based on the environmental aspect of PESTEL, it is clear, that the environment is in bad shape and it is necessary to undergo strict and fast steps in order to decrease the impact of a waste pollution on the planet. This is also supported by the social pressure of the public with the new lifestyle of low waste policies. In regard to the political aspect, it is clear that governmental institutions are fully aware of existing problems. Therefore, they are trying to improve the current state of the situation with the implementation of different legislation. The project group also found various financial benefits in the implementation of new waste management schemes which offer higher recycling and material repurposing rates. Lastly, but not at least, looking into the technological aspect of PESTEL the project group found that technological possibilities of dealing with CDW are better than ever before and further development of technologies is expected.

3.5 Stakeholder analysis

Stakeholder analysis is the second step of LFA. The purpose of this analysis is to first identify stakeholders relevant to CDW generation and then analyse whether their influence is direct or indirect. This is based both on literature review and generic understanding of construction industry.

The identification of stakeholders relevant to construction industry with effect on generation of CDW is based on research of Lu, et al., (2015). This research is used as a basis for the list of stakeholders, because it takes into consideration stakeholders relevant to construction waste management. They identified 9 unique stakeholders who take part in the level of waste generated. For the purpose of this report, the list was slightly altered. Subcontractors and material suppliers were divided, as they differ too much for the purpose of this analysis. On the contrary, environmentalists are merged together with general public, as their role in this analysis is similar.

For this analysis, following stakeholders are identified and analysed:
Public or private clients, designers (architects, engineers, etc.), client advisors, main contractors, subcontractors, material suppliers, CDW recyclers, regulators, and public. (Lu, et al., 2015)

Stakeholders are first analysed through a literature review. Then, it is elaborated, what influence the stakeholder holds to affect the level of CDW generated. After that, it is explained whether the influence of the stakeholder is direct or indirect together with some examples. These also include explanations of the group members for better understanding of the topic. At the end of the analysis, stakeholders are placed on a stakeholders' card and relationships between stakeholders are illustrated.

Public or private clients:

Clients are the ones who pay for the execution, often even entire life-cycle cost, of a project. What some of them might overlook is the cost of waste generation. However, the clients are the ones, who ultimately bear the costs of WM (Lu, et al., 2015). Waste produced during construction, maintenance and demolition is also representing a cost, but not as visible as other expenses, such as cost of materials or labour. It is in the interest of clients to implement WM for their projects, as it can save them money, it prospers the environment and increases the image of the client towards general public.

Since clients are the ones paying for a project, they steer the way the project is executed. This gives clients great power to influence the level of CDW generated. They set the standards for stakeholders to meet (Akinade, et al., 2018). They have the opportunity to include WM into the tender requirements. However, many of clients are not aware of the CDW problem. Osmani, et al., (2008) goes as far as saying that clients are under-educated or even ignorant about the issue of CDW generation.

Clients affect CDW generated both directly and indirectly:

Directly, by having last-minute changes in the design of the project, which contributes to level of waste generated enormously (Osmani, et al., 2008), or by requirements for a non-standardised design or solutions.

Indirectly, on the one hand, it is poor communication with other stakeholders and ignorance to pay for WM by the clients, which affect the level of CDW generation. On the other hand, clients can affect CDW minimisation through requirements for WM or waste minimisation design.

Designers:

As it was already touched upon in the topic Waste generation in design phase, improper design results in high amount of construction waste (Ding, et al., 2018). Waste minimisation design is critical for lowering of CDW (Baldwin, et al., 2009). Generally, it is accepted by the literature, that the best approach to WM is minimisation through a design.

It was proposed by Akinade, et al., (2018), that one of the responsibilities of designers should be to ensure that waste is considered as a priority. There are many authors, such as Coventry & Guthrie (1998), Osmani, et al., (2008) and Akinade, et al., (2018), who believe, that designers should be the ones to explain benefits (both economic and environmental) of WM to clients. This is reasonable, because designers are often the first professionals who clients meet with when considering a construction project. Contrary to designers, clients might be unaware of CDW issue.

The influence of designers to minimise the level of waste generated is great. It can be considered even greater than of the clients. The role of designers is critical when considering the level of CDW generated. After all, they are the ones who design the building. The design affects stakeholders such as contractors, facility managers, demolishers and so on. However, to fully use the potential of designers, they must be supported by clients. Still, since designers have the power to convince clients to implement WM, their perceived power to influence the level of waste generated is higher, that clients have.

Designers affect CDW generated both directly and indirectly:
Directly, they affect it by poor design, design and construction errors and design changes (Osmani, et al., 2008).
Indirectly, designers have the power to convince other stakeholders (predominantly clients) to employ WM and waste minimisation design.

Client advisors:
In terms of influence towards minimisation of level of CDW generated, client advisors play similar role as designers. In this sense, they often have even greater influence than designers, as they are usually the closest stakeholder to the client when asked for advice. Therefore, they should take the responsibility to inform clients about the benefits of WM, in case the designers do not bother.

Client advisors affect CDW generated indirectly:
Just like the designers, they should inform clients about the potential benefits (both economic and environmental) of WM. They can convince clients to implement WM into tender documents, to employ WM during the project execution and to ask for waste minimisation design, as for some examples.

Main contractors:
Contractors, in general, are often blamed for the waste generated. The architects believe that contractors are liable for waste minimisation (Osmani, et al., 2008). Contractors argue, that they are not the ultimate polluter, as they only provide service of building, to their clients (Lu, et al., 2015). As construction companies need to make profit, it is rational that they want to avoid additional costs connected to WM, making contractors reluctant towards implementation of WM measures (Hao, et al., 2008). The contractors often allow for considerable amount of waste to be generated, because it is cheaper for them than put human resources to solve the issue of waste generation (Poon, et al., 2004). Main contractors often pass their responsibilities down the subcontractors, the process is further explained below.

Compared to other stakeholders in this analysis, the ability to influence the level of CDW generated by contractors is partial. Contractors hold no power to influence waste generating activities preceding the actual execution of the building, such as poor design in terms of waste management, which might lead to unnecessary amount of waste generated. The area where contractors have the power to influence the amount of waste generated is on a construction site.

Main contractors affect CDW generated directly:
They are in contact with physical materials. They influence the amount of waste generated on site, for example through sorting of the materials, ordering only the necessary amount of materials or educating their employees about WM. As main contractors often opt to pass their responsibility to control waste down to the subcontractors, they can influence the level

of CDW generated through the type of arrangement between main contractors and subcontractors (Tam, et al., 2007).

Subcontractors:
In the hierarchy of construction projects, subcontractors are very low. The responsibility for waste generation is often passed to subcontractors by main contractors (Johnston & Mincks, 1995). Subcontractors are keen to take the responsibility at no additional expense due to competition in the market, and this applies even to labourers hired by subcontractors, as the labourers are willing to take the responsibility from subcontractors (Poon, et al., 2004). As it was already touched upon in the topic The connection between procurement and waste generation, the amount of waste generated by subcontractors depends on the contract involved between the parties.

The way how subcontractors influence the level of CDW generated is very similar to main contractors. However, since subcontractors are very low in the hierarchy of the construction project, their influence is even lower than of main contractors. Designers and main contractors determine the design and scope of work of subcontractors. On top of that, due to high competition in the market, subcontractors often have to bear the responsibility of waste generation of a main contractor. Since they have to be competitive, there is no much room for WM improvements.

Subcontractors affect CDW generation directly:
The way how they affect the level of CDW generated is very similar to main contractors, but since their bid must be competitive, they do not have enough financial room to implement WM and they miss the incentive to do so by themselves alone.

Material suppliers:
Compared to other industries, the supply chain in the construction industry is the least innovating. While other industries managed to implement schemes such as LEAN or JIT, this does not happen in construction. This is partly caused by fragmented nature of the industry, and one-off approach to materials procurement, due to every project being unique. This leads to large quantity of waste. (Vrijhoef & Koskela, 2000) However, this is improving slowly, as the need for more efficient supply chain management is eminent. The industry is further now, as it was in year 2000. The suppliers are more willing for implementation of various delivery schemes and become more environmentally conscious.

Material suppliers have partial power to influence the level of CDW generated. If they are given initiative from clients, suppliers can affect the level of CDW generated greatly. However, if a client is ignorant of the issue, the power of suppliers is limited, yet they still have many options how to influence the CDW generation.

Material suppliers affect CDW generated both directly and indirectly:
Directly, suppliers can reduce waste by better handling of the materials to reduce waste generated by damages to materials before assembly (during packaging, loading or delivery) (Gavilan & Bernold, 1994). They can also pre-cut materials before delivery, allow for delivery of small quantities of materials and reduce the amount of packaging (Ajayi & Oyedele, 2018). Indirectly, suppliers can reduce waste by more efficient material take off in form of bill of

quantities, preventing under or over ordering resulting in waste. They could provide a take back scheme for packaging, unused materials, reusable, and recyclable materials. Material suppliers should supply quality and durable products. (Ajayi & Oyedele, 2018)

Construction and demolition waste recyclers:
By 2020, it was agreed in *Waste Framework Directive* (WFD) that every country belonging to EEA will recycle minimum of 70% of construction waste (EC, 2008). This was an impulse for recycling facilities to prepare.
In general, most of the materials in CDW are either reusable or recyclable, but the materials must be separated first, which is usually done on-site. However, in the construction industry, profit is always the priority, thus such reusing/recycling must be economically feasible to happen. Most common material recycled by weight is concrete rubble, which is usually used as an aggregate for roads. Bricks are easy to reuse, as long as they are not polluted (with mortar for example), because if polluted, it is cheaper to make a new brick. Both ferrous and non-ferrous metals are commonly recycled and used as a new resource. Paper and cardboard make up the most of waste by volume, making it a target for recyclers. If handled properly, even glass can be reused, but often it is recycled. (Tam & Tam, 2006)

The need for reusing/recycling facilities is questionable. The main goal of the WFD is to move EU closer towards recycling society, yet from the initial literature review it is clear that to avoid generation of waste the society should design waste out. It is assumed, that this directive is only a step between current state of the waste issue moving towards no-waste society. However, if the pressure will be on designing out waste, what use will these facilities have?

Recyclers have very limited options how to influence the level of waste generated. They are the last in the hierarchy of waste. They receive waste and it is down to them how much they can manage to recycle. They are dependent on legislation being in their favour. Other stakeholders can help recyclers through on-site sorting and not landfilling.

CDW recyclers affect CDW generated directly:
In this case, however, they rather save waste from being landfilled, than generate waste by themselves. The number and accessibility of recycling facilities affects the amount of waste recycled. The technologies of these facilities determine the ratio between recycled/incinerated and landfilled materials.

Regulators:
Regulators, through introduction of legislative and fiscal measures, are one of the most important stakeholders when it comes to drivers behind waste minimisation (Osmani, 2012). As this was already touched upon in the topic Legal side of construction and demolition waste, there is no need to examine this stakeholder again, as the necessary information about legislation is presented already.

Regulators, through legislation, have an immense influence on the level of CDW generated. They are the ones who push rules which have to be followed. Till this stakeholder, clients seemed to be the one with the highest influence on the level of CDW generated, since the client is the one with money. However, even client has to follow legislation. Regulators are usually the ones who drive the way CDW is handled.

Regulators affect CDW generated indirectly:
The regulators do not produce CDW by themselves. Through legislation and various policies, they affect all the stakeholders of construction industry. However, it was already pointed out, that regulators still fail to impose responsibilities on architects to minimise waste in the design phase, which is much more practical way of waste minimisation, than minimisation measures during construction, when it is too late already (Osmani, 2012).

Public:
As both environmentalists and the general public have similar influence and affect towards the level of CDW generation, it was decided to merge these two together and refer to them as public.

The enormous power of public is illustrated by the case of Brent Spar, in which Shell U.K. wanted to dispose of oil storage buoy through deep-water disposal. However, environmentalists from Greenpeace raised awareness and through the power of general public forced Shell U.K. to dispose of the buoy in more environmental way. This is important, because the deep-water disposal was already approved by government, and still, general public managed to make the company to change the plans. (Zyglidopoulos, 2002)

There is increasing concern in public about the CDW (Lu & Yuan, 2010), (Osmani, 2012), (Yuan & Shen, 2011), (Udawatta, et al., 2015). This concern translates into measures taken by construction companies or considering adopting such measures. Companies are aware that the practice of waste minimisation can increase their public image in form of CSR, thus, their competitiveness (Tam, et al., 2007), (Gangolells, et al., 2014).

The influence of public, as it was illustrated in the Brent Spar case, can be enormous. In construction industry, the importance of awareness of public about CDW is important in the sense, that there are many private clients, and as it was already examined, it is crucial for clients to be aware of CDW to influence the level of CDW generated.

Public affects CDW generated indirectly:
They can do this through different techniques, such as pressuring at politicians (government) to improve legislation. Public can also stagnate construction projects, if unsatisfied with the way of execution. They can even target entire company to change their WM. Public should not be overlooked.

Stakeholders' card:
Stakeholders' card on the Figure 6 on the following page is the summary of the stakeholder analysis in terms of influence of stakeholders towards CDW generation and whether they affect the CDW generation directly or indirectly. This method is inspired by Kousholt's (2012) stakeholder's card. However, for the purpose of this stakeholder analysis, different axes are used. Horizontal axis illustrates the level of influence of the stakeholder on CDW generation and vertical axis illustrates, whether the stakeholder affects the CDW generation directly, or indirectly.

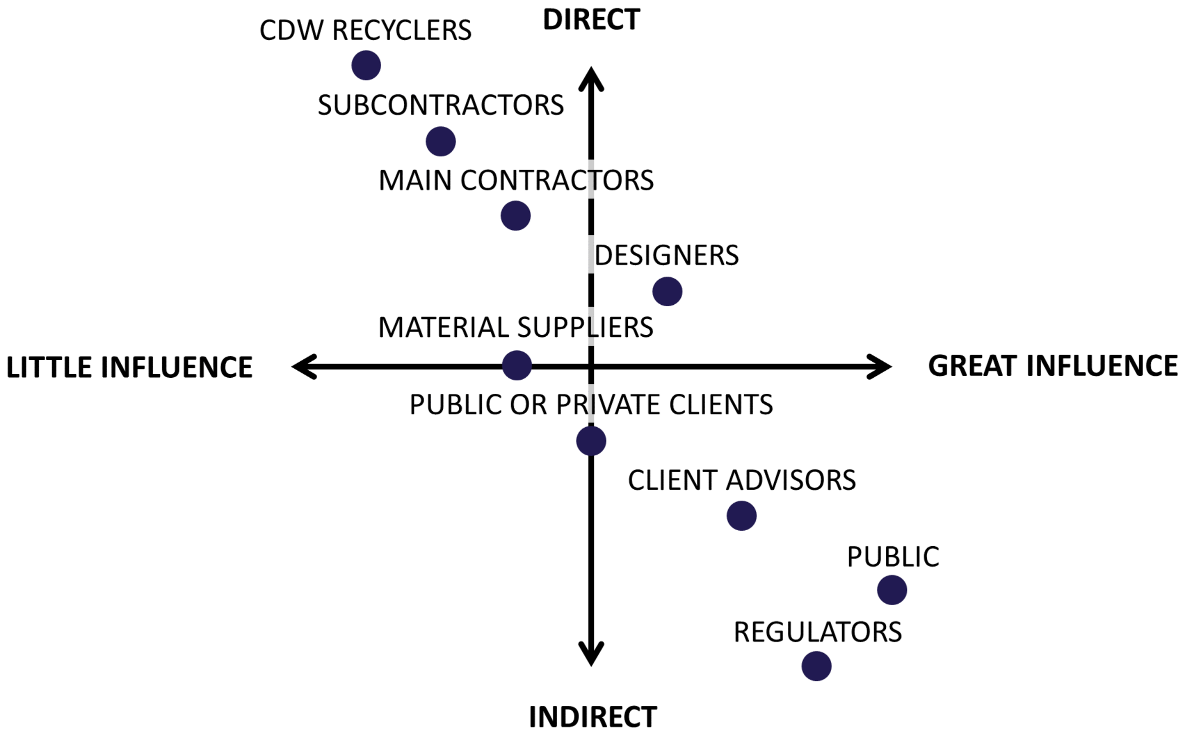


Figure 6 – Stakeholders' card illustrating the influence of stakeholders to affect the level of CDW generation

The position of the stakeholders on the card is determined based on the findings in the stakeholder analysis. The stakeholders are not sorted based on quantification, instead, they were sorted one by another based on perceived influence found both by the literature review and experience of the group members with the construction industry.

The stakeholders' card revealed a pattern between influence and whether the stakeholder affects the generation of CDW directly or indirectly. The pattern indicates, that closer the stakeholder is to the actual physical materials, lower is the stakeholder's influence. This is supported by the literature reviewed, which advises to minimise waste in the design and planning phase, because it is already too late during execution and subsequent phases of the project.

From the findings, it is possible to see that public and regulators have the highest influence towards CDW generation, however, they are not directly connected to certain projects. Stakeholders with highest influence on given projects are advisors and designers and should inform clients about the possible benefits of WM in their projects. The role of clients and their positive attitude towards efficient WM is crucial, because their decision affects the rest of the stakeholders' attitude towards WM. Most stakeholders have various options (some of them mentioned in the analysis) to reduce the level of CDW generated. However, they often need the push from the client, who pays them. Unfortunately, it is not as easy as that, as following illustration of stakeholders' relationships reveals.

Summary of CDW stakeholders' relationships:

The stakeholder analysis revealed a tendency of various stakeholders to shift the responsibility down to others. It is apparent, that there is no clear clarification of who is actually responsible for the waste generation and WM in general. This is further supported by Osmani (2012), who pointed out that regulators fail to assign responsibility for waste minimisation in design phase to architects (designers). This is an important finding, as the analysis revealed, that perceived influence of the regulators is great. This comprehensive overview of stakeholders and their relationship towards WM was an inspiration to come up with a map of various responsibilities and the shifts between the stakeholders illustrated in the Figure 7:

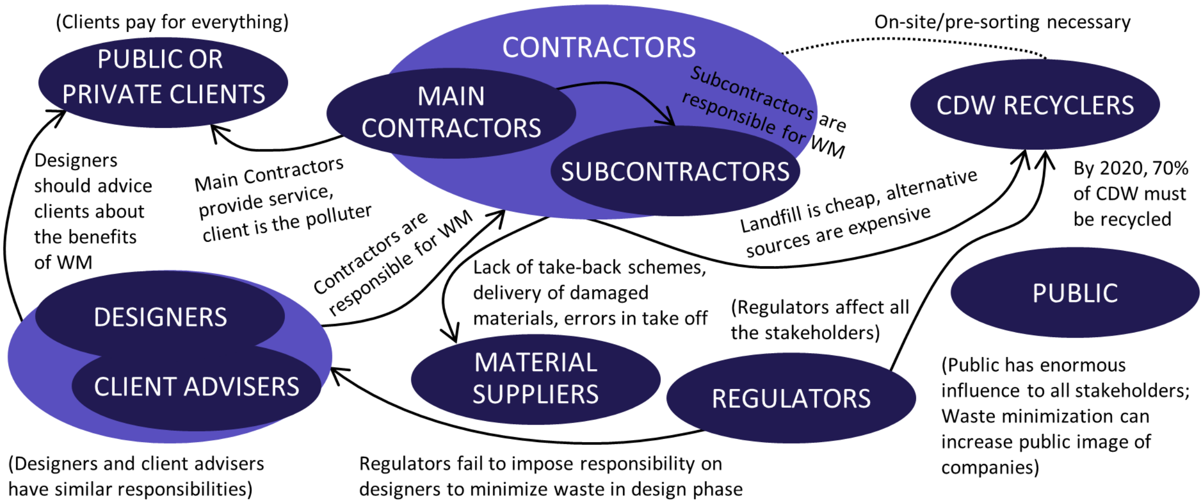


Figure 7 – Relationships between stakeholders in the connection to CDW

It must be taken into consideration, that the data come from many different authors, all utilising varying methodologies. However, it serves the purpose to show how the industry is fragmented. The figure sums up and visualises the connections that are apparent between the stakeholders after the stakeholder analysis. It does not include any new information, but it compiles the findings into one figure, solely focusing on the relationships between various stakeholders towards CDW.

3.6 SWOT

In regards to concluding results of PESTEL and stakeholder analysis, the project group performed SWOT analysis, which also serves as a conclusion of the first step of LFA - the analysis of the project's context. The main purpose of the SWOT was to help the group summarise the findings which occurred in the previous part of research and localise opportunities and threats which are occurring in the case. Therefore, the data extracted for previous parts of initial analysis, together with general knowledge of the project group, becomes a basis for this SWOT analysis.

Current situation regarding construction and demolition waste in Denmark becomes focus area of this analysis. This is due to Denmark being one of the member states of EU which in the eyes of the group presents suitable example of the status quo. The group is fully aware that results of this analysis cannot be applicable on all 28 member states of EU, however, it can serve as an example to every other country. Some strengths in Denmark's situation can be considered as opportunities for others and vice versa. All findings of SWOT analysis were placed in the SWOT diagram in the Figure 8 on the following page and will be further discussed in this part. Result of SWOT analysis will serve as basis for the creation of the final problem tree and the objective tree.

STRENGTHS:	WEAKNESSES:
- Legislation supporting waste sorting - Sorting facilities on construction site - High quality materials, recyclable - Advanced technology (concrete recycling, glass recycling) - Social movement for better environment - CSR of companies is strong	- Low awareness of CDW pollution - Too much of CDW - Increasing amount of CDW - Design is not considering whole construction life-cycle - Fragmented industry, responsibilities to control CDW are not clearly defined - Profit based industry - Hazardous waste cannot be recycled - Tax for landfill presents only 0,15% of construction turnover, low
OPPORTUNITIES:	**THREATS:**
- WFDs divert waste from landfills - Implementation of circular economy - Incentives for waste sorting - Improved stakeholder collaboration - Life-cycle way of thinking - Construction cost decrease - Long-term project savings - Environmental benefits - Recycling/reusing of materials brings new jobs to the market - Recycling/reusing of materials improves self-sufficiency of scarce materials - Movement towards recycling society - Denmark can be considered an example for CDW management for other countries with varying results.	- Global catastrophe - Costly to implement and useless if it is not followed - Too long life-cycle - Data transfer (change of building owner without data exchange) - Low will of clients to implement (fast money)

Figure 8 – SWOT diagram

STRENGTHS:

Legislation supporting waste sorting

Current legislation in Denmark is highly supporting waste sorting of CDW. As mentioned in previous parts of the report, Denmark as a member state of EU agreed to WFD and, therefore, agreed to actively support waste sorting and recycling with common goal to achieve recycling rate of at least 70% of CDW.

Sorting facilities on construction site

As Danish building regulations state, it is mandatory to assure sorting facilities on the construction site. That means that system of CDW sorting is already on the construction sites.

High quality materials, recyclable

Denmark is known as one of the countries where quality and choice of materials are important. This can be reflected in the situation when materials used in the new constructions are more environmentally friendly and recyclable.

Advanced technology (concrete recycling, glass recycling)

Denmark is well known for high level of recycling facilities, this is due to high environmental focus of the country represented in daily life of citizens. Level of CDW recycling is currently reaching 87% of all CDW recycled and new projects which are working with recycled concrete and concrete elements promise even better future.

Social movement for better environment

As mentioned above, there is visible change in the Danish lifestyle which is currently more focused on environmentally sustainable way of living.

CSR of companies is strong

Together with public focus on environment, it becomes construction companies' policy to play good public bodies and to focus on more environmentally friendly solutions.

WEAKNESSES:

Low awareness of CDW pollution

While there is visibly strong focus of public on the environment, CDW and waste in general is still considered to be one of the less discussed environmental issues.

Too much of CDW

Denmark is still considered as one of the biggest waste producers per capita in area of whole EU.

Increasing amount of CDW

With already high generation of waste in Denmark, numbers of waste generated by country are growing annually.

Design is not considering whole construction life-cycle

Construction projects are often distinguished by long life expectation. Therefore, whole life-cycle is considered only in limited amount of projects. That means, that clients together with design teams tend to neglect future states of a building, including maintenance, but more importantly, demolition and recycling or repurposing of construction at the end of life-cycle.

Fragmented industry, responsibilities to control CDW are not clearly defined

Construction industry is specific by high number of stakeholders. There is no clear definition on whose shoulder the burden of CDW stands and, therefore, the responsibility is constantly moved between the individual project participants.

Profit based industry

Construction industry is highly competitive industry with cost placed as main requirements in most of the projects. Therefore, the focus on ways how to limit generation of CDW is very limited as it might seems as costly.

Hazardous waste cannot be recycled

While at the beginning of new millennium, Denmark was able to recycle over 95% of CDW, however due to recently found difficulties with recycling of hazardous materials, the current static is that Denmark recycle only 87 % of CDW.

Tax for landfill presents only 0,15% of construction turnover, low

While amount of money paid for landfill tax might seem as very high, it represents only fracture of 0,15% from total turnover in the construction industry.

OPPORTUNITIES

WFDs divert waste from landfills

Landfill directive from 1999 together with WFD from 2008 accepted by all member states of EU are trying to divert all waste from the landfills in member states. Denmark applied total ban on landfill for all materials which can be incinerated.

Implementation of circular economy

Implementation of circular economy looks like viable opportunity for Denmark to fight against CDW. Some of the pioneering projects around the globe are currently showing promising results in decreasing CDW.

Incentives for waste sorting

Taxes and penalties do not represent only fiscal policies applicable by state in order to motivate companies to sort and recycle CDW. Incentives might present right amount of motivation to change current way of construction processes.

Improved stakeholder collaboration

As it was already mentioned, construction industry is fragmented, therefore, finding the wright way to improve collaboration might be big opportunity to improve current state of the industry.

Life-cycle way of thinking

Consideration of whole construction life-cycle might bring a benefit of decreased CDW generation as designers will be more aware of CDW as a problem and possibilities of recycling and repurposing project will become vital from the beginning of design phase.

Construction cost decrease

While implementation of new methods for CDW might look as expensive added benefit of low landfill taxes, together with saving on repurposed materials and possible financial incentives might decrease actual cost of construction.

Long-time project savings

In consideration of whole life-cycle of a project, there might be added value from repurposing and recycling of building materials.

Environmental benefits

Lowered generation of CDW is certainly going to improve current state of environment.

Recycling/reusing of materials brings new jobs to the market

Increased recycling rate might bring more working positions as there is higher demand for workforce in case of recycling facilities, compared to landfill and incineration.

Recycling/reusing of materials improve self-sufficiency of scarce materials

Recycling and reusing of scarce material might significantly decrease a need for extraction of raw materials.

Movement towards recycling society

Any improvement in fight against CDW might be considered as step forward to new more sustainable recycling society.

Denmark can be considered an example for CDW management for other countries with varying results

While many other countries can take example from Denmark in a way how to deal with waste, some of the Danish policies in regards to CDW might show what should be avoided.

THREATS

Global catastrophe

The way of constant producing of waste and landfilling is unsustainable. It might result in the pollution and occupation of whole land by waste.

Costly to implement and useless if it is not followed

Implementation of new systems for dealing with CDW might be costly. While this cost might seem adequate for improving the environment, it is useless if new system is not used and followed.

Too long life-cycle

With very long life-cycle of construction projects and individual materials it is often hard to predict what are the possibilities of dealing with construction project at the end of life-cycle.

Data transfer (change of building owner without data exchange)

In case of changing the ownership of a building, problems with data transfer are significant. In many construction projects, data for maintenance and project documentations are often lost during the phase of ownership exchange. If all data needed for life-cycle waste management are lost during the process, it might result in failure of whole system.

Low will of clients to implement (fast money)

Most of the constructions are focused on fast profit, that means, that client is trying to keep construction and design costs as low as they can. That might be even in case where implementation of new CDW management might bring financial benefit in long term.

3.7 Problem tree

The problem tree is the third step of LFA and it is a result of information collected during the initial analysis. This problem tree is the final version and it is the successor of the initial problem tree. The initial problem tree was performed before initial literature review and following analyses. The final problem tree was performed after the initial analysis was completed.

This problem tree is based on topics which were found relevant and confirmed by scientific articles. As some of topics in the initial problem tree were found irrelevant, they are left out in this problem tree. Following text is the explanation of the problem tree, which can be seen in the Figure 9 on the following page.

Poor design in terms of CDW management was identified as the focal problem connecting all causes. High number of stakeholders on construction projects, thus poor collaboration of stakeholders and no clear definition of waste responsibility result in industry being fragmented – affecting CDW management design. The industry is money driven, and with fierce competition, budgets are tight, making stakeholders less likely to invest into WM. With the addition of low waste awareness of stakeholders, this results in low consideration of a project life-cycle, which affects the design in regards to CDW management. It was found, that there is low motivation of stakeholders to decrease CDW generation. Root causes of this problem are: hard to recycle construction materials, low taxation on waste generated and missing incentive to recycle, all affecting the design in terms of CDW management.

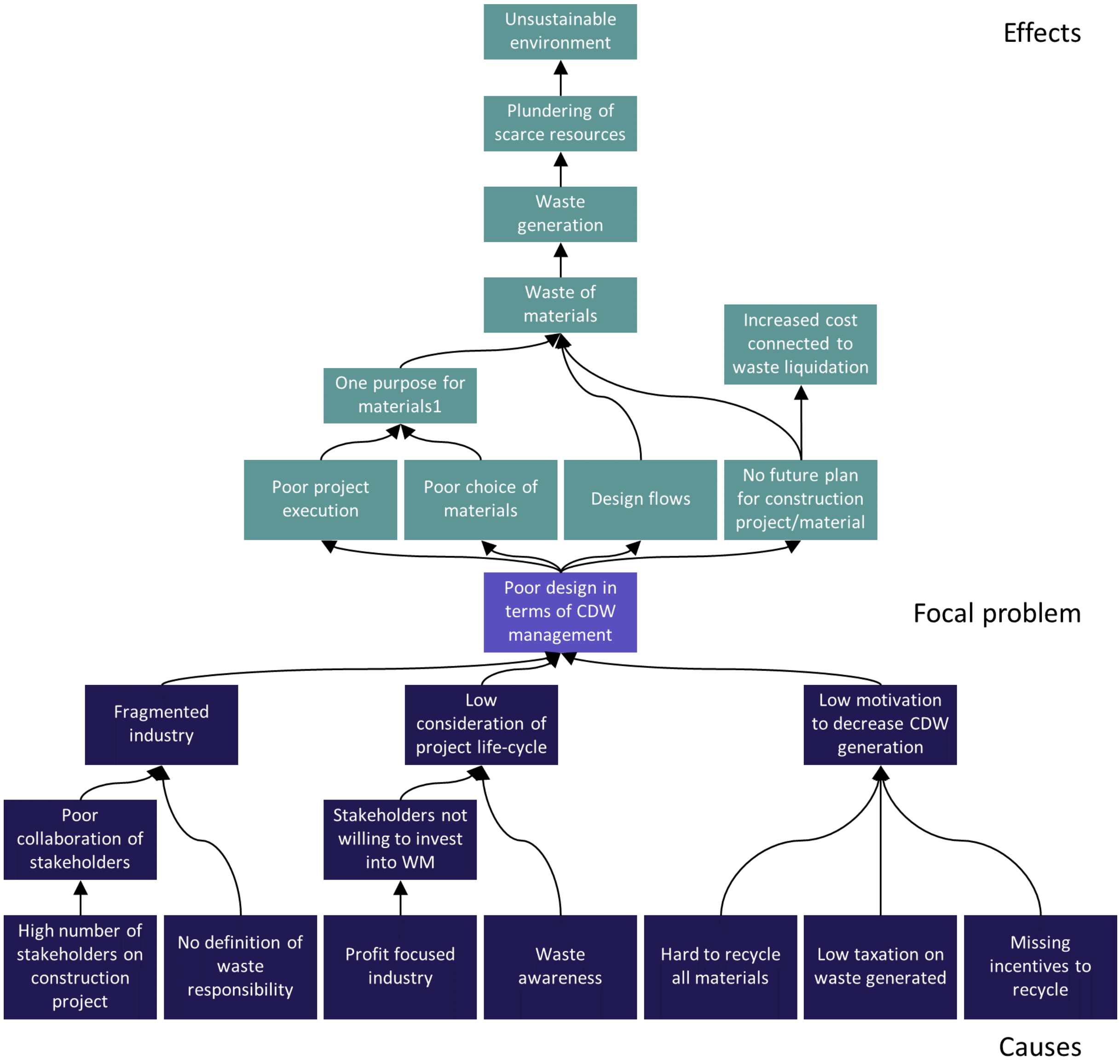


Figure 9 – Problem Tree

The causes, through the focal problem, result in various undesirable effects. In this case, it was found, that the outcome of the causes are effects such as poor project execution, poor material choices, design flows and no future plan for construction projects and materials. This increases cost connected to waste liquidation, which results in materials being used only once, and, therefore, wastage of materials. This leads to waste generation, followed by plundering of scarce resources and as the literature suggests, this results in unsustainable environment.

3.8 Objective tree

The objective tree is the fourth step of LFA, and, for the purpose of this thesis, this is the last step of LFA conducted. The objective tree is based on the problem tree and, simply said, it is a reverse of the problem tree. The outcome of the objective tree is to identify activities necessary to implement to achieve desirable objectives.

Results of the initial analysis were finalised in a form of the problem tree, which highlighted focal problem of “Poor design in terms of CDW management”, as can be seen in the Figure 9. Based on results of the problem tree, the project group came up with objective tree in order to figure out and structure activities which are in the understanding of the group necessary to implement to reach desirable objectives. The objective tree can be seen in the Figure 10:

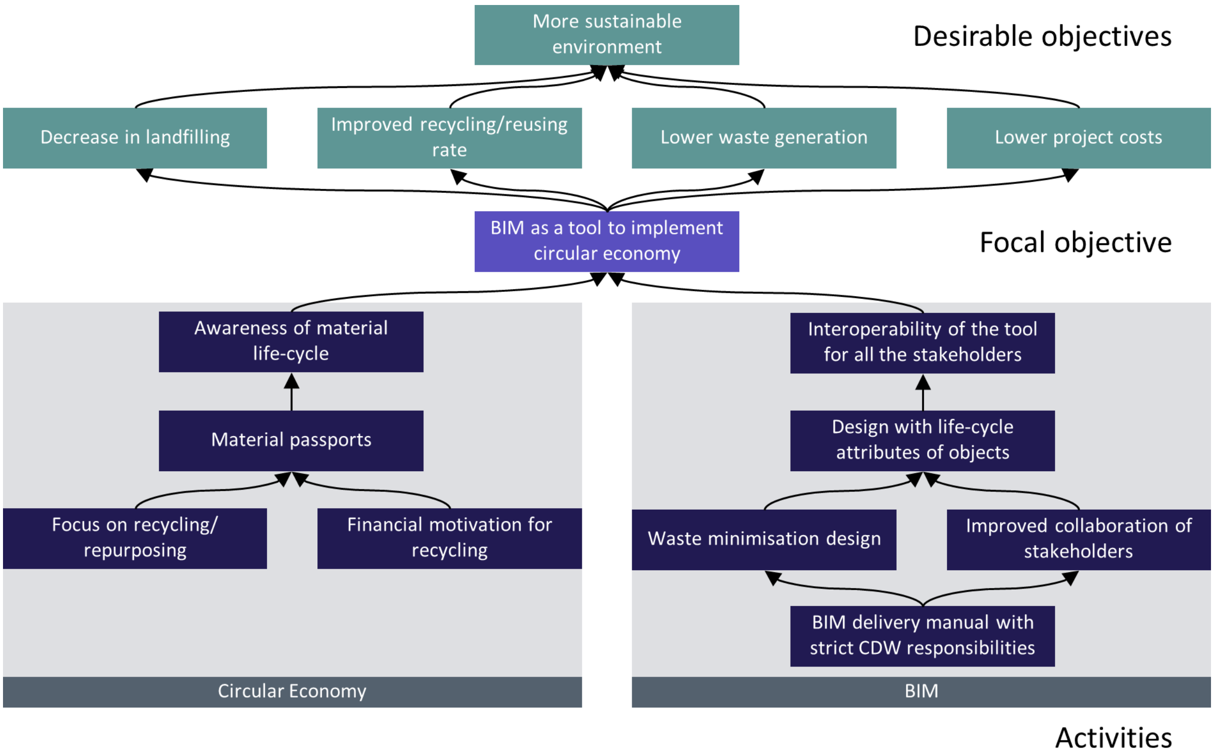


Figure 10 – Objective tree

The main desirable objective is the creation of more sustainable environment. The project group is aware of their limited ability to fully solve the problem with unsustainable environment. Therefore, the goal is not to focus on the total solution, but partial improvement. Another desirable objectives needed in order to achieve more sustainable environment are decrease of landfilling, improved recycling/reusing rate, lower waste generation and lower project cost. For the purpose of this report, BIM as a tool to implement circular economy becomes the focal objective. This is due to the project group’s understanding how beneficial both BIM and the concept of circular economy can be for construction projects. Another reason for seeing this as a focal objective is the focus of the report, as BIM and circular economy are the group members’ areas of interest. Lastly, the project group presented activities necessary for achievement of the desirable objective, which are rooting from both BIM and circular economy paths. In these paths, project group clearly stated the need to improve interoperability between stakeholders and their awareness of project life-cycle in regards to materials and project life-cycle.

4. Problem formulation

The sequence of activities performed throughout the initial analysis led the project group to a creation of the problem tree and the objective tree. These trees are based on data found during the initial analysis and result is the following problem formulation:

“How can implementation of circular economy through BIM minimise the CDW generation during the project's life-cycle?”

This problem formulation fits the scope of the report sufficiently, as it contains the implementation of the circular economy through BIM. In this case, BIM is going to be used as a tool for the implementation. The objective of the problem formulation is based on the desirable objectives of the objective tree, which are: decrease in landfilling; improve recycling/reusing rate; lower waste generation; and from the economic standpoint, lowered project costs. This all is illustrated in the problem formulation in the minimisation of the CDW generation during the project’s life-cycle, desirably solving current issues identified in the problem tree.

5. Definitions

Subjects of the circular economy and the building information modelling are widely acknowledged and developed by the academia. This, however, results in different opinions about what both terms represent. In order to assure the common understanding of what terms of the circular economy and the building information modelling mean, the project group decided to adapt definitions of these terms, which are presented in this chapter. Other topics and terms presented in this report, were by the project group deemed as self-explanatory, and therefore, are not defined. One exception is the definition of construction and demolition waste, which is defined in the earlier part of this report and can be found in the Definition of construction and demolition waste in the initial analysis chapter. This was done in order to assure a better flow of the report and due to the need to assure a common understanding of the term for the purpose of the first part of the project, the initial analysis.

5.1 The circular economy

To define the circular economy, it is necessary to introduce the linear economy first, as the circular economy is a response to the linear economy. The first impulse to produce in large quantities, to increase the wealth of a nation, was introduced by economist Adam Smith in 1776. However, the linear economy, as we know it in the present, started in the beginning of the 20th century with products being designed for a mass production. The model of the linear economy is based on the principle of take-make-use-dispose. Modern economy and society in its entirety were developed around this model, but the supply of resources is finite. It was already proven, that current situation is unsustainable, and something has to change. (Andrews, 2015)

One of the responses to the linear economy is the circular economy. Based on the literature reviewed, there are two predominant goals of the circular economy. The first goal is to take into consideration that resources are scarce and finite, thus eliminate "take" from the previously introduced principle as much as possible and to promote reusing and/or recycling of already available materials. The model of circular economy aims to keep materials in the circulation for as long as possible. The second goal is to reduce the amount of "dispose" from the above-mentioned principle through a better design and a smarter choice of materials. (Benton & Hazell, 2013) (EMF, 2013) (Andrews, 2015) (EC, 2015a) (EMF, 2015) (Leising, et al., 2018) (ZWS, 2015) (Ghisellini, et al., 2018)

The above-mentioned sources are mostly in consensus, that there is no common definition of the circular economy. Some authors use definitions of others, the rest come with their own. However, in general, the definitions do not vary much and have the same idea of two previously mentioned main goals. Therefore, for this report, slightly altered and combined definition by European Commission (2015a) and EMF (2015) is used:

> *"A Circular Economy is an economic and industrial system maintaining the value of products, materials and resources in the economy for as long as possible, thus minimising the generation of waste."*

This definition takes into the consideration both of the main goals of the circular economy. Materials, that are recyclable, or reusable can be returned back into the economy. This minimises the "take" and "dispose", which is typical for the linear economy and aims to stabilise the supply of scarce materials and to reduce the generation of waste, which is negatively impacting the society.

5.2 The building information modelling

The building information modelling (BIM) as an idea was developed in the middle of the 20th century, when Douglas C. Englebart presented his idea of the futuristic construction planning based on attributes and parameters. However, BIM, as a process, was developed quite recently, as proper implementation of the idea into a software started around 20 years ago. However, only in the past ten years, we are able to talk about serious implementation of the building information modelling into the construction industry. According to surveys, usage of BIM in the construction processes doubled over the last decade and it continues to grow (McGraw-Hill Construction, 2012), (NBS, 2016), (bips, 2015).

BIM as an abbreviation for the building information modelling is known worldwide, however, it is hard to find one common definition of what BIM exactly is, as many organisations tend to define BIM according to their needs and the purpose of their work.

Sacks, et al., (2018), in their book *BIM Handbook,* which was co-authored by Chuck Eastman, one of the leading researchers in the field of BIM, define BIM as:

> *"We define BIM as a modelling technology and associated set of processes to produce, communicate, and analyse building models. BIM is the acronym of "Building Information Modelling," reflecting and emphasizing the process aspects, and not of "Building Information Model." The objects of BIM processes are building models, or BIM models."*

Another definition is provided by internationally acknowledged National Building Specification (NBS) (2016):

> *"BIM or Building Information Modelling is a process for creating and managing information on a construction project across the project lifecycle. One of the key outputs of this process is the Building Information Model, the digital description of every aspect of the built asset. This model draws on information assembled collaboratively and updated at key stages of a project. Creating a digital Building Information Model enables those who interact with the building to optimize their actions, resulting in a greater whole life value for the asset."*

However, for the purpose of this report, the definition used by Royal Institute of British Architects (2012) is used:

> *"(...) (BIM is a) digital representation of physical and functional characteristics of a facility creating a shared knowledge resource for information about it forming a reliable basis for decisions during its life cycle, from earliest conception to demolition."*

This definition is used due to the simplicity of it, as it is easily understandable for a wide spectrum of readers, while representing the definition of BIM, complex enough for the purposes of this report.

While the understanding of the building information modelling as a process plays an important role, it is also necessary to understand what the specifics of the BIM model are. This necessity occurs from the need to differentiate between the process of creating the model and the model by itself. In order to define the building information model, definition by Borrmann, et al., (2018) is used:

> *"A Building Information Model is a comprehensive digital representation of a build facility with great information depth. It typically includes the three-dimensional geometry of the building component at a defined level of detail. In addition, it also comprises non-physical objects, such as spaces and zones, a hierarchical project structure, or schedules. Objects are typically associated with a well-defined set of semantic information's, such as the component type, materials, technical properties or costs, as well as relationship between the components and other physical or logical entities."*

This definition captures the complexity of the building information model, as it is represented in this report, and understood by group members.

6. Theory

Based on the objective tree, the project group localised topics relevant to a solution of the focal problem. All localised topics lie in the project group's area of interest. These topics are the circular economy, the design for disassembly, material passports and the building information modelling. The project group afterwards conducted an extensive literature review of these topics. This was done in order to gain better understanding of topics, which is by the project group considered a must for a development of the conceptual solution of the focal problem. Findings of the literature review were compiled in the theory chapter. All findings were discussed within the project group to assure common understanding and knowledge about topics. While some of findings represent straight citations from the literature, others present the project group's understanding of topics based on the literature compilation and a common knowledge of the project group.

6.1 Circular economy

The circular economy is a model of economy with an aim to promote maximum reuse and/or recycle of materials and goods, while keeping or improving the value of materials. Within the goal of improving a chain of production, consumption, distribution and recovery of materials and energy, the circular economy is trying to achieve the main goal of decreasing waste generation. (Ghisellini, et al., 2018)

While many researchers tend to call this model new (Ghisellini, et al., 2016), (Ghisellini, et al., 2018), (Pomponi & Moncaster, 2017), the origin of the concept is dating back to the 1970s. Understanding of the circular economy as a newly developed model is connected to the development in the academical research around the topic in the past few years.

The reason why research about the circular economy is gaining momentum is a hope of some researchers, that it might answer some of the current ecological needs. However, the concept of the circular economy, which was already presented in 1976 by Stahel and Ready-Mulvey (1976) was mainly focused on the economy of industries. This was based on the economical loop - in order to prevent waste production, create new job positions and increase resource efficiency of the industries. (Geissdoerfer, et al., 2017)

While the first formalised work about the circular economy is coming from 1976, the idea of it was well known even before the industrial revolution, as it played an important role in the everyday life of people, as people's possessions were commonly repaired, repurposed or recycled. (Lieder & Rashid, 2016)

The circular economy promotes maximum reuse and/or recycle of materials and goods with keeping or improving the value of materials. Within the goals of improving the chain of production, consumption, distribution, and recovery of materials and energy, the circular economy is trying to achieve the main goal of decreasing waste generation. (Ghisellini, et al., 2018) In general, it can be stated, that the main goal of the circular economy lies in the better management of the resources. (Pomponi & Moncaster, 2017)

In general, the idea of the implementation of the circular economy is globally focused, as it is believed, it might bring brighter future for waste disposal. Based on the area of the implementation, researchers are distinguishing between two different ways of implementation. First concept aims on the implementation of the circular economy in the wider macro-environment, the other concept proposes only focused implementation on specific sector, product or material. (Kalmykova, et al., 2018)

In most of the researches, the circular economy is closely connected to three main actions: Reduction, Reuse and Recycle (3R) (Ghisellini, et al., 2016). However, for the purposes of the construction industry, the definition of the main actions varies slightly. According to Ghisellini, et al., (2018), actions, which are closely connected to the circular economy in regards to the construction industry, are: Recycle, Reuse, Refurbish or Renovate, Restore and Repair.

These can be described as:

- Recycle means to close the life-cycle of the building or the material used in the construction in order to reintroduce the material and to reuse it in the future life-cycle of new products. Simply, just turning individual materials used in the construction and giving them a new life as a new product.
- Reuse means reusing of the original product with a minimal or no adjustments for the same or similar purpose.
- Refurbishing or renovation are connected to retrofitting and upgrading of a product in order to improve its quality. Main goal of refurbishing and renovation is to assure that product is up to current standards and can perform the intended task for prolonged period.
- Restoration means to bring the structure into its original state.
- Repair is fixing and restoring the structure in order to prolong the original function. (Ghisellini, et al., 2018)

Many researchers tend to see the circular economy in different ways. This is due to its young nature in regards to the academical research. However, based on the literature review conducted for the research by Adams, et al., (2017), they formalised main principles of circular economy used through recent researches:

- Increasing the productivity of the materials by doing the same or more with less.
- Eliminating waste by defining materials as either technical or biological nutrients enabling them to be within closed material loops.
- Maintaining or increasing the value of materials, environmentally and economically.
- Thinking in system by studying the flows of materials and energy through industrialised systems, understanding the links, how they influence each other and the consequences, enabling closed-loop processes where waste serves as an input.

Concept/Idea of the circular economy

It is important to understand the reasons for the development of the circular economy. However, the idea of the circular economy is not based on the actions of 3R, which are by many researchers connected to it. It is more or less standing on the principles and ideas how the circular economy should work and what it should achieve.

The circular economy as a concept aims to change the concept of a material production from the linear way into closed loops. This is done in order to close production loops in industrial ecosystem and to minimise the production of waste. The circular economy shifts the logic of a production, from generating new goods from raw materials, into production with sufficiency. (Stahel, 2016) The production with sufficiency, according to Stahel, means:

"Reuse what you can, recycle what cannot be reused, repair what is broken, remanufacture what cannot be repaired."

The main objective of the circular economy is to maximise the value of a material at each point of a product's life-cycle. This is done with the ultimate goal of the circular economy to be able to recycle material's parts up to atoms. (Stahel, 2016)

In order to achieve this ultimate goal, products following the concept of the circular economy should be restorative by design. This should be done in order to keep a product and all of its parts in the highest utility and value at all times. (Webster, 2017)

There are currently two most common views on how to follow the road of the circular economy. While the first view is focused on reusing of the already produced goods and prolonging their life-cycle by reusing, repairing, remanufacturing, upgrading or retrofitting. The second view is focused more on the materials from which are the goods consisting of and recycling these materials in order to produce new goods. (Stahel, 2016) However, according to research by Ghisellini, et al., (2016), fully implemented model of the circular economy, following the first view of reusing the goods of high value would be promoted, instead of focusing on the second view – on the recycling of low value materials.

Most often, the idea of the circular economy is only connected to the more sustainable way of the waste management. This understanding of the circular economy increases the chance of a model failure, as it is seen more as a treatment of the existing waste problem by recycling, reusing, and repurposing, rather than the way of prevention by the design for disassembly and other ways. This is especially true in a situation, where recycling might become more expensive and less feasible due to inappropriate design. (Ghisellini, et al., 2016)

On the first sight, the concept of the circular economy can be seen as the concept of sustainable industry. However, based on past researches, it can be stated, that rather than directly linking sustainability to the circular economy, the circular economy can be seen as one of the conditions for sustainability. (Geissdoerfer, et al., 2017)

Benefits of the circular economy

With the eminent need to address different social problems, such as unemployment, excessive land use, scarce material depletion, environmental pollution and others, the circular economy might be the solution for many of these problems. (Geissdoerfer, et al., 2017)

The concept of the circular economy is expected to bring multiple economic, environmental and social benefits. It is expected to create new businesses and job opportunities, decrease the cost of materials, improve the security of materials supply and improve other socio-economic factors, while reducing impacts on the environment. (Kalmykova, et al., 2018)

Reusing of the goods is considered to be a faster and a cheaper way of a production, as cleaning of materials and using them again and again is faster than producing a new material. It generates more job positions, while decreasing waste production, resource, and energy consumption. (Stahel, 2016)

With the inevitable relationship between an industry and the environment, the recent environmental impacts of an industry increased pressure on the businesses to implement the circular economy and other measures for a better sustainability. (Lieder & Rashid, 2016)

European commission estimates, that by implementing ideas of circular economy as eco-design, waste prevention and reusing can create savings of up to 600 billion EUR with additional increase of resource productivity up to 30% by 2030, increase GDP of whole EU by 1% and in addition, create 2 million working positions. (EC, 2014a), (EC, 2014b)

Another example of expected benefits from implementation of the circular economy is from United Kingdom. According to Environmental Services Association (ESA), implementation of the circular economy in United Kingdom can bring significant boost of GDP by up to 3 billion, create 50,000 new working positions and bring over 10 billion in new investments. (ESA, 2013)

Lastly, another research conducted by Netherlands Organisation for Applied Scientific Research (TNO) stated, that market value opportunities connected with implementation of circular economy can raise up to 7,3 billion EUR, which correspond to creation of around 54,000 new job positions. (TNO, 2013)

The concept of the circular economy is especially valid for the construction industry, as it is considered to be the world's largest consumer of raw materials and responsible for the production of one third of CO2 globally. Due to this considerable impact on the environment, the implementation of the circular economy to the construction industry might bring significant reduction in energy usage, pollution and waste generation. (Pomponi & Moncaster, 2017)

Adoption of the circular economy in the construction industry might bring severe environmental benefits in different categories as an energy use, decrease of landfilling and incineration, improved waste management and others. (Ghisellini, et al., 2018)

Barriers for the implementation of the circular economy

With high expectation of academia from the circular economy, the question is, why it is not already implemented and fully functioning system.

One of the reasons is, that the field of the circular economy is considered to be quite undeveloped, at least in a comparison to other theories, which are focused on the economical sustainability. (Ghisellini, et al., 2016)

With all expectations from the circular economy, there is no analysis of the circular economy implementation strategies and the experience of the circular economy implementation in order to prove the concept. This decreases the possibility of an effective circular economy implementation and putting all investments into the model at risk. (Kalmykova, et al., 2018)

Another barrier connected with missing academical research of the topic is the trust and awareness of the society about the circular economy and its possible impact on different social problems. Therefore, the promotion of implementation of the circular economy is considered to be the one of the biggest challenges in order to start with global implementation of this concept.

Stahel is aware of problematics with awareness of circular economy and, therefore, states, that deeper research is needed in order to convince governments and businesses, that circular economy is feasible (Stahel, 2016).

However, based on the research conducted by Geissdoerfer, et al., (2017), where they analysed recent researches in regards to the circular economy, it is clear, that the circular economy is currently focused more on environmental performance improvements, rather than taking holistic view with three dimensions of sustainability. These dimensions are social, economic and ecological. Therefore, the need of conducting a more holistic research of the circular economy still stays unanswered.

The problem with the trust issues of the society in regards to the circular economy might be closely connected to the understanding, that the concept of the circular economy is going strictly against the academia and commonly used economical concept, where wealth is generated through the constant production of new goods, rather than making them to last long. (Stahel, 2016)

In order to change the society’s opinion, it is necessary to show the possibility of the circular economy’s implementation on all industry levels. Yet, most of the circular economy focused knowledge is currently centralised inside big companies. This is, again, connected to the low interest of academia about the subject, and limited academical training in regards to the circular economy. This makes it hard for SMEs to hire graduates with economical and technical knowledge, sufficient to implement the circular economy. (Stahel, 2016)

Another barrier for the implementation of the circular economy is closely connected to technological development. With the ultimate goal of recycling of materials up to atoms, it is necessary to state, that the technology is not already there. And while in some of examples we can see promising future, the sufficient technological solutions for many problems of the circular economy are not here, yet. (Stahel, 2016)

Specifically, for the construction industry, the relationship between materials used in construction projects and main principles of circular economy lying in 3R (reuse, repurpose, recycle) is quite specific. This is due to the large amount of different materials used in the construction projects. These materials are, often, distinguished by different attributes and their lifespan. During the construction project, these materials are bounded together in order to create rigid and homogenous units. Another problematic part is connected to the long lifespan of the construction, together with all changes in the structure's service life, as these might have a severe impact on expected scenario of 3Rs. This complexity of the construction is the reason why the circular economy is often rather focusing on goods with short lifespan, rather than on the construction, which is characterised by long-lasting service time. (Pomponi & Moncaster, 2017)

Much of CDW, which is recovered during the demolition or maintenance of a construction, is downcycled. This means, that the value, quality, or functionality of the original material, were lowered during the process of recovering, which is going against one of main ideas of the circular economy. (Adams, et al., 2017)

Lastly, Ghisellini, et al., (2016), in their research, analysed the barriers for the implementation of the circular economy, which can be seen through the scientific literature. These are presented in the Table 3, as they provide a complex overview in regards to implementation barriers:

Cultural The lack of awareness and/or willingness to engage with the circular economy	- Hesitant company culture - Limited willingness to collaborate in the value chain - The lack of consumer awareness and interest - Operating in linear system
Regulatory The lack of policies in support of the circular economy transition	- Limited circular procurement - Obstructing laws and regulations - The lack of global consensus
Market The lack of economic viability of circular business models	- Low virgin material prices - The lack of standardisation - High upfront investment costs - Limited funding for circular business models
Technological The lack of (proven) technologies to implement the circular economy	- The lack of ability to deliver high quality remanufactured products - Limited circular designs - Too few large-scale demonstration projects - Lack of data, e.g. on impacts

Table 3 – Barriers of Circular economy implementation (Data from (Ghisellini, et al., 2016))

Often, the ideas presented in scientific reports are not relying on real-life scenarios, rather, they rely on a researcher's theoretical understanding. Therefore, Adams, et al., (2017) conducted the research, where they question the actual representatives of the construction industry, to see, what are the biggest barriers seen by them, in regards to the implementation of the circular economy model into the construction industry. The result of the research is illustrated in the Figure 11 on the following page.

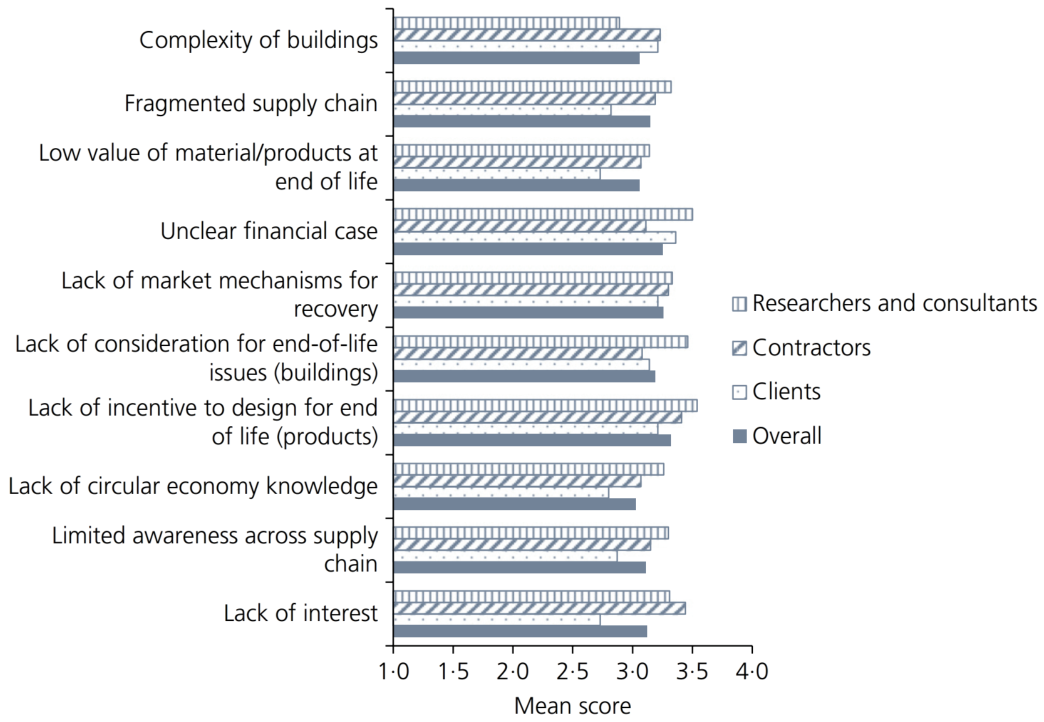


Figure 11 – Most significant barriers of circular economy implementation in the construction industry (Adams, et al., 2017)

The biggest barriers for implementation of CE, identified by representatives, are: unclear financial case, lack of consideration for end-of-life issues, lack of incentive to design for end of life, lack of interest, and lack of market mechanism for recovery. Barriers, that were less occurring, are: complexity of buildings, fragmented supply chain, low value of material/product at the end of life-cycle, lack of the circular economy knowledge and limited awareness across supply chain.

Successful implementation of the circular economy

In regards to successful implementation of the circular economy, only limited number of researchers offer the solution.

In regards to adoption of effective circular economy program on the micro-environmental level, it is necessary, that companies involve different strategies in order to improve the circularity of their production, and they put high importance on the collaboration with other producers over and bellow the company's supply chain. (Winkler, 2011)

In order to be able to plan and to actively maximise the recovery rate of materials used for a construction at the end of a product's life-cycle, it is necessary to consider, and to follow, few principles. The first one is a transparency, meaning that all materials are visible and trackable, a regularity means, that materials are used for the same purpose, as they were intended. Last principle is a simplicity, as it is necessary to assure, that each element is containing only limited amount of materials, which are easy to separate and reuse. (Gálvey-Martos, et al., 2018)

The idea of the reusing of the product has to be considered from the earliest stages of the product development. Therefore, for successful implementation, the idea of designing the product to reuse must become a norm. (Stahel, 2016)

Adams, et al., (2017), in their research, also analysed the industry's understanding of enablers for successful implementation of the circular economy in the industry. Results of this data collection can be seen in the Figure 12:

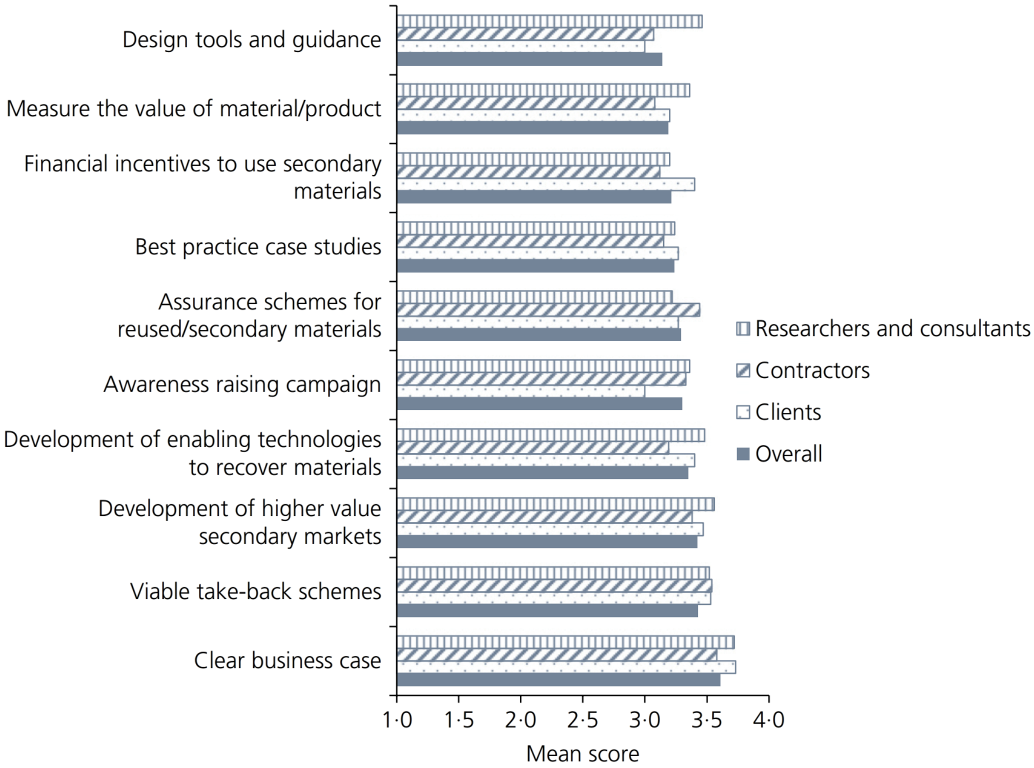


Figure 12 – Enablers for implementation of the circular economy in the construction industry (Adams, et al., 2017)

In the research, they also looked on the different aspects which should be controlled during the whole life-cycle of the construction projects in regards to successful implementation of the circular economy.

- Design – design for disassembly, design for adaptability and flexibility, design for standardisation, design out waste, design in modularity, specify reclaimed materials, specify recycled materials
- Manufacture and supply – eco-design principles: use less materials/optimise materials use, use less hazardous materials, increase the lifespan, design for product disassembly, design for product standardisation, use secondary materials, take-back schemes, reverse logistics
- Construction – minimise waste, procure reused materials, procure recycled materials, off-site construction
- In use and refurbishment/maintenance – minimise waste, minimal maintenance, easy repair and upgrade, adaptability, flexibility
- End of life – deconstruction, selective demolition, reuse of products and components, closed-loop recycling, open-loop recycling (Adams, et al., 2017)

The research conducted by Ghisellini, et al., (2016) illustrates steps necessary for the implementation of the circular economy into the industry. In their research, they finalised the biggest challenges in connection to design, waste reduction, reuse and recycling of the materials. These are presented in Table 4:

Design	Optimal product life scenario Design for disassembly, reuse and recycling
Reduce **Reuse**	Design for durable products Design for new business model of consumption Overcome rebound effect of eco-efficiency and eco-sufficiency strategies Technical reusability of materials Increase of consumer demand towards reuse of products and materials Development of take-back mechanism from the companies Ensuring repair and secondary use of products after their original use Taxation based on non-renewable energy rather than labour and renewable energies
Recycle	Reinforcement of local markets of recycled materials Risk of global trade of materials Improved technologies for resource recycling

Table 4 – Challenges of the successful circular economy implementation (Data from (Ghisellini, et al., 2016))

Examples of the circular economy implementation

With all barriers of the implementation in regards to the circular economy, is it even possible to successfully implement this model in the global, or industrial scale? To answer this question, there are few examples of circular economy ideas, which were already implemented. While the number of practical examples is currently limited, it is more the principle of the circular economy which is being slowly adapted by governments and different organisations.

Countries like Sweden, Germany or Japan are by researches commonly seen as the ones pushing the industry production from the open resource cycles into the more closed ones by leaning towards the different waste reduction and recycling programs, which are closely related to the circular economy (Lieder & Rashid, 2016).

Another European country, which is seen as European leader in the connection to the circular economy, is Netherlands. Dutch government started together with private facilitators the project called Realisation of Acceleration of Circular Economy (RACE). Project was launched in 2014 with goals to facilitate implementation of circular economy in the country and making Netherlands a global leader in the field of CE. (EC, 2015b)

Need for the implementation of the circular economy might be also seen in the recently proposed legislations around the globe. China, as the biggest global producer, accepted Chinese Circular Economy promotion law in 2002 and it was fully implemented in 2009. Another example is European Circular Economy package, promoted by EU in 2018, which sets a main goal of promoting the idea of both circularity and waste management. (Geissdoerfer, et al., 2017)

One example of the currently working project of the circular economy can be found in Denmark. The Kalundborg industrial park, so called Kalundborg Symbiosis, is the collaboration of nine public and private companies in the city of Kalundborg. This project is considered to be oldest industrial example of the circular economy in the world, as it started in 1972. The main principle of the park is that waste of one company becomes the resources for another, resulting in benefits for both the environment and the economy. (SymbiosisCenter Denmark, 2018)

6.2 Design for disassembly

In regards to the circular economy and its implementation to the construction industry, the design for disassembly (DfD) plays important role.

Currently, whole buildings are often demolished before they reach the end of their technological life expectancy. This is due to low possibility of a building's adaptation and the pressure from different socio-economic trends. The process of demolition creates significant amount of waste. (Durmisevic, 2006)

In order to assure the possibility of reuse and/or recycle of materials used for the construction of these buildings, deconstruction or disassembly is the first step. In order to assure the possibility of deconstruction, it is necessary to consider this from early stages of the project to ease activities connected to future deconstruction. (Osmani, et al., 2008)

If the option for remanufacturing is not considered in the early stages of the project design, the possibility for further remanufacturing or reusing of individual parts at the end of its life-cycle might be limited. Therefore, in order to achieve the possibility of remanufacturing, it is necessary to consider the product's ease of disassembly during the design phase with the aim to reuse, upgrade or recover individual components. (Tao, et al., 2012)

Therefore, according to Kibert (2013), in order to achieve the circularity and to shift downwards to closed-loops of the material production, the implementation of DfD is considered to be mandatory. The process of closing the production cycle in the construction industry can be seen in the Figure 13:

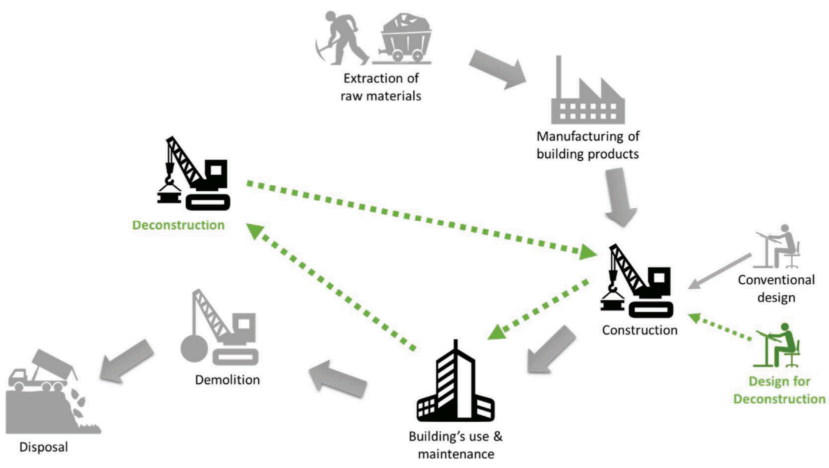


Figure 13 – Changing the construction cycle from linear into circular by implementation of DfD (Rios, 2018)

However, why is the process of disassembly so important for the implementation of the circular economy? It is the process of a systematic removal of desirable components from a product at the end of its useful life in order to make the components available for different reusing/recycling processes. As a result of the product disassembly, individual salvaged components can be further reused, recycled and/or sold as they are. This way of decreasing waste production can have significant impact on the environment. (Huang, et al., 2017)

The idea of design for disassembly is to facilitate a repair or an adoption of a building for new purposes or reusing original components of a construction on a new project. By this step, the lifespan of certain elements can be prolonged up to its technological limits. Further, this might reduce the life-cycle cost of constructions and contribute to environmental savings. (Paduart, 2012), (Durmisevic, 2006)

However, not all components can be disassembled. Lambert and Gupta (2005) distinguish between three categories of products where there is no possibility for disassembly:

1) Homogenous components – homogeneous mixture of different components which were put together in order to create one. (mortar, consisting of cement, sand and water)
2) Composite components – consisting of multiple materials which are irreversibly linked to create one component. (particle board – particles of wood bonded with glue)
3) Complex components – consisting of multiple homogenous components, which were irreversibly linked together in order to create one homogeneous component. (prefabricated wall made from concrete, steel, insulation etc.)

The disassembly phase of a product plays a crucial role in evaluating possibilities of a product to repair, reuse or recycle. This improves possibilities of prolonging material life-cycle and helps to develop a product's circularity. Therefore, it can be stated, that the disassembling of products plays a significant role in the development of the circular economy. (Peiro, et al., 2017)

During the phase of disassembling, products are separated into components and/or subassemblies. This should be done in a non-invasive way, where whole or at least the most of a component is kept in a very good state. This is done in order to follow with further repair, upgrade and reuse of the parts. (Lambert & Gupta, 2005) In case of parts with lower possibility of repairing, reusing or upgrading, recycling should be considered as a further step. This can also involve components, which were destroyed by a destructive nature of the disassembling.

In order to ease the process of disassembly, Huang, et al., are promoting solution of a web-based storage. The process should be based on remote computing services, as these offer architects an opportunity to easily configure the product components. Data, regarding the products, are then easily accessible from anywhere and the collaboration of project participants is improved due to easier accessibility. Another advantage is, that data are stored safely for a long period of time. (Huang, et al., 2017)

Whole process of using web-based storage solution for design for disassembly can be seen on the Figure 14:

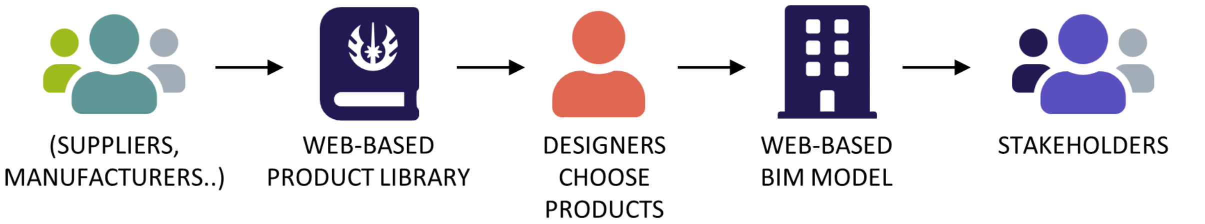


Figure 14 – Web-based workflow for the design for disassembly

While the implementation of DfD might look only as one of the steps towards the circular economy, it, alone, brings significant improvements to the current system. This is due to the consideration that the building designed in DfD manner is considered to be easier to maintain, transform and upgrade in general. (Paduart, 2012) Another advantage connected to DfD is the possibility of a product remanufacturing. Enterprises can significantly reduce their costs and increase their competitiveness on the market, while decreasing the environmental impact of a production. (Tao, et al., 2012)

While the idea of the design for disassembly might sound catchy and necessary for the implementation of the circular economy into the construction industry, Rios (2018), in her work, estimated, that currently less than two dozen of buildings around the globe were actually designed in DfD manner.

The reason for such a small number of implementations of DfD in the real world might be hidden behind the complexity of this design method. Blindly following the idea of DfD might bring no results. In order to understand the complexity hidden behind DfD, Guy & Ciarimboli (2008), in their research, introduced five main principles of design for disassembly:

1) Proper documentation of materials and methods for deconstruction.
2) Design of accessible connections to ease the dismantling. (e.g. minimising chemical and welding connections, using bolted, screwed and nailed connections, using prefabricated and/modular structure)
3) Separation of non-recyclable, non-reusable, and non-disposable items such as mechanical, electrical and plumbing systems.
4) Design of simple structures and forms, that allow the standardisation of components and dimensions.
5) Design, that reflects labour practices, productivity and safety.

Based on their literature review, Huang, et al., (2017) concluded some of the main principles of DfD in which the academia tends to agree. These principles are:

1) In regards to the final product, the materials used for production, way how they are assembled, and the assembling sequence should be considered from the early stages of a design. This should be done in order to further ease the disassembly at the end of product life-cycle.

2) In order to assure easy disassembly of a product, the implementation of a modularity should be considered at the design phase, in order to guarantee a product simplification and an increase of a disassembly efficiency.
3) It is necessary to create some sort of disassembly standards which can be followed in order to simplify the process of disassembling. Therefore, the products which aim for the disassembly at the end of the life-cycle should be accompanied with design guidelines.
4) In the disassembly process, toxic and hazardous materials of the product might increase potential human and environmental impact, therefore, they have to be considered for the product's life-cycle. (Huang, et al., 2017)

Lastly, Peiro, et al., (2017), in their research, provided five specific strategies which might improve DfD:

1) Use the modular construction
2) Minimise the number of disassembly operations
3) Minimise the number of connection (i.e. to limit dependencies)
4) Use tools as simple and as generic as possible
5) Connectors shall be resistant to damage and reusable

6.3 The building information modelling

BIM stands for an activity of the building information modelling. It is a rapidly developing process of comprehensive digital representation of a built facility with rich information level. The background knowledge for this part of the theory chapter is based on *Building Information Modeling* by Borrmann, et al., (2018) and *BIM Handbook* by Sacks, et al., (2018).

The concept of BIM, previously presented as "building description system", was originally presented by Eastman, et al., (1974). The term "Building Information Modelling" was firstly introduced by van Nederveen & Tolman, (1992). Major advance towards modern BIM was achieved in the late 1990s, during which the ability to create and edit solid, volume enclosing shapes, was developed by three separate research groups. However, the widespread use of the technology did not begin before the 2000s, mostly due to a cost associated to the equipment and software purchase, the underdevelopment of the technology and overwhelming processing requirements on a hardware. The widespread dissemination was initiated by the publication of *Building Information Modeling* whitepaper by Autodesk in 2003 and its acquisition of Revit Technology Corporation and its BIM capable software, Revit. Currently, in the late 2010s, there is a large range of a software with powerful BIM capabilities. BIM is becoming to be an established industry practice. In some countries, such as Denmark, the establishment is so far, that it is a requirement to use BIM for large, publicly procured projects.

To fully cover BIM is out of the scope of this thesis due to its complexity. Instead, the focus is on the areas of BIM that provide a solution to causes identified in the final problem tree, which are predominantly the fragmentation of the construction industry and low consideration for the entire life-cycle of the building. These are introduced and explained accordingly:

The fragmented nature of the industry

As it was already mentioned in the initial analysis, the nature of the construction industry is fragmented. However, there are many reasons connected to the fragmentation of the industry and many of these reasons are connected with the way the building information (both geometry and semantics) is created and delivered.

The current facility delivery process is dependent on a communication by 2D drawings. These drawings are prone to errors, resulting in additional costs, delays and often in a lawsuit between various stakeholders of a project. As most of these drawings are produced by different companies, it is difficult to control their consistency, or to collaborate in general. This is, mainly, due to the fact that different companies work according to different standards.

The solution is to use collaborative processes, that are offered by BIM. Different disciplines are able to work simultaneously on a project. The collaboration can be done either on one model, or on more coordinated models with managed change control. Since BIM does not allow for more than one representation per object, it does not matter which drawing view is used, it will always end up with consistent drawings. In case a change to a project is done, all drawings are updated immediately. These improvements lead towards the reduction in time and less design errors.

Accurate building model, which is also rich in information, benefits all the stakeholders connected to a project. There is lower risk for errors and conflicts, as it is possible to detect many potential errors already in the design phase. All the stakeholders, who have access to the model, are able to see how their contribution reflects in the master model and they can perform corrections accordingly. Such a building model also allows for a virtual pre-construction of a building, leading to better management of a construction process. Even though 2D drawings are still a requirement for a building approval, it is predicted that in the future the model will become legal requirement by itself.

Naturally, the above-mentioned propositions differ dramatically compared to processes stakeholders in the construction industry are used to. This requires significant changes in the relationships between stakeholders. Successful project will require intense exchange of information between its stakeholders throughout the entire project duration. This collaboration should be built on a trust and a common goal, instead of seeking individual goals, which broadens the fragmentation by creating a competitive environment. Unfortunately for the construction industry, it is rather difficult to build a trust, as most of the collaboration between the stakeholders is an ad-hoc partnership for a given project, rather than a long-term relationship. Out of all the construction companies in European Union, 93% of the companies have less than 10 employees. Therefore, it is troublesome to build long-lasting partnerships between stakeholders, as they are so fragmented.

Smooth exchange of information is often interrupted by stakeholders who are unwilling to share information. Their reasons might be contractual, security or intellectual property based, and it proves to be rather critical issue to deal with. Currently, this issue could be covered by the procurement selection (procurement based on the integrated project

delivery, which promotes collaboration of project's stakeholders) or by the client's specification and requirements for the ownership of the data.
The integrated project delivery (IPD) contract covers the allocation of risks, time and costs between stakeholders, who form cohesive team with a common goal. As they fully share potential costs and benefits, it is in the interest of all of them to successfully complete a project, because all of them benefit out of it.
In case IPD contract is not a possibility, a comprehensive building execution plan (BEP) might be used instead. BEP specifies the level of detail (of the model) of each stakeholder for a given phase, as well as mechanisms for a model sharing. In this way, the ownership of data is covered contractually and conflicts between stakeholders are reduced, as requirements are specified for every participant before they join a tender. To further support the specification of the requirements, BEP might be supported by the employer information requirements (EIR) document. EIR allows stakeholders to understand their roles, responsibilities, technical issues, submittals and management of models.

Another reason for the fragmentation of the construction industry is credited to the number of stakeholders necessary for a building creation. As it was already mentioned, most of the companies are smaller than 10 employees, thus there are many companies who serve only one specialised discipline (architects, engineers, HVAC, ect.). A specialisation of stakeholders comes with its own problems. For first, many companies equal to many stakeholders who need to cooperate together on a construction project. This increases the risk of inaccuracies and errors happening. For second, these specialised disciplines usually use tools that are suited especially for their job, and the interoperability between the stakeholders, thus, is not guaranteed This results in a redundancy of the exchange related tasks and a problematic exchange of information in general.

The movement towards BIM results in significant workflow changes, both inside the company, but also in the cross-company processes, when moving from traditional paper-based workflows. The magnitude of the change depends on the kind of BIM exchange necessary for the project and can be projected on two axis BIM map in the Figure 15.

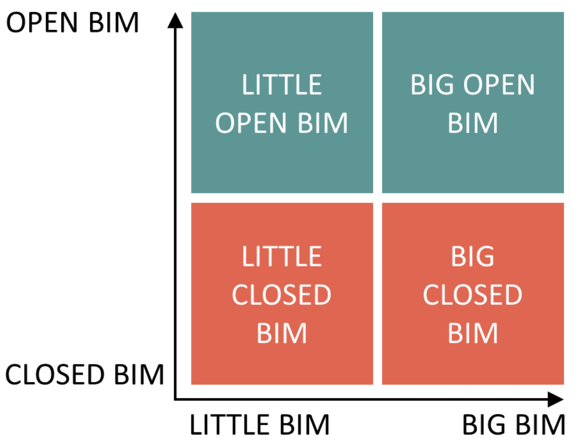


Figure 15 – BIM map, adopted from Borrmann, et al., (2018)

Closed BIM stands for BIM software provided by one vendor, which uses proprietary formats for data exchange. On the contrary, the exchange in open BIM is processed through open formats and allows for a collaboration of more BIM software packages. Little BIM is described as a BIM solution used in an isolation by one discipline. On the contrary, big BIM is the collaborative usage and data exchange of different disciplines throughout entire project life-cycle.

Closer to the origins of the axes, closer is the workflow to traditional paper-based practices. This, however, limits the benefits of BIM to the bare minimum. Further away from the origin, closer one moves towards anticipated usage of BIM, unlocking more potential benefits. These benefits, unfortunately, come with many technological obstacles at the moment, of which the major one is the issue of interoperability.

The workflows for certain disciplines are varying, as each discipline's focus is on different elements of a building. This results in different rules for creation and representation of a seemingly same object. To give a simple example, let's take a column to describe the difference. For an architect, the spatial representation is important, but for a structural engineer's needs, a column is only represented as a stick. When an architect sees a floorplan, the architect sees the floor and walls and columns above it. A structural engineer sees the same floor, but walls and columns below it. The issue is, of course, more difficult than this example, but it proves a point. As long as these two disciplines work individually (in little close BIM), there is no problem. However, when these two need to exchange data (in big open BIM), problems appear. BIM is rich in semantics. Without the richness of the model and all the semantics data connected to it, it would only be a 3D CAD. The potential of BIM is, however, in data connected to objects, and these are difficult to exchange between various BIM software packages.

There are four main approaches to exchange information in BIM:

First approach is to require every stakeholder to use software from only one vendor. This allows for an easy exchange between disciplines in both directions. Unfortunately, it is also impractical in a sense that certain stakeholders might be accustomed to their software and are unwilling to spend money and time to obtain software from a different vendor, just to be able to collaborate with different stakeholders.

Second approach is to use software from vendors, who collaborate together and allow for direct exchange through application programming interface (API). Even though the range of possibilities of software usage increases, most of the obstacles connected to the first approach remain.

Third approach is to use software, which allows for an exchange of data through open file format, such as Industry Foundation Classes (IFC). This reduces the need to create direct translators between proprietary data formats of specific vendors, as the exchange is facilitated through IFC. Therefore, it is necessary for a vendor to create only one translator to allow collaboration with other IFC enabled software packages. However, in the time of the writing, this exchange is highly dependent on a software developer's will to fully support IFC, as otherwise, the exchange results in a data loss.

Fourth approach is based on a usage of model server-based data exchange, which is facilitated through a database management system (DBMS). This system is stored either locally or on a cloud. This approach is often also called BIM or IFC server, as it is often based on standard data model, such as IFC. It allows all stakeholders to work on the same information in the same time, as these servers work on a building object level, instead of a file level, which can relieve some interoperability issues, such as version control and concurrent engineering issues.

There is nothing such as the "best approach", as this always depends on a given case and all approaches come with their advantages and disadvantages. However, it is anticipated, that open formats, such as IFC (irrespective whether they are based only on the schema exchange or on DBMS) are going to be used more and more. This is anticipated mostly due to the fact that a government is in the most of cases the largest client of the construction industry, and as such, must be neutral towards the choice of a software solution. In a case that the government would choose a proprietary file format, this could result in unfair market conditions and could lead to a monopoly of a software vendor and consequent law suits.

Low consideration for the entire life-cycle of the building

Typically, companies are not the same for every phase of a construction project. For example, there are often different companies responsible for design, construction and facility management (FM). As much as this affects the fragmentation of the industry, it also significantly affects the effectiveness of information exchange between projects' phases. This is illustrated in the Figure 16:

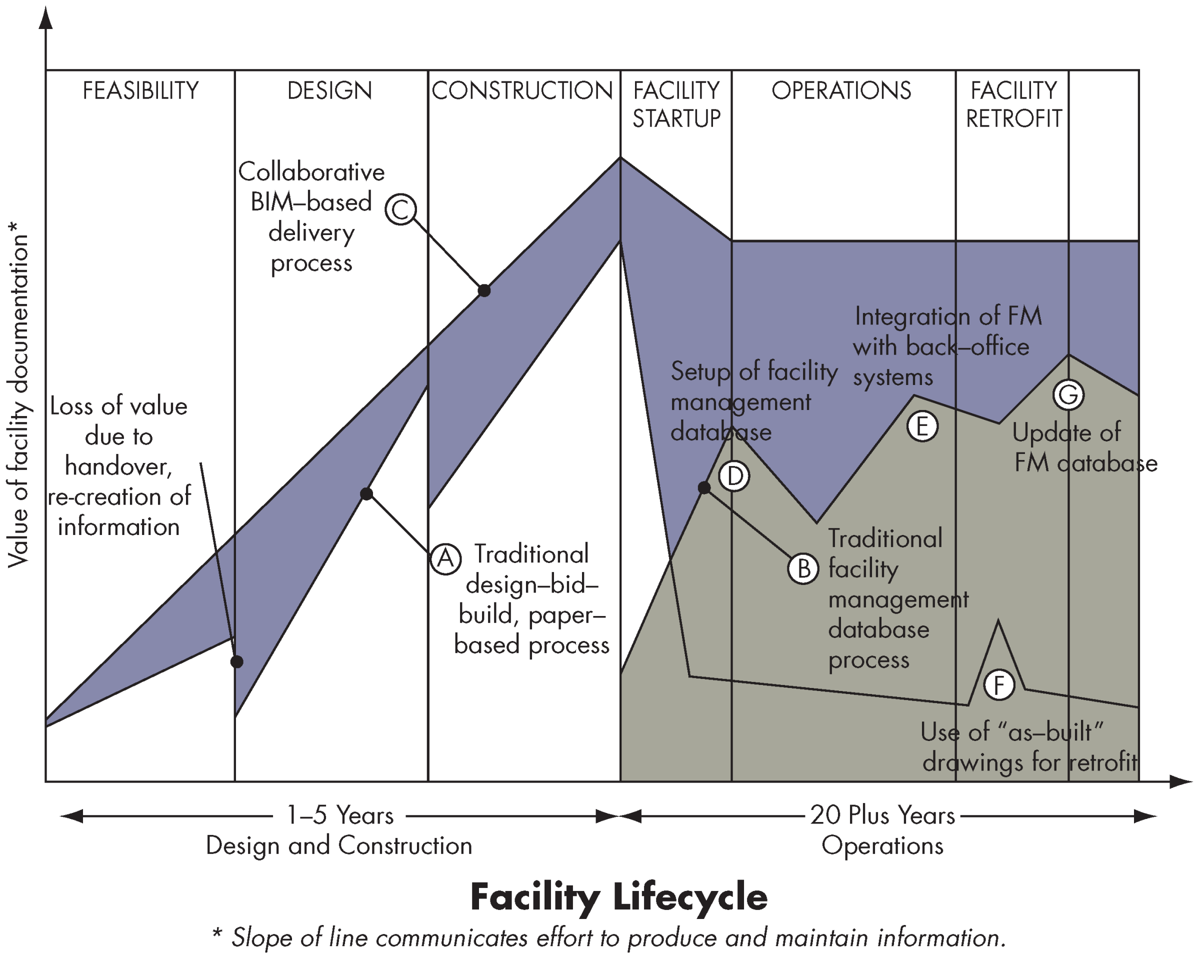


Figure 16 – Comparison of the build-up of information over entire life-cycle of a building (Sacks, et al., 2018)

As it can be understood from the figure, traditional, paper-based practices, come with a loss of information in the beginning of each succeeding phase. To catch up with the loss, increased effort is needed to maintain information compared to collaborative BIM-based delivery process. This is mostly attributed to an inability to re-use data between phases, as every analysis requires unique information, that must be solely inserted for it to function properly. During collaborative, BIM-based, delivery process, this is different, as the main model is getting richer and richer in semantics by contributing stakeholders. The idea of BIM is to continuously use a digital model throughout the entire life-cycle of a building. This information is there to stay in the model, but the stakeholders might filter out some semantics instead, to assure their analysis software runs appropriately. The only time the richness of information drops is after a handover of a project, as facility managers do not need too much information to maintain a building.

Since a manual re-entering of information is limited during BIM delivery due to continuous re-use of already filled in information, laborious and error-prone work is minimised. This results in an increase in quality, in lower project costs and reduced duration of a project. BIM models, rich in semantics (relative to given phase), allow for better (and continuous) analyses than traditional paper-based approach. The most important part of the collaborative approach of BIM approach is the early possibility to perform these analyses. The importance is demonstrated in the Figure 17, which is based on The MacLeamy curve:

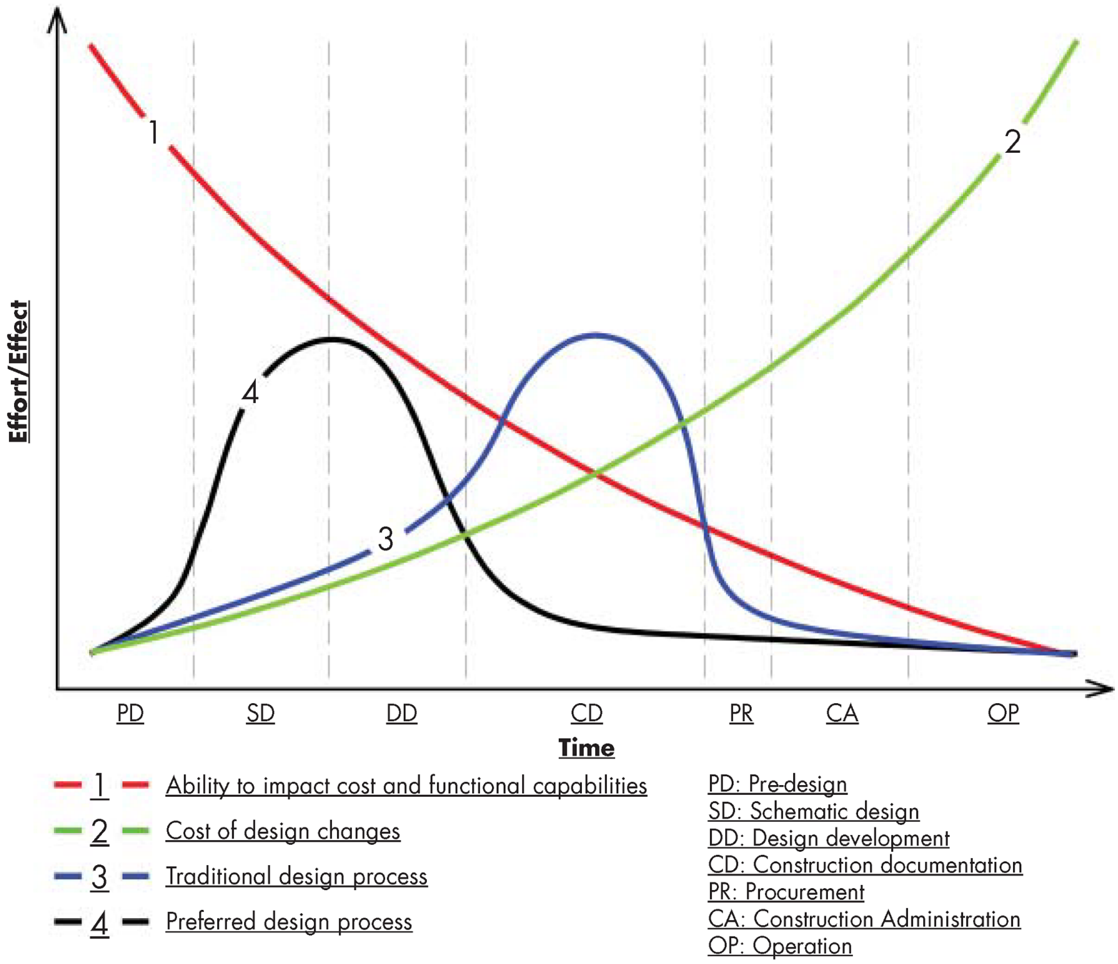


Figure 17 – Time to effort/effect curve (Sacks, et al., 2018)

This figure illustrates the importance to make significant decisions as early as possible, as it is easier and cheaper to make changes during design phases. Unfortunately, with the traditional, paper-based approach, these changes are often only fixed as they come, resulting in expensive changes and often, not ideal solutions. This late approach to changes is contributing to considerable expense and time cost necessary to perform analyses, such as cost estimates, energy requirements, structural analysis, sustainability report and such. To perform these, a design, at least, must be complete. Therefore, these analyses are often done as the very last part of the design phase, which is too late.

In a collaborative BIM approach, geometry and semantics supporting the beforementioned analyses are available faster, as stakeholders collaboratively add information to a model. This allows to identify necessary changes before it is too late and to adapt a design of a building for an anticipated usage. These processes result in a building of a greater quality, in a reduction of a delivery time and in a reduction of costs – for entire life-cycle of a building. This is due to early performed analyses allowing the stakeholders to aim for a perfect solution, instead of a compromise between the anticipated usage and a cost of a late change in the project.

The movement towards BIM approach was initiated by architects, but soon, other disciplines have started to join in. The possibility to collect and to capture the rich semantics and connect them with the model offers possibilities, that were not available in the construction industry before. As such, BIM is compared to product life-cycle management, as these two are sharing many similarities. Product life-cycle management originated in the 1980s in a car industry and it is a process of managing a product throughout its life-cycle. This ultimately leads to an improvement of a product quality, lower risks and a reduction of waste. These benefits are accredited to the integration of a design and engineering processes, together with a continuous reuse of information. Similarities between BIM and product life-cycle management are so clear, that BIM is often referred to the building life-cycle management, as it allows for a creation and management of information about the building for entire life-cycle of a building.

The major obstacle to collaborative working is the interoperability problem, which was already introduced. To assure a full support for entire life-cycle of a building, collaboration level must be high, as all information necessary should be interoperable and, preferably, stored in one repository for an ease of access. Therefore, to use BIM model as a life-cycle platform, the interoperability of information must be assured. To do that, big open BIM approach has to be used. This allows every discipline to contribute to the main model, regardless of which software vendor they use, and regardless where the main model is located. However, one problem collaborating stakeholders might get into is the expected level of detail they are supposed to fill into the model for each phase.

The level of detail required from every stakeholder for each phase was rather clear in the paper-based delivery process, during which each delivery of a phase results in drawings of a certain scale. This scale limits the level of detail possible to fill into the drawing and semantics wise, the paper is “dead”. On top of that, every discipline delivers drawings separately, thus there is no issue with responsibilities, as everyone is responsible for drawings produced by themselves. However, BIM approach requires different method.
The scope of work is “measured” by the level of detail (LOD) which defines both the required

detail of the geometry, but also semantics that are connected to it. The LOD was defined by US-American BIMForum (2018), and there are six standardised levels of LOD (100, 200, 300, 350, 400, 500). BIMForum's documentation provides rather explicit description of each level, but to simplify this, the difference between the levels can be seen in the Figure 18. Notice, that level 400 is the most detailed, as level 500 is not currently used. Level 500 is expected to be used for field verification, instead of more detail in a model. These levels can be paired with individual phases, and if used, these are specified in employer's information requirements.

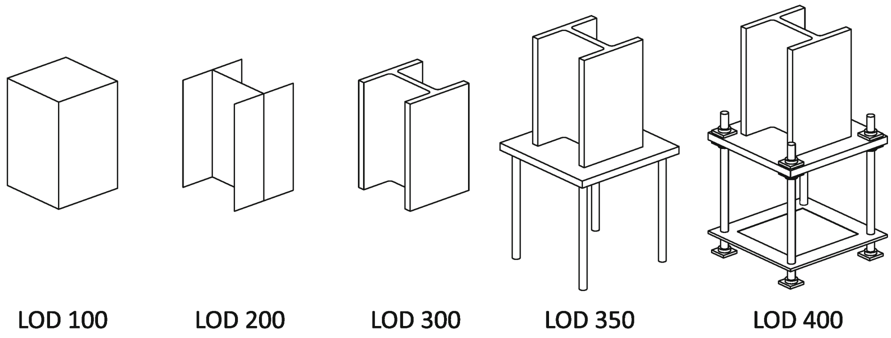


Figure 18 – Level of Detail illustrated on a column (Borrmann, et al., 2018)

It is getting clearer and clearer, that more disciplines and further in the project's design process, more and more information is added. On the one hand, this is great, as model rich in semantics is going to be usable throughout entire life-cycle. On the other hand, large models often face the issue of scalability of BIM. The way data are structured, and the processing power an average company owns, are not always compatible. Major reasons to encounter scalability issues are attributed to the size of a building in general, the level of detail, and to inefficient ways of modelling. The scalability issue is usually represented by sluggish work, during which even the simplest task is almost impossible to complete.

It is not always necessary to work with an entire model and all information stored in it. The processing power will, probably, be more available in the future, but till then, it is necessary to work around the issue. One of solutions is to filter out the data. And specific solution lies in model view definitions (MVD) developed by buildingSMART. These are developed in cohesion with the information delivery manual (IDM), in which the anticipated use of a model is illustrated. Thanks to the IDM, it is possible to make a definition of a model view, which will capture all information required for a certain exchange and make a file lighter for a smoother operation.

However, this is only one side of the coin, the other is the problematic exchange of data, when multi-gigabyte models are not uncommon. Software vendors are looking for a way to solve this issue, one of solutions is to only update parts of the model that were changed, which is called an incremental update. Another way is to use external spreadsheets and databases and link them to a model. In this way, rich semantics are stored separately from a model. Required information is available by a link, therefore, a model stays lightweight. Last possibility is to use BIM (or IFC) server, stored in cloud. These servers allow for object-based management, which allows for query, transfer, updating and management of model data in a partitioned way, allowing many stakeholders to work on a constantly updated model simultaneously.

Accurate model, rich in semantics, should not only be used to construct a building. If one looks at a generic life-cycle of a building, the design and construction phases together will mostly be much shorter than the operation phase. Traditionally, these phases were performed apart from each other, but with the introduction of BIM, it would be a pity to not connect these two phases with the facility management. This way, as-built model might be used as a basis to the facility management. Instead of a loss of data during the handover of the building, these data serve for a smoother building operation.

Completed model is a source of data for information systems used to maintain a building during its operation phase. Currently, COBie is the most common standard to transfer data from as-built model to FM systems. As the as-built model contains too much of irrelevant data, it is first optimised. This optimisation consists of processes such as simplification of a model, merge of operational attributes to one model, spaces are added and so on. However, the as-built model still serves as a rich source for BIM FM model.

6.4 Material passports

The material passport (MP) is a documentation consisting of comprehensive description of given material or product. It is one of the main prerequisites that needs to be fully integrated into a process to prepare buildings for a circular future (Jensen & Sommer, 2018). In the following text, material passport stands for both a material passport, a part passport and a product passport, as the solution for these is the same.

The original idea of the material passport, as it is known in the present, is captured in *Cradle to Cradle: Remaking the Way We Make Things* by McDonough & Braungart (2002). Originally, they called for an “upcycling passport” which would encode all the ingredients in materials, allowing for a future usage of materials. They envision this as necessary due to their belief, that “waste equals food”. They distinguish between biological nutrients (useful to the biosphere) and technical nutrients (useful to the “technosphere”, systems of industrial processes). They strongly advise against a combination of these materials into hybrids, as it is impossible to take them apart and their reuse is dangerous. The “upcycling passports” would allow for an identification of used materials and the intended future of a material after its original purpose reaches the end.

Later, the idea of material passports reappeared in *Resource Repletion: Role of Buildings* by Hansen, et al., (2012) which is co-authored by Braungart. In this book, the MPs are called nutrient certificates. Thus, the inspiration from previously mentioned source is present, as “upcycling passports” are about nutrients as well. The definition of nutrient certificates is adopted by Buildings as Material Banks (BAMB2020), which is a project funded by EU, consisting of 15 partners trying to shift the building sector towards circular solutions. However, their solution will be introduced later. Firstly, it is more important to explain why material passports are important.

It was the industrial revolution, during which the mankind started to exploit material nutrients. Until then, the cycle of materials was circular, as humans were mostly using biological nutrients. These were, due to scarcity of materials, always reused, as it was too difficult to source raw materials. However, during the industrial revolution, it became easier and more affordable to obtain materials in a form of technical nutrients. With the invention of heavy machinery, humans started to have a surplus of products for the first time in the history. (McDonough & Braungart, 2002)

With the level of a progress in a research and new inventions, the situation started to be unsustainable, and the greed for money of corporations got so far, that they even started to produce materials destined to break in certain time, to make customers buy new products. However, every time a product is broken, some valuable materials are lost. This is mostly due to a combination of biological and technical nutrients in one product, which results in a hybrid. One example could be a common textile blend of a polyester and a cotton. If separated, cotton can be composted and polyester reused, yet once they are woven together, it becomes close to impossible to take these apart. Unless products are made with the intention to reuse them later and the ingredients are fully covered in a documentation. And this is, when material passports come into place. (McDonough & Braungart, 2002)

At first, it is necessary to indicate requirements the material passport must satisfy. New buildings are normally designed to be permanent and it is not uncommon for buildings to be fully functional for 50+ years. For this reason, the documentation must be future-proof and readable after 50+ years. Therefore, the priority is to keep information either printed and safely stored or in a future-proof digital file format, which is safely stored and backed up. The information included in the passport might be inputted either in a custom or in a standardised way. It is preferable to input data in a standardised way, as it allows for a consistency and an automation. (McDonough & Braungart, 2002)

Next, it is essential to identify information, that must be included in the material passport. Each product must be identifiable. Thus, it is necessary to include a manufacturer and a name of a product. On top of that, each unique product has its own unique number, to allow for connection with other software and an easy search for the product when needed during its life-cycle. Combination of more materials/products produces an assembly, which is sold as a unique product – all of these must be linked and documented.
Every product should include an illustration, together with main dimensions, which makes it easier to find new purpose for a product in the future. This is accompanied with a “list of ingredients” of a product, which allows for a calculation of the value of materials. (McDonough & Braungart, 2002)

The materials of a given product are categorised based on groupings proposed by McDonough & Braungart (2002). First, they are sorted based on their origin – a material might be either a biological nutrient, a technical nutrient, or a hybrid. Then, each of the materials is rated on a negative-positive list – each material is either an X-material (banned substances), a grey material (dangerous substances necessary for manufacture, which currently have no substitute) or a positive material (substances which are healthy and safe for use).

Lastly, the information necessary for reuse/recycle must be documented. Proposed duration of a product is to be specified. This is accompanied by an instruction how to maintain the product, how to and which parts of the product to recycle/reuse and instructions to separate the materials in a case of a hybrid product. In this step, materials, which should go to a landfill are identified, and this information might then be used for reusability/recyclability report. (McDonough & Braungart, 2002)

The form of material passports is not defined, as it is rather a novelty in the building industry. However, it is possible to present various foreseeable forms these passports can take, the workflow and their advantages and disadvantages. These forms are inspired by the literature review conducted for the previous parts of the theory chapter. However, they still contain some ideas of the project group, as it was not possible to find relevant literature covering this topic.

Paper documentation:
As long as required information is included in the documentation, material passport can be as primitive as handwritten or printed documents. The proposed workflow is illustrated in the Figure 19. The owner of material passports (stakeholder 1) fills them all in with necessary information. The collection of material passports is the base for the material passport report, which is then physically stored in a local (physical) archive of a company. In case other stakeholders (stakeholder 2, …) need information stored in material passports, they must ask the first the owner (stakeholder 1) to share information with them.

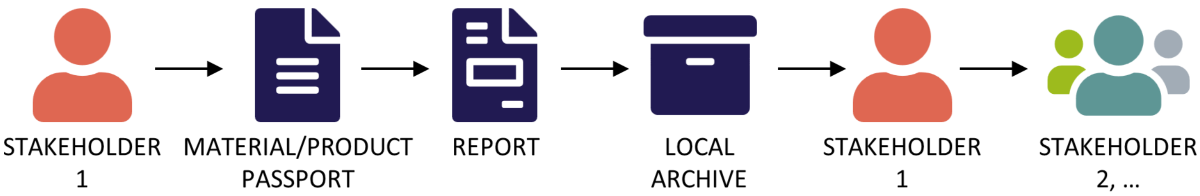


Figure 19 – The workflow of material passports in a paper form

This option comes with more disadvantages than advantages, compared to other forms of material passports.
As for advantages, the paper form is simple to fill in. In order to simplify the task even more, a template can be used. There is, also, no additional learning required to fill information into the template. In the case the condition of the paper and the ink remains readable in 50+ years, there is no risk that future systems will not be able to read data.
However, disadvantages prevail. Physical binders of material passports require a storage, and since these are made for 50+ years into a future, the storing process becomes problematic, as the storage will have to be enlarged over the time to be able to accommodate all the binders. It is impossible to search in physical copies. A register will have to be made and updated to keep the binders in order. Physical copies are prone to damage, in 50+ years, both the paper and the ink will show signs of a deterioration. In addition to that, physical copies can be permanently destroyed by elements like a fire or a flood. All the work behind physical copies of material passports is manual, there is no possibility to automate the process, proving it burdensome to the company and inefficient.

Digital documentation – local storage:

In this sense, the idea is, that all necessary documentation in digital formats is stored locally in premises of a company or an organisation. The proposed workflow is illustrated in the Figure 20. The owner of digital material passports (stakeholder 1) fills them all in with necessary information. Digital material passports are stored in a digital local storage and used to create reports. In case other stakeholders (stakeholder 2, …) need information which is stored in material passports, they must firstly ask the owner (stakeholder 1) to share it with them.

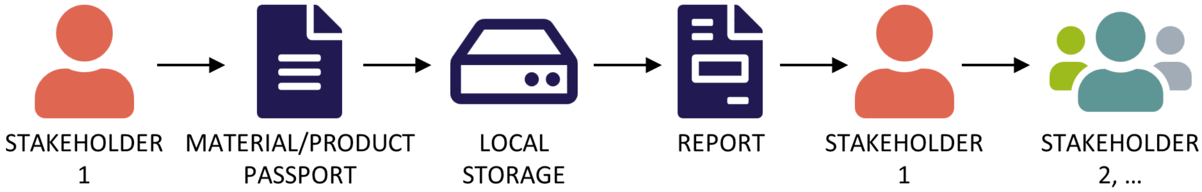


Figure 20 – The workflow of digital material passports stored locally

The main advantage for the company is, that it has full control of the documentation, meaning that the company has the ownership of MPs, just as with physical copies. In case the documentation is stored in formats which proved to be future proof, such as text files (txt), rich text format (rtf), MS word (doc and docx), MS excel (xls, xlsx) or portable document format (pdf), there should not be a problem to access these files in over 50 years. In the case the documentation is indexed well, it is easy to search these files, or even apply some form of an automation. Since all of abovementioned file formats are rather universal, it is easy to share these files with other stakeholders.
For disadvantages, there is a large responsibility of the company to assure these documents are safely stored. Currently, storage solutions are prone to breakage, and a local storage requires continuous back-ups and a frequent exchange of an outdated hardware. In the case of sharing of data with other stakeholders, while keeping the documentation stored locally, it might become troublesome to keep track of the revisions. This is especially true during maintenance and renovation works, where all alternations must be inserted into the system (the access to local files might not be available to stakeholders doing maintenance and renovation work).

Digital documentation – web-based storage solution:

This solution moves all locally stored information to a provider of a web-based storage solution. In this example, it is assumed, that entire solution is executed on an internet. Thus, users must be connected to the internet in order to update or download remotely stored information. The workflow of this proposed solution is illustrated in the Figure 21:

Figure 21 – The workflow of digital material passports stored on a web-based storage

In this case, it is possible to grant access to all of the stakeholders (stakeholder 1, 2, …), throughout the life-cycle of the building. These stakeholders collaborate together to fill in all necessary information and all information is stored on a web-based storage. This collection of information is used to produce reports and all stakeholders might be granted access, if necessary.

There are many advantages to this solution. The web-based storage provider bears the responsibility of a data storage. The storage is literally unlimited, at least for needs of material passports. This solution is available for sharing, it is possible to give certain permissions to various stakeholders and it is easy to keep a track of all revisions and changes in a project. All data stored might be based on a standardised template, which allows for an automation and various calculations, predictions and a visualisation to achieve a better performance of the solution. All data might be downloaded in formats presented in the local solution – or other file formats, based on needs.
However, this solution also comes with some disadvantages. The main disadvantage is, that there is no fully functional platform for such a task. This is due to missing functionalities, such as MPs report creation, on existing web-based storage solutions (Dropbox, OneDrive, iCloud etc.). However, a specialised MPs platform is non-existent at the moment. There are two organisations funded by EU trying to provide a solution (bamb2020.eu & madaster.com), but the functionality is not there yet. The reliance on other storage providers might be risky, as they might bankrupt, for example. Information stored online is prone to hacks, which might affect the competitiveness of the company. Lastly, a web-based storage solution, both offered by other parties or developed inside the company, might become rather expensive to run or to develop.

Naturally, the connection of material passports with BIM model comes into mind. BIM model is a good visualisation of a project and with data included in material passports, the combination could be a strong competitive advantage, especially when a bidding process will be based on a lowest life-cycle cost procurement. This is the belief of the problem group, at least. Group members identified three different solutions with their advantages and disadvantages, as how to connect material passports with BIM model:

Material passports incorporated into BIM model:

The idea here is, that all information that were listed previously as requirements for the scope of material passports are incorporated directly into BIM model. The proposed workflow is illustrated in the Figure 22 on the following page. The stakeholder with an access to the model (stakeholder 1) fills in all required information. All information is stored directly in the model. This model is kept in a local storage. All necessary information (circularity report, reusability report etc.) are exported directly from a proprietary software the model is built in. Files are exported in previously-mentioned future-proof file formats, to assure that every stakeholder (stakeholder 1, 2, …) can read data. However, since data are stored locally, the stakeholder who owns data (stakeholder 1) is the one to share it with other stakeholders (stakeholder 2, …).

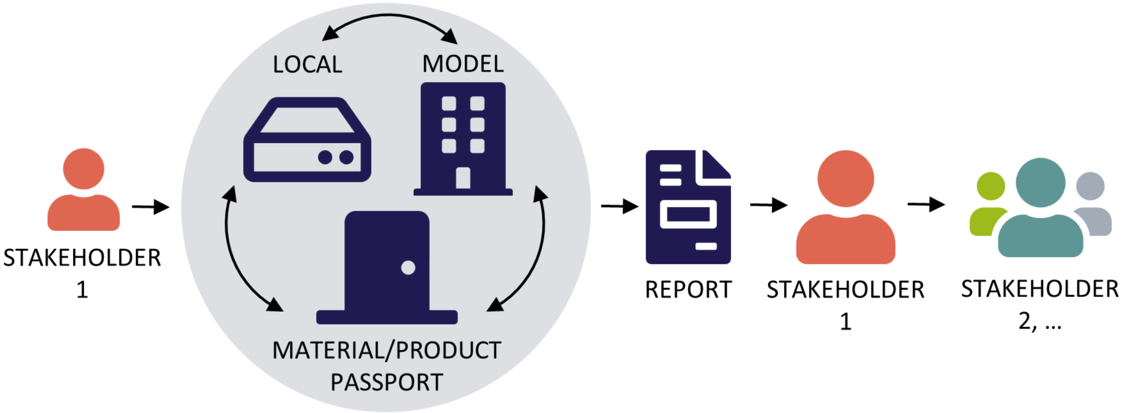


Figure 22 – The workflow of material passports incorporated into the building information model

The implementation of material passports in BIM model could be done through two ways. These are either through user's defined custom attributes of the materials inside the model, or by an implementation of the functionality by the software developer. Advantages and disadvantages for these two ways are addressed at once, as they are identical.
The main advantage of such solution is the user friendliness. All information that are necessary, are accessible from the same model and are stored at the same place.
However, there are too many disadvantages, that are connected to this solution. This solution is not future-proof, as BIM solutions develop rapidly, and their back-functionality in 50+ years is not assured. In over 50 years, BIM might not even exist anymore. The volume of data necessary to be part of a material passport is immense. Within larger projects, this solution would make the model unusable, due to the scalability issue of BIM. Lastly, this solution calls for a proprietary solution, which is troublesome in the case material passports are to be accessible to all stakeholders during the life-cycle of a building. It would be silly to ask every stakeholder to buy specific software package in order to access and to edit a material passport.

Material passports connected with BIM model:
This proposal functions in a similar way as the first one, but with a major difference. The difference is in the connection of MPs and BIM model. The proposed workflow is illustrated in the Figure 23:

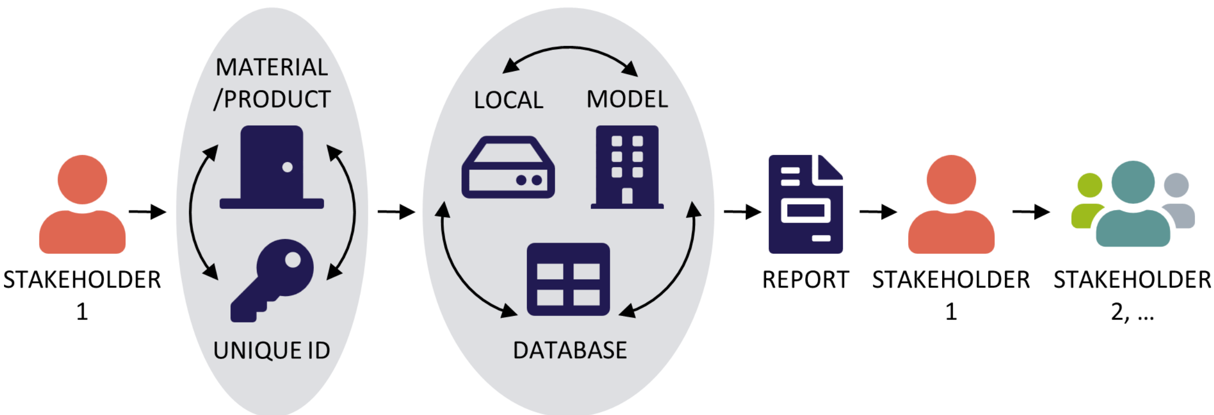


Figure 23 – The workflow of material passports connected with the building information model through a unique ID

The stakeholder with an access to the model (stakeholder 1) fills in required information. This information is stored locally in a database, apart from the model. The connection of the material passport and the model is executed through a unique ID for each material/product. All necessary information (circularity report, reusability report etc.) linked between the database and the model are exported regardless of a software package the model was built in. This is possible through a unique ID, which is a universal identifier of all objects in BIM software packages. This allows all stakeholders (stakeholder 1, 2, ...) to access information they need, in the form of future-proof file formats of reports. However, since data is stored locally, the stakeholder who owns data (stakeholder 1) is the one to share it with other stakeholders (stakeholder 2, …).

Information stored in material passports is located outside of BIM model and are connected with BIM model through unique IDs. The functionality of more advanced tools (such as visualisation reports), that could be incorporated, is turned on only when there is a demand. Once in a demand, the application loads necessary information from the database and connects it temporarily with the model. This solution tackles many disadvantages of the previous solution, the scalability issue of BIM and adds some advantages.
The advantages are, that this proposal of the connection is lightweight and will barely affect the performance of the model. The accessibility of material passports is independent of the model, as all information can be accessed individually. This makes the solution future-proof and accessible to every stakeholder with the access to the local storage, regardless of which software package is being used.
Disadvantages of this solution are in a problematic sharing of the information. This solution implies a local storage of material passports, which makes it difficult to keep a track of revisions and to keep the database up to date with all stakeholders involved in the process. In the case that other party needs the connectivity between the model and material passports, both the model and the content of the database must be shared. BIM models are usually large in size and stored in a proprietary file format, that it might not be possible to open by every stakeholder.

Material passports connected with open BIM model stored in a web-based storage and accessed through a web-based application:
This solution takes all the previously-mentioned benefits of material passports on a web-based storage and adds open BIM model (as described in the theory chapter about BIM) of a building. The proposed workflow is illustrated in the Figure 24 on the following page. Individual stakeholders (stakeholder 1, 2, …) can collaborate and fill in information necessary for given materials/products through a web-based application. This happens at the design phase and is updated throughout the life-cycle of a building. This information is linked to the model through a unique ID. This unique ID is then used to connect the material passport with both the database and open BIM model that are stored on a web-based storage. This interlinked information is used to produce reports (circularity report, reusability report etc.). These reports and information stored on a web-based storage are always available to individual stakeholders (stakeholder 1, 2, …).

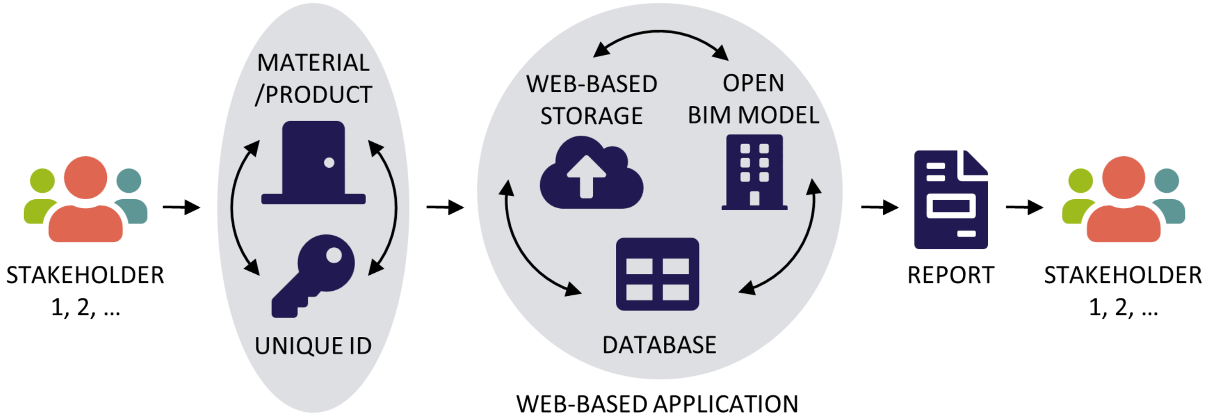


Figure 24 – The workflow of open BIM model connected with a database, stored in a web-based storage and accessed through a web-based application

Open formats, such as IFC, are recommended, as there is no need for a proprietary software to access them. All information, which is part of a material passport, is stored in a standardised way in the database. The standardisation allows for an automation, and a connection with the model. The model and material passports are connected in the same way as in the previous solution, through a unique ID. The functionality of this solution was demonstrated by Dankers, et al., (2014). They used BIMserver as a platform for IFC model, and connected to a content management system of Drupal – both BIMserver and Drupal are open-source. In their solution, Drupal database entities are connected with BIM objects through globally unique IDs.

Both advantages and disadvantages of this solution are very similar to an already introduced solution of material passports stored on a web-based storage, but in this case, open BIM model is added.

The main advantages are the ease of accessibility for every stakeholder, without the need for additional software to be installed. They can edit data throughout the life-cycle of a building without the need to have an access to a local storage of the stakeholder (stakeholder 1), who built the model. Since all material passports are stored in a database, they can be downloaded independently from the model. This independency allows for a download of data in future-proof formats and an edit of data without the need of a connection to BIM model. This assures the future-proofness of data. Data stored on a web-based storage are deemed to be safe. The provider is responsible for the safety of a storage. With the connection of the model and material passports, there are many tasks which can be automated, such as illustration of the product with dimensions or analysis tools to name a few.

One of disadvantages is the need for an internet connection, which might be troublesome in some cases. The other disadvantage is the cost connected to a web-based storage and application, as they are expensive to develop and there is no existing solution with the expected functionality at the moment.

Current development of material passports and their supportive systems is still in a progress. There is one system, which is already available for purchase and usage. It is funded by European Union's *Horizon 2020* research and innovation programme. The origins of the

system are in Netherlands and it is called Madaster. (Madaster, 2018) However, the information contained in their material passports is scarce and the functionality of the system is still rather limited for the intended purpose of this thesis.
Another project funded under European Union's *Horizon 2020* research and innovation programme is *Buildings as material banks* (BAMB2020). This project is in a prototype stage already. The goal of the project is to make a system for systemised material passports. Their idea is to capture all materials in the buildings, aiming to change the thinking about buildings as something permanent. Instead, they propose that buildings are material banks and, once their intended usage is over, these materials can be used in another project. (BAMB2020, 2018)
In the *Proof of Concept for a BIM-Based Material Passport* by Kovacic, et al., (2019), they demonstrated a working concept of a direct connection between BIM-software (ArchiCAD and Revit) and databases containing environmental information about materials.

However, during the research of the current development of material passports for the construction industry, one problem became apparent. This problem is the lack of sufficient information about materials themselves. Ideally, these passports need to cover as much information as "ingredients list" of food or cosmetics industries, which are examples of industries that already provide full documentation of ingredients (materials) for their products.

It was already touched upon that there are material, parts, and product passports, which needs more explanation to clarify the difference between these passports. Based on the literature review conducted throughout the report, the functionality of these passports can be represented by three levels. All these levels have the possibility to be interlinked by unique IDs. Foreseeable link between the levels is illustrated by the Figure 25. This is explained on a simplified wooden door. First, in level 3, there are many materials to make the wooden door panel, such as wood, glue and paint (material 1, 2, …), thus level 3 MP represents a material passport. When these materials are combined together, they create a finished wooden door panel (part 1), thus level 2 MP represents a so-called part passport. To complete the product passport of a door; a door hardware, such as hinges, fasteners and a handle (part 2, …) must be added, creating a product passport – level 1 MP. Further in the report, these are called Level 1 MP, Level 2 MP and Level 3 MP.

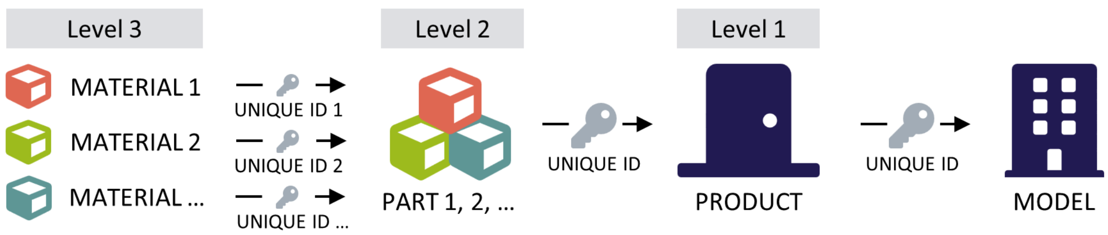


Figure 25 – The hierarchy of material passports

Completely documented product consists of all of these levels of MPs. Due to the complexity of individual levels represented by MPs (Level 1 MP, Level 2 MP and Level 3 MP) the responsibility of a creation of these MPs might be divided between more stakeholders.

The research group, based on the literature reviewed throughout the report, identified three different possibilities of stakeholder's responsibilities for the material passport creation, together with their advantages, disadvantages, and the possible motivation:

The client

As it was already identified, the client is the stakeholder with money. In the case the client requires a building to be circular, the client should bear the financial responsibility to collect all necessary information. The information input would be fulfilled by designers, who are hired by the client. In the case the client wants his building to be circular, designers are stakeholders who make decisions to choose specific materials. Client could be motivated to make a circular assessment of a building by a "circularity rating" certificate, which would specify the level of a circularity of a building. The motivation for the client is the general image of the company for public, which can be increased by achieving the circularity certification, resulting in better CSR. However, this solution might be problematic in a sense that every client would create new material passports, resulting in an unnecessary repetition of the task. Instead, one central organisation, which would provide necessary information for material passports, would be preferred, and the client would buy the access to the data. This organisation could be the government, which happens to be the biggest employer in construction industry (Borrmann, et al., 2018), would benefit from these material passports as well.

The government

The government is the largest employer and as such, should be an example to others and collect data about materials used in public projects. The collection of MPs data by public authorities should lead to a standardised form of material passports without bias. The government agreed to fulfil the waste framework directive to recycle or re-use the minimum of 70% of non-hazardous construction and demolition waste (CDW) by 2020. It is too late to change results by the implementation of material passports, as 2020 is too close, but material passports could be a basis to the fulfilment of upcoming waste directives. This becomes more relevant, as European Union is slowly transforming towards the circular future and material passports could be a good beginning. In the case the government takes the responsibility to provide necessary information for material passports, they will have a good leverage as how to treat CDW. This way, the government can control what materials are used and how they are re-used at the end of a buildings' life-cycle. This can be controlled through implementation of circularity targets for a given building, which would have to be achieved for a building to receive a permit. Similar to energy requirements at the moment. Since government is in this case the provider of data about materials, this gives them the control to privilege the materials that are suitable for re-use or recycling.

Manufacturers

Manufacturers are stakeholders who have the control over materials used in a product. This suggestion is inspired in a food and cosmetics industries, in which manufacturers are responsible for a provision of the list of ingredients and the documentation about ingredients that make up the product. This way, the information contained in material passports would be accurate and precise, as it would be made for every product by an individual stakeholder. This would probably reflect in a price increase of the materials, but the cost could be reimbursed when a building is at the end of the life-cycle and materials now can be sold for a higher price, than they could be in the case they were undocumented. There are two ways identified as how manufacturers could be motivated to provide necessary information for material passports. Since European Union is turning towards circular economy, the number of clients who require this kind of information is going to be increasing. The availability of data could be a turning point for a client to choose a specific manufacturer, leading towards a competitive advantage – in this sense, this motivation is based on positive incentives for a manufacturer. Other way would be a legislative motivation controlled by financial penalties, if not provided. Once again, this idea is inspired in the food and cosmetics industries, where there is a legislation to provide all ingredients and a documentation of the product and not doing so results in penalties.

Above-described problem of varying responsibilities in regards to creation of MPs levels is further discussed in the discussion part about the practical implementation of the concept.

7. Discussion

Waste is, as it was already mentioned throughout the report, considered as one of the biggest global problems. It is causing different problems, which are affecting the environment in a negative way. From the increased toxicity of a soil caused by a usage of landfills, to problems with air pollution caused by the incineration of waste in some of the countries. Only in the area of EU, the construction industry is responsible for one third of waste produced annually and based on some researches, these numbers are growing on a yearly basis. This is, mostly, due to increased rate of construction, connected to constantly growing cities. However, the construction industry is not only producing waste during the initial construction, where buildings are erected, but during the whole life-cycle, including the demolition phase. Due to the size of this problem, governments decided to act and to actively support the decrease of CDW. One of the examples can be EU, where member states agreed to a common goal – to recycle up to 70% of CDW before 2020. While some countries already reached the goal, for others, there is still a long way till they reach the target.

In order to provide a possible solution for this problem, the project group conducted a literature review of subjects, closely connected to the focal problem, which lie in the area of the interest of the project group. These subjects are circular economy, design for disassembly, material passports and building information modelling (BIM). The principle of how the CDW should be treated is based on topics of the circular economy, design to disassembly and material passports and this principle is explained in the first part of the discussion chapter – Discussion of the theoretical background of the concept. BIM is seen more as a tool how this principle should be implemented into the reality, which will be explained in the second part of the discussion chapter – Discussion of the practical implementation of the concept.

7.1 Discussion of the theoretical background of the concept

The circular economy

The circular economy (CE), in recent years, became the more and more discussed subject of the academia. While initially the concept was developed as an economic model with the ecology in the mind, most of current researchers see CE as a way how to deal with a growing problem of waste generation.

One of the main benefits of CE is to transfer the current industry from the linear way of the production into more environmentally friendly closed loops of CE. Currently, the most of the construction industry is working in the way of linear production, where brand new products are used for every project with no intention to reuse them after they serve their purpose. This results in a plundering of scarce resources and an increased waste generation, where the material, which was used only once, is becoming waste. However, the main principle of the circular economy is advising to stop the linear way of production and to shift into the closed loop of a production. In this case, the materials, that were used already, and are seen as waste, will become new materials for a new project. This shift of the industry from the linear way of a production into the circular is also illustrated in the Figure 26:

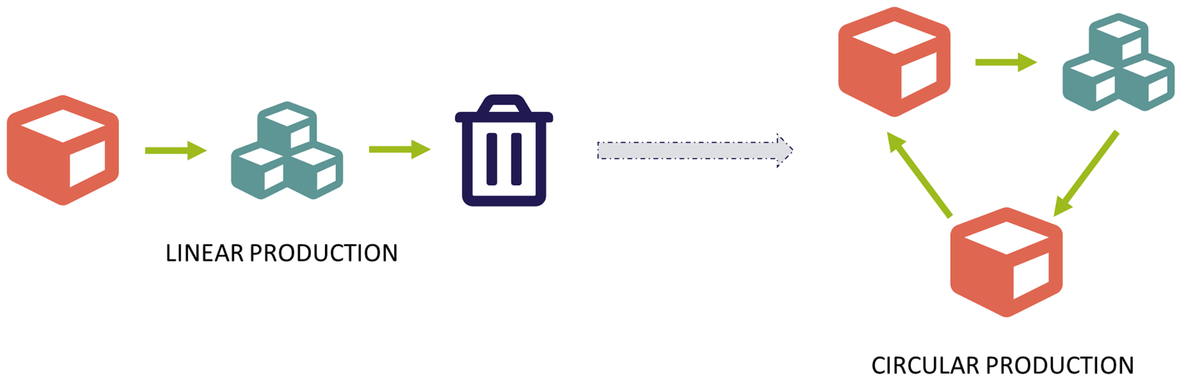


Figure 26 – The shift from linear production into the closed circular production

One of the basic principles of the circular economy is, that all of materials or products should be reused and/or recycled in the way, where their initial value is either improved or kept as a same. With this in a mind, the quality of a product should not be lowered. This might result in different options how to repurpose materials. Currently, the best possible way how to work in closed loops, is to repurpose final products. This means to reuse whole products again, instead of taking them apart and reusing individual parts of the whole product. The example can be a repurposing of a door from a building, which will be demolished, and using the door in a new construction. This offers a solution more reasonable than taking the door apart and reusing or recycling individual parts, such as a handle, a lock or a wooden frame. However, the circular economy might go much deeper, where individual elements can be broken down into individual parts and these can be further reused or recycled. This allows more possibilities in regards to circularity of production in the industry.

To implement this way of work in the construction industry, it is necessary to start thinking in the way of CE. This means, that the process has to start from the early beginning, when a building is planned. All projects have to be planned with the consideration if materials can be reused after the end of a building's life-cycle, and in what way they can be reused. This presents another benefit of CE, as one of the biggest reasons why the construction industry is actually generating significant amount of CDW, is a low consideration about materials and CDW.

Another benefit of the circular economy is the improved consideration of materials used in the construction industry. This is mostly due to the fact that one of the main reasons for such a significant waste generation in the industry is a low consideration of materials. However, with currently increasing pressure from a government and a public movement towards the greener society, the construction industry will have to consider the switch from a linear work into closed loops, in order to satisfy social needs. This is even more specific for some areas, as China or EU, where governments believe that the implementation of CE is a way to decrease a waste production. These governments, therefore, developed plans to promote and to implement CE into their regions. While the Circular economy package, developed by EU, is currently not binding for the member states, it shows the interest of EU to follow such plan. Therefore, it can be expected, that some of the circularity steps will become mandatory in near future.

These expectations come with an improvement to the industry fight against waste. This is done by forcing designers to consider their ideas from the beginning of projects. With the circular economy as a goal for some of constructions, a designer will be forced to choose right materials to allow her to reuse or recycle these materials at the end of the life-cycle. Another example of improved design in regards to the circular economy is connected to the way how a building should be built. This is because not even a material which is highly recyclable, cannot be recycled if it creates a homogenous/composite/complex component. Therefore, the shift towards the circular economy will not only bring changes in the way how CDW is created, but more importantly, it will increase awareness of the problem in early project phases, in order to avoid a creation of CDW.

A big advantage of the circular economy is the improved development in academia. While the circular economy as a model is over 50 years old, it is only recently when the development in the CE research happened. CE became an area of interest in the recent five years due to researchers' belief, that it can present a solution to the current problem with waste production. This is already presenting a significant improvement, as one of the biggest downfall for an implementation of CE is a limited research conducted about the model. However, with a current pressure on the academia, researchers conduct more and more studies to assure a sustainability of the model, to decrease the uncertainty of the implementation of the model, and to develop tools how CE can be implemented. This results in the increased awareness about the circular economy and, therefore, it makes CE more accessible for companies.

Last identified advantage connected to the increased interest about CE by academia is, that more students are educated in the CE and, therefore, the access to the knowledge about CE will be more available for the market. While now with the limited availability of CE educated people, only the biggest companies are able to afford their services, more educated people will increase the probability of them being hired by small and medium sized enterprises (SMEs). This is important, as SMEs' present the most of the global production. Another improvement connected to the increased interest of academia on CE is the development in the field of the technology. While the main goal of CE is to recycle up to an atom, possibilities of doing so are limited. While there are some examples in fields of chemical or precious metals, the possibilities are still limited. However, with the high importance assigned to the implementation of CE, it is only a matter of time when more and more technologies suitable for reusing and recycling of products will be available.

Based on advantages gained from closing the loops of the production and switching from the linear way of work in the building industry, the project group considers the implementation of CE as the right way of decreasing the generation of CDW. The implementation of the circular economy should lead into improved consideration of materials used for construction projects in the early stages of planning. The future of these materials should be considered in the process, when they will not be seen as a future waste, but rather as resources which can be used again. This should be closely connected to the research development in the circular economy in order to find the best practices for the industry and in improved possibilities of CE implementation by developing new technologies.

Stating that the implementation of CE will solely solve the problem of CDW would be short-sighted. Therefore, the project group also considered causes of the focal problem, defined in the final problem tree, as seen in the Figure 9 in the Problem tree. This was done in order to understand whether the implementation of CE can solve these causes of the problem or if it is only trying to neglect and/or avoid them:

No definition of waste responsibility

One of the main causes of increased generation of CDW detected in the problem tree is no definition of waste responsibility. While in the construction industry, it will be always a client who should be responsible for the final attributes of the project, it is hard to state that she should be the only responsible stakeholder in regards to CDW generation. The circular economy is, therefore, taking more holistic approach, rather than just making one stakeholder responsible for the whole problem. When the circularity approach of the production is followed, it is necessary that whole supply chain, which is participating on a project, keeps the circularity in the mind. It is not possible to build the circular economy building, if the products used for the construction of it, are not produced in a way to allow the circularity. This works also in the other way, that even when the components are produced and assembled in the way that they can be fully recycled or reused, this attempt to implement the circular economy will fail, if the principles of circularity are not followed at the end of life-cycle. Therefore, this must be a joint movement, where a client will wish for the circularity; designers will design with CE in the mind; producers will produce out of recycled/reused materials, and offer recyclable or reusable components; and builders will build with the circularity in the mind (sort waste on the site, reuse what can be reused and recycle what cannot). The maintenance must be also done in a manner of CE, and the same goes for the demolition. At the end, a client is the one who has requested the implementation of CE into the construction process, but with the pressure of the society, it is only a matter of the time when other stakeholders will have to join the movement towards CE. In order to successfully implement CE, the whole supply chain has to follow principles of CE. Based on these findings, it can be stated, that while CE is not putting waste responsibility on one specific stakeholder, it puts this burden of a responsibility on shoulders of all stakeholders, which are actively contributing to the construction process.

Profit focused industry

Another cause of the focal problem detected in the problem tree was the profit focused industry. While currently CE is seen mostly as the ecological movement to decrease the waste generation, the origin of the idea is in the economic model. Constructing with CE in mind might offer significant savings in the construction cost of materials. This is due to the possibility of turning waste into new materials, which can be used for a construction and by that, a decrease in a cost of new materials. This is due to the lower cost burden connected to the reusing of materials used in previous projects, rather than constantly buying new products. Reusing of bricks from buildings, which are being demolished, might present a better option that just buying new ones. In this case, the problem can be in elements such as windows or doors. These might not always follow current standards in regards to technology, safety and/or aesthetics. However, the possibility of updating these parts might still present the way of significant cost savings. Lastly, the idea of recycling of CDW, rather than dumping it into the landfill, presents more economically suitable option. This is due to lower tax rates for the recycling of materials, connected to an annual increase of tax rates for using landfills.

Other reasons for better cost efficiency might be an impact on the employment rate and GDP of countries. Based on researches conducted in the area of EU, it can be predicted, that full implementation of CE might present a possibility to create millions of working positions, and increase a profit produced by the industry in countries. These expected benefits of the implementation of CE into the industry might increase motivations of the government to support the decision of CE implementation into companies. This is often connected to different incentives aimed to motivate companies to take the step forward and to invest. Therefore, it can be expected, that this might be also the case of CE implementation, as it can be seen that the whole concept is already catching the attention of governments, as they can see the solution for waste problem in it. While it might seem expensive to implement the circular economy in the construction industry, this can be mostly seen as a misconception connected to the high initial investment. In a long-term return, the circular model might be actually more cost effective than keeping traditional linear model. This is due to cost savings connected to CE and possible incentives for companies implementing CE.

Waste awareness

Another cause of the focal problem was connected to the waste awareness. Connection of CE to waste awareness was already discussed in the text above. The implementation of the circular economy is already becoming a point of an interest in many countries (China and EU member states) This will increase the awareness of waste and ways of dealing with it. This, in the connection to increased attention of academia given to the subject, supports the implementation of CE as one of the possible ways how to increase waste awareness in the construction industry.

Hard to recycle all materials

Ability to recycle some materials found in CDW was identified as one of the main causes. Academia expectation connected to the implementation of CE are, that switching to CE might have a positive impact on the development of recycling methods, and new, better recyclable materials.

Low taxation on waste generated & Missing incentives to recycle

Lastly, low taxation on generated waste and missing incentives was another problem identified in the problem tree. The connection of CE to this cause was discussed above in parts about the understanding of annually increasing taxes connected to non-recyclable waste and high potential of incentives for companies implementing CE.
These are the last causes that were identified in the problem tree, barriers to circular economy implementation follow.

Barriers of the circular economy implementation

The connection of the above-mentioned causes of the focal problem is even more obvious in barriers for the implementation of CE. Most of researchers tend to agree on possible benefits connected to the implementation of the circular economy. However, they also agreed on barriers, which are stopping CE from the full implementation. These are closely connected to cultural barriers, such as low concern and awareness about waste; legal barriers connected to incentives and forcing of CE by governments; market barriers connected to differences in the supply chain and, lastly; technological barriers about a lack of a developed technology needed for the implementation of CE. Yet, based on the project group's analysis and further discussion of CE topic, it can be stated, that these barriers do not represent the actual problem for the implementation of CE.

Steps of the circular economy implementation

With the understanding of benefits connected to the implementation of CE the question which currently stands, is not if the circular economy should be implemented, but what steps are necessary to successfully implement it into the construction industry. For this purpose, Adams, et al., (2017) came up with different aspects of the implementation of CE into the construction industry. They looked into different phases of a building life-cycle, in order to understand what processes, and why, these processes should be controlled, in order to achieve full circularity of a construction.

First aspect of CE implementation starts with a design phase. In order to have a building following the idea of the circularity, it is important to start with the implementation of the idea in the earliest possible stage. Therefore, buildings should be already designed in a way to allow the circularity of a building. This means, that individual components used for the construction of CE building have to be separable and it must be possible to disassemble them. This has to be done in order to allow the construction to be taken apart and to use individual components on other constructions, or allow for the recycling of individual parts. With high consideration of the circularity during the design phase, designers are also able to choose the correct material to allow later reusing or recycling of materials. Adams, et al., also proposed to implement design for disassembly, design for adaptability and flexibility, design for standardisation, design out waste, design in modularity, specification of reclaimed materials, and a specification of recycled materials.

Second aspect is a manufacture and supply. This aspect is mostly focused on the manufacturing of components used in the building industry. If the circular economy is implemented into the certain aspect of the construction industry, individual elements used for the construction should allow better circularity of products. That means, that during the design process, types of materials, shapes, types of a construction and other attributes should be considered to allow better disassembly and a later repurposing of materials or components in general. Steps, advised by Adams, et al., to allow circularity in this aspect, are following eco-design principles: use less materials/optimise materials use, use less hazardous materials, increase the lifespan of materials, design for product disassembly, design for product standardisation, use of secondary materials, take-back schemes, and reverse logistics.

Third aspect is in regards to a construction process. Main purpose is to minimise the creation on waste on a construction site and an implementation of the closed loop of products into the construction. This means, that reused and recycled materials should be used as a primary material on construction sites, and waste production on a site should be minimised in every possible way. For the third aspect, Adams, et al., advise to minimise waste production, procure reused materials, procure recycled materials and prioritise off-site construction.

Fourth aspect is in regards to a refurbishment/maintenance phase. For the purpose of this phase, a building should be designed in a way to allow minimal maintenance of a building with easy access to any repairs and upgrades of a construction in order to easily adapt a construction to new needs and standards, and therefore, to prolong a lifespan of a construction. Minimisation of waste, minimal need for the maintenance, easy reparability and upgradability, adaptability and flexibility are processes advised by Adams, et al.

Last, fifth aspect, is in regards to the end of life of a construction. During this phase, a building should be deconstructed, instead of demolished, to allow the reuse of materials and components on future projects. In the case of products which are not suitable for reusing, the recycling should be the primary option. At this step, Adams, et al., advise to follow processes of deconstruction, selective demolition, reuse of products and components, closed-loop recycling, and open-loop recycling.

Design for disassembly

While many actions are advised by different researchers, the project group decided to focus on the design for disassembly (DfD) as a specific way of the implementation of CE into the construction industry. The reason for solely focusing on the design for disassembly is the project group's belief, that most of advised processes of CE implementation in the five above-mentioned aspects are partly, or fully, covered by DfD. The connection between the design for disassembly and few other proposed ways of CE implementation into the construction industry is described by the Figure 27:

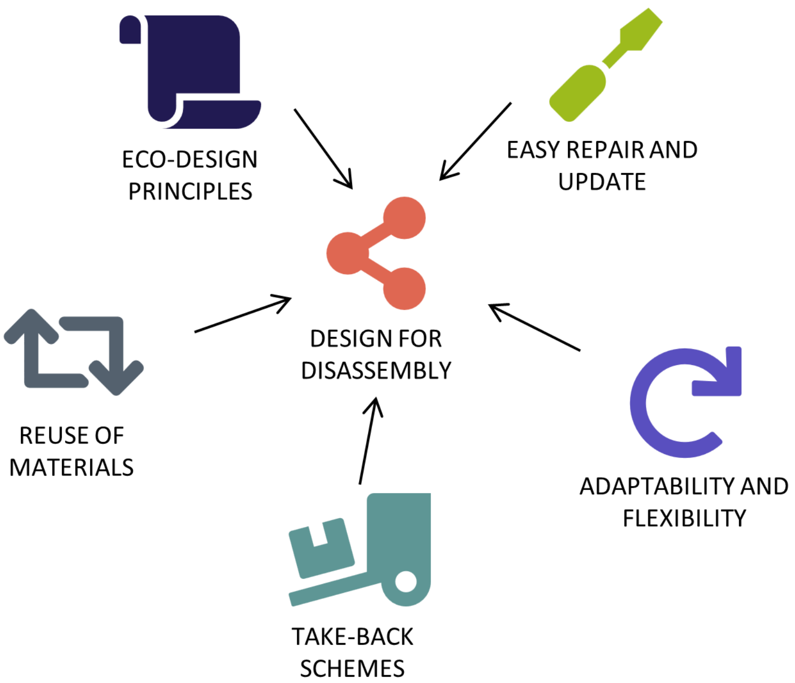


Figure 27 – DfD connection to other advised actions connected to CE implementation in the construction industry

The Figure 27 shows a close connection between the design for adaptability and flexibility and DfD. This is due to the project group's understanding that in order to create adaptable and flexible design, it is necessary to allow a construction to be updated over the time. Here, the DfD plays an important role, as it allows parts of a construction to be individually disassembled and changed, in order to adjust a construction to new standards.
Another example shown in the figure is a connection of the easy repair and upgrade with DfD. Here, similar to adaptability and flexibility, the DfD allows to simplify the process of a repair and an upgrade, mostly based on the simplified process of disassembling, allowing an easy access to all parts of constructions, which need to be changed, or repaired, during a construction's lifespan.
Another connection can be seen in eco-design principles, which are commonly accepted as one of the main principles for DfD. This is due to DfD's main focus on the prolonging of a building's lifespan, by easy upgrading and allowing of a reuse of materials used for a construction.
Next connection can be seen in take-back schemes for the suppliers, which allows suppliers to recover original products used for a construction, for further upgrading or reusing. Here, DfD plays a crucial role, as it allows individual elements to be taken apart without any damage caused to the element. By this way, a decrease of the original component's value is limited.
Last but not least, the figure shows, that in order to reuse materials on construction projects, it is necessary to separate them. With the traditional methods of design and construction, individual elements often create homogeneous/composite/complex component, where the separation is not an option, at least not without a permanent

damage of materials. Therefore, in order to allow easy deconstruction of individual elements/materials and in order to allow their reuse, DfD should be implemented.

The connections presented above, are used only as an example to show the interconnection of advised activities for the implementation of CE with DfD. It is not in the intention of the project group to state, that other activities are not connected to DfD, or that stated activities cannot work separately. However, the project group has a strong belief, that implementation of design for disassembly in the construction design process might be highly beneficial on the other CE implementation activities and, therefore, in the implementation of CE in the construction industry.

Disassembly, as a process by itself, is a process of a systematic removal of desirable components from a product at the end of its useful life. This allows these parts to be further changed, fixed or updated, in order to prolong the lifespan of a whole construction project.

In the case of traditional design methods, the disassembly of a building is not usually possible, as individual materials and components often create complex components, which are irreversibly linked together, without any possibility to take them apart. This situation is common in the case of a prefabricated concrete element, where possibilities of taking a construction apart without a damage are very limited or none. Another example can be a brickwork, where, without a cautious design and a suitable connection between individual bricks, a complex component is created, without any possibility to take components apart and reuse them. This is going exactly against the main goal of the circular economy, as it should allow us to recycle all of the produce up to atoms.

In order to achieve this goal, it is, therefore, necessary, to focus on it from earliest stages of a project. The implementation of DfD allows for an optimal solution to achieve such goal. DfD forces designers to think not only about a look and a buildability of their design, but also about the end of the life-cycle of a construction. Designers have to focus on the choice of right materials, to allow prolonging of the product's lifespan and further reusing and/or recycling of materials. These choices help designers to fully follow the idea of the circular economy. Another advantage connected to DfD is, that the whole process of the deconstruction is easier than in the case of the traditional construction. This is due to the goal of DfD to minimise the number of disassembly operations by limiting the number of element connections, and their simplification.

As the process of DfD might be beneficial for all stakeholders participating on a construction project, the idea of working on the web-based storage is worth the consideration. It provides all stakeholders with an easy access to data connected to individual products. This includes the producer of a product, who might produce online libraries with their DfD product, designers designing buildings and finally, access for construction workers responsible for the assembling and disassembling of a construction at the end of life-cycle.

The project group considers design for disassembly as a suitable way for the implementation of CE into the construction industry. This is due to the DfD goal of allowing systematic disassembly of individual building components, which can be done in sequences. By this method, individual parts of a construction can be easily updated to prolong the lifespan of the whole construction, but more importantly, used components can be simply disassembled at the end of their life-cycle. These components can be further reused or recycled. Another reason why the group sees such an opportunity in the implementation of DfD is, that rather than dealing with CDW problem at the end of a building's life-cycle, it tries to prevent occurring of the problem in the earliest stages of the project.

However, the project group is fully aware of the complexity connected to the execution of DfD projects. All DfD projects must consider connections used on a construction, separability and recyclability of materials, and the best practices for a disassembly. All these data, about the materials, must be stored in the proper way and used during deconstruction.

Material passports

In this case, material passports can play an important role, as they present the way of a comprehensive description of materials or products used in a construction. After the literature review, the project group shares a strong belief, that material passports present a suitable way of consistently storing all data necessary for the disassembly and the circularity purposes of used components. It offers a way how to store this data for the extended period of time, as the expected life expectation for some of constructions is over 50 years.

For the successful usage of material passports, it is necessary to consider, what are information, which need to be stored. This is important in order to avoid a surplus, or a lack of information, and therefore, a confusion. Based on theory chapter about material passports, all products should be easily identifiable by a unique ID, geometry and basic data such as dimensions. This should be followed by a list of materials or components, from which the final product is composed. This, together with instructions how to maintain and disassembly a product, should satisfy needs for information in regards to fulfilling goals of DfD and CE. However, more specific information about a composition of material passports will be presented in the second part of this discussion – Discussion of the practical implementation of the concept.

Other questions in regards to material passports are connected to the way how they should be stored and operated. One of the options is to create traditional paper reports stored in archives. This, however, present more disadvantages than advantages, as problems occur with the accessibility to information and the ability to store sufficient amount of data for a period over 50 years. Another option is to store digitalised data on the local drive. While this option might bring some improvements in the easier way of storage of data, a possibility of losing the data and still occurring problems with the accessibility for all stakeholders makes this option insufficient. The project group, therefore, believes in the usage of the web-based storage and application, as this solution offers a sufficient way of a data storage with a back-up option, together with an easy accessibility of data. The project group advises the implementation of BIM model into the process.

Building information modelling

Building information modelling is, still, a relatively new method in the construction industry. It allows stakeholders to work with a 3D based model filled with information connected to specific components and parts of a project. Therefore, together with a web-based solution, it presents a suitable way of storing material passports in a close connection to an actual project, with an easy accessibility for stakeholders. However, the incorporation of a material passport into BIM model might occur as problematic and could result in more disadvantages than advantages. Thus, the connection of material passports, stored in a database, and connected to BIM model by unique IDs of components, is seen as a viable solution by the project group. This will be further discussed in the following part of the discussion – Discussion of the practical implementation of the concept.

To finalise, the project group members, based on their understanding of the project case, consider the implementation of CE as a possible solution for the problem with increasing CDW in countries of EU and globally. Based on switching the construction industry from the linear approach to the circular, it will be possible to support better reusing and recycling of materials used in the construction industry, with the ultimate goal of recycling up to atoms. The project group is fully aware, that this switch might not initially include whole construction industry. However, even with a partial implementation, the decrease of waste production can significantly improve environmental and social conditions. Further, the project group believes, that CE should be implemented in the connection to DfD, as this allows the reusing and the recycling of the most of components, without decreasing their original value. To keep the track of data necessary for DfD and CE, the material passport should be generated in a connection to necessary attributes. Data of material passports, stored in a database, should be further interlocked to BIM models by unique IDs. This should allow higher usability of the whole concept, and, therefore, easier implementation of CE.

The aim of this part of the discussion chapter is to present the reader with the understanding of the principles used in the concept, advised by the project group. This is necessary, as the concept of CE is still quite new and there are no specific data resulting from the implementation of CE in any of construction projects. While this part of the discussion chapter presents the project group's understanding and the connection between three topics of the circular economy, the design for disassembly and material passports, the next part of the discussion chapter will present the project group's proposal how this concept can work in the real-life scenario and in the connection with building information modelling.

7.2 Discussion of the practical implementation of the concept

Information obtained throughout the theory chapter and the first part of discussion chapter suggests, that BIM could be used as a tool to implement the circular economy into the construction industry. Major part of this implementation are the principles of circular economy and design for disassembly, connected through material passports (MP) with BIM model. However, as it is mentioned throughout this report, BIM is a tool to implement the circular economy into the construction industry. Material passports represent a connection necessary to implement CE and DfD into the construction industry. While the circular economy cannot be fully achieved without a detailed specification of materials used, BIM is not mandatory for the implementation of CE and DfD into the construction industry. However, BIM can make the implementation easier, as it uses already created geometry and allows for a visual connection with material passports.

This part of the discussion elaborates on topics identified in the theory chapter and connects them together in order to create a basis for the concept. Topics of the theory chapter are combined as illustrated in the Figure 28:

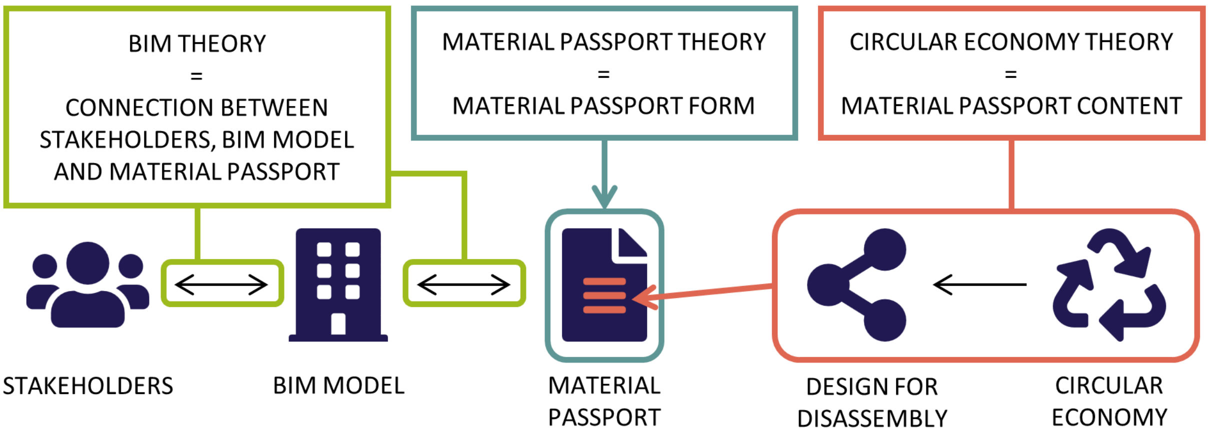


Figure 28 – Theory direction

The theory chapter about material passports serves as a basis for the form of the documentation. Theory chapter about circular economy and design for disassembly serve as a basis for the content of the material passport. The connections between stakeholders, a material passport and BIM model are based on the theory chapter about BIM.

Very long duration of the life-cycle of a product and a fragmentation of the industry represent two most significant obstacles to overcome, in comparison to other industries, when it comes to the implementation of the circular economy into the construction industry. Therefore, these obstacles are primarily considered, when it comes to this concept, as they are the major influencers to the form of the material passport.

Since a building's life-cycle duration is usually expected to be over 50 years, this must be considered when it comes to the form of the material passport. This mostly means, that data that were inputted in the present must be accessible in the future. Six different forms of material passports were introduced in the theory about material passports. The form is, apart from the need to be future-proof, influenced by the number of stakeholders who have to have the access to the documentation. Since it is desirable that all stakeholders have the possibility to access material passports throughout the entire project's life-cycle and from many locations, the solution proposed for this case is based on a web-based solution (a web-based storage and a web-based application). Data necessary for a content of the material passport are stored in an open-source database in a standardised way, to which every stakeholder can contribute, and download data from. This is explained in more detail further in this part of the discussion. The storage of information in the database in a standardised way allows stakeholders to export into various file formats through pre-defined templates. Information can be exported into formats, which are deemed to be future-proof – data in the database is not formatted, but templates used for the export to these formats make the data organised and user-friendly during the export. This solution additionally allows for more templates for file formats developed in the future, in the case there is a need for it.

The construction industry is fragmented and there is no actual leading company which would own the entire supply chain. Therefore, the responsibility for the creation of material passports is also fragmented. Because of that, this concept relies on three gradual implementation phases represented in three levels of materials passports. These levels were identified in the theory chapter about material passports and they define both the scope of the passport (level 1 MP – elements; level 2 MP – parts; level 3 MP – materials), but also the stakeholder responsible for the creation. This solution allows for a partial implementation, which can be initiated solely by a client (represented by designers, main contractors and subcontractors). However, it is necessary to connect more detailed material passports (level 2 and level 3 MP) in the future, as they become available, to achieve a full implementation of material passports. This is illustrated in the Figure 29:

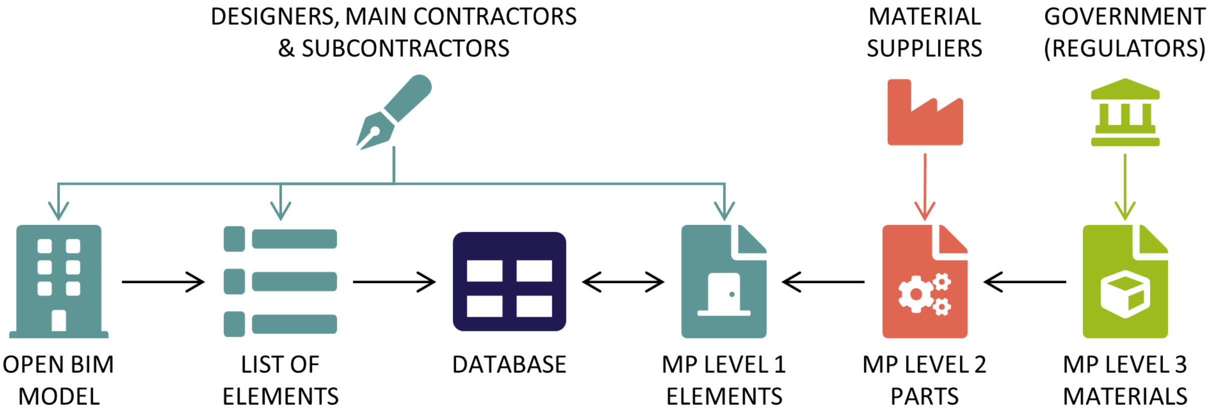


Figure 29 – Material passport levels

At first, it might sound contra productive to separate responsibilities for the creation of material passports. And if there was a possibility to make the entire industry to instantly shift towards circular economy, it could be. However, the construction industry is known for a slow innovation and it requires a gradual, instead of radical, shift. The need for a gradual implementation of material passports is the main reason to separate MPs to levels and to connect each level with a different stakeholder group. This solution comes with many advantages. The advantages and disadvantages linked with the abovementioned stakeholders contributing towards creation of MP are preliminarily introduced in the theory about material passports. Following section explains differences between material passport levels, main contributors for each level, the form and workflows, as well as the functionality.

Level 1 material passport:
The first level of a material passport is the backbone of the circular economy implementation. Without any regulation in the present that would force clients to create material passports, the motivation is solely on clients to create such documentation and the circularity assessment of a project. However, with the steady movement of EU towards the circular model, it can be expected to see regulations asking for the circularity in the future. Nevertheless, throughout the report, many motivational aspects why clients could be motivated to implement the circularity into their projects were identified, the major ones are:

1. Improvement of companies' corporate social responsibility.
2. Better control of property's elements due to a detailed documentation which can easily be connected with facility management systems.
3. Fiscal savings throughout and at the end of the building's life-cycle – documented elements can be sold/reused for other purposes and the landfill tax avoided.

As it is indicated in the Figure 29, designers, main contractors and subcontractors are responsible for the creation and contribution towards the BIM model, list of elements and the first level of material passports. This is mostly due to the fact that earlier the decisions and changes are made, easier it is to implement them – as it was demonstrated on The MacLeamy curve in the Figure 17 on page 60. Large percentage of construction waste generation is attributed to designers and poor design choices in regard to the end of the project's life-cycle. Early implementation of level 1 material passports allows for timely circularity analyses and suitable changes to the design. After the handover, facility managers join to contribute, as they cover the rest of the life-cycle of a building and are responsible to keep the material passports up to date.

Since the proposal relies on a collaborative contribution (big BIM) of stakeholders in open BIM model, the matter of the ownership of data is taken care of by BIM execution plan, employer information requirements and by the specific choice of a contract, such as the integrated project delivery contract or similar.
As the proposed concept relies on a collaboration of stakeholders, it is foreseeable, that it will be necessary to merge BIM models originally modelled in different BIM software packages. Since these often use proprietary file formats, it is recommended to use an open file format, such as IFC or similar to merge the files for collaborative use. It was already introduced in the theory chapter about BIM, that IFC is often associated with interoperability issues. IFC is great when working with geometry, but it lacks when it comes to semantics. For the purpose of the proposed concept, however, there are only few properties that are needed for the functionality of this proposal. This means, that IFC is appropriate for the task even with these drawbacks. What could become a problem is the scalability issue of BIM. One of the problems connected to BIM models is, that they are prone to be overfilled with information, and this might be even bigger problem when more models are merged together. This results in multi-gigabyte files that are sluggish to work with and often must be

partitioned to make these workable. The proposed solution to both the interoperability issue and the scalability problem is illustrated in the Figure 30. These problems are, additionally, minimised by an introduction of a web-based database to store additional information indirectly from the BIM model. This is explained later in this part of the discussion chapter.

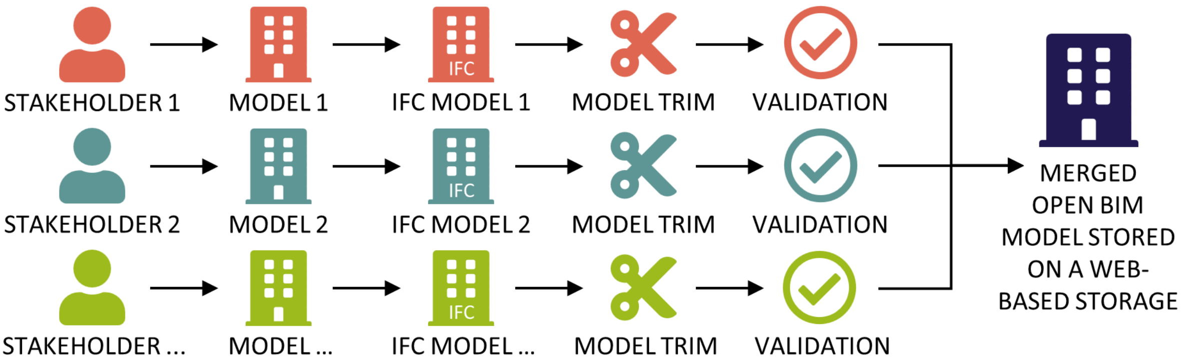


Figure 30 – BIM model workflow

In the proposed workflow, illustrated in the figure, before the model merge, all stakeholders work on their own model, which can be in a proprietary format. When it is time to deliver the data for the circularity assessment, individual stakeholders export the model into IFC (or another open file format specified by a client). This is followed by a model trim (filtration of redundant data), either through a trimming template, or by a custom model view definition. This idea is partly inspired in the functionality of COBie, which is used to export data from BIM model for subsequent use with facility management software packages. The trimming step should solve the scaling problem of BIM. Before data are merged into one model, there is one last step, which is the model information validation. During the validation step, it is assured that all required information is part of the model. The validation is based on a validation template and in case there is data missing or in a wrong form, this is fixed before files are merged. The validation step should solve the interoperability issue of BIM.

The proposed content of the material passport consists of two parts. First part is pulled from BIM model – is primarily used for identification purposes of each BIM element (BIM representation of an element). The second part is manually inserted by stakeholders in a standardised way – this part is used to describe principles of the circularity and it is a basis for circularity analyses. Both first and second part of MP are stored in a web-based database, which will be identified and explained later in this section.
BIM attributes that are pulled from BIM model are required to be defined by stakeholders before they start the merging process. These attributes are checked after the model trim (as illustrated in the Figure 30) by the validation step. Required attributes are used to assure the trackability of the element, by the identification of the element, which is one of the principles of the circular economy. The information pulled from BIM model for level 1 material passport are:

1. Name
2. Globally unique ID
3. Object class
4. Object type
5. Quantity
6. Building storey name
7. Geometry
8. Dimensions

Example of the properties trim and the source for the abovementioned attributes is illustrated in the Figure 31:

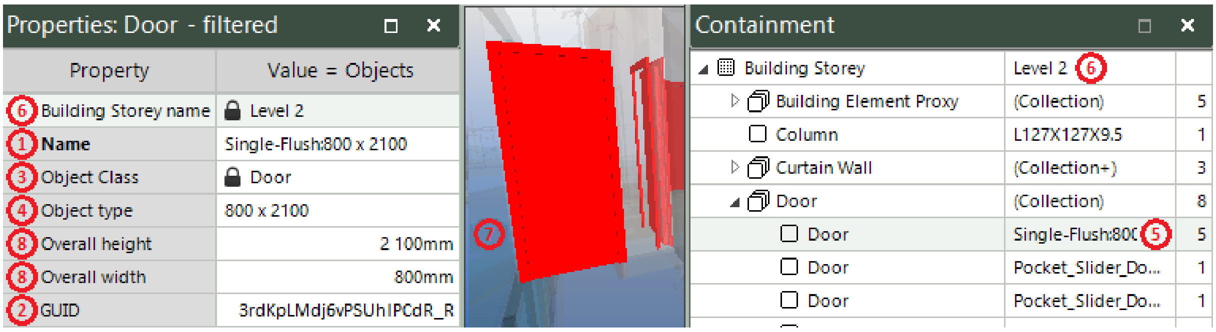


Figure 31 – Properties derived from open BIM model

These attributes (1-8 in the Figure 31) form the basis of the material passport and are in the top part of the document (example in the Figure 33 on the next page). The following, second part, is filled in by the user inside the web-based application. The user has two options to locate the specific element in the building model. First option is to choose it in a list of object types, the second option is to navigate through the building model to locate specific element. Once the object is selected, all objects of the same type inside the model turn purple for an easier identification, and a pop-up window, like it is illustrated in the Figure 32, appears. In this pop-up window, the user manually fills in necessary information (9-15).

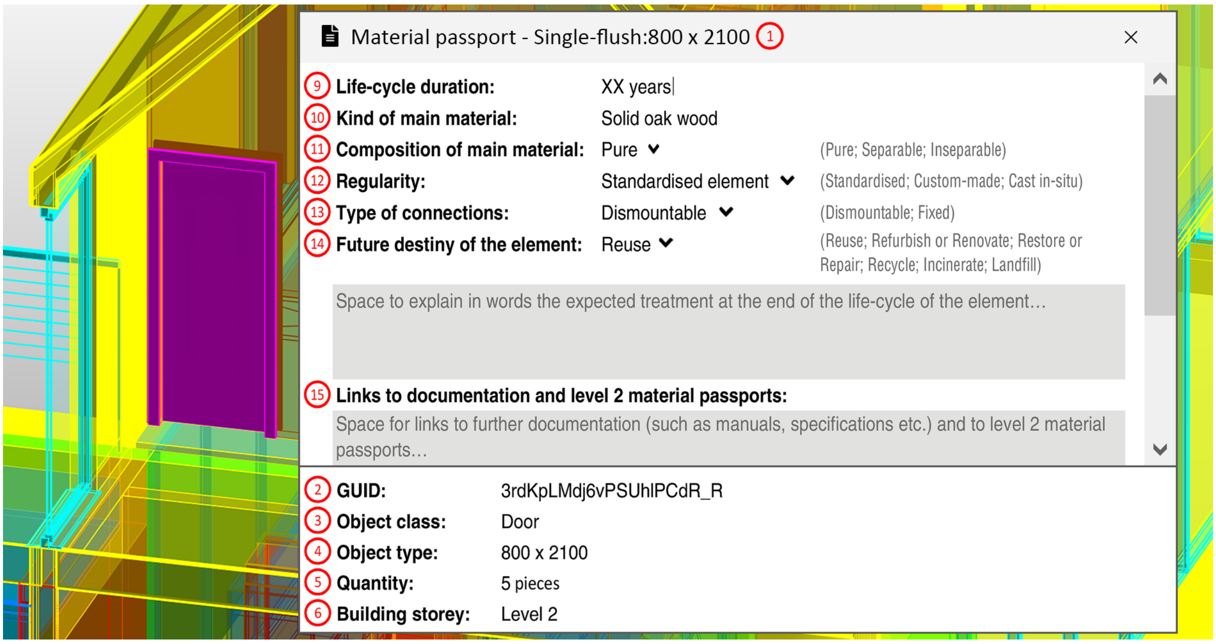


Figure 32 – Proposed interface for the insertion of information required for level 1 material passport

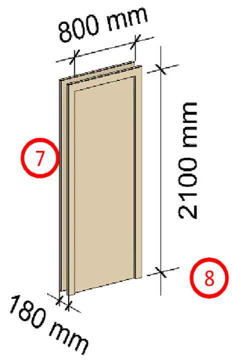
The choice of user filled information is based on principles of the circular economy, the design for disassembly and the cradle to cradle. Level 1 material passport is not a full description of a building, thus some principles are left out and will be filled additionally in level 2 and level 3 of MPs. This way, the implementation is gradual, and not too overly extensive task to fulfil, yet with a possibly significant impact on the minimisation of the level of CDW generated. In level 1 material passport, information that are filled in manually relate to the element as a unit (this is also why BIM objects are called BIM elements in this section). Since information is filled-in in a standardised way, in moments there are more correct choices than one, then the choice which prevails is selected. Data to be filled in are:

9. Life-cycle duration (in years)
10. Kind of main material (such as wood, concrete, reinforced concrete etc.)
11. Composition of the main material (Pure; Separable; Inseparable)
12. Regularity (Standardised element; Custom-made element; Cast in-situ)
13. Type of connections (Dismountable; Fixed)
14. Future destiny of the element (Reuse; Refurbish or Renovate; Restore or Repair; Recycle; Incinerate; Landfill) with explanation
15. Links to (preferably both) manufacturer documentation and level 2 material passport

The example of level 1 material passport with both information pulled from open BIM model (1-8) and manually inserted information (9-15) can be seen in the Figure 33:

1 Single-flush:800 x 2100

2 **GUID:**	3rdKpLMdj6vPSUhlPCdR_R
3 **Object class:**	Door
4 **Object type:**	800 x 2100
5 **Quantity:**	5 pieces
6 **Building storey:**	Level 2



9 **Life-cycle duration:**	XX years	
10 **Kind of main material:**	Solid oak wood	
11 **Composition of main material:**	Pure	(Pure; Separable; Inseparable)
12 **Regularity:**	Standardised element	(Standardised; Custom-made; Cast in-situ)
13 **Type of connections:**	Dismountable	(Dismountable; Fixed)
14 **Future destiny of the element:**	Reuse	(Reuse; Refurbish or Renovate; Restore or Repair; Recycle; Incinerate; Landfill)

Space to explain in words the expected treatment at the end of the life-cycle of the element…

15 **Links to documentation and level 2 material passports:**

Space for links to further documentation (such as manuals, specifications etc.) and to level 2 material passports…

Figure 33 – Proposed composition of level 1 material passport for a solid oak wooden door

As some of information is based on a drop-down list with standardised options, these are used for visual analyses of an entire building, to help stakeholders with a better design in terms of a level of CDW generated. The user can choose between life-cycle duration analysis, material separation analysis, regularity analysis, connection analysis, future destiny analysis and overall analysis. These analyses provide visual representation of the state of a building in terms of circularity. Example of the future destiny analysis of a building's elements can be seen in the Figure 34:

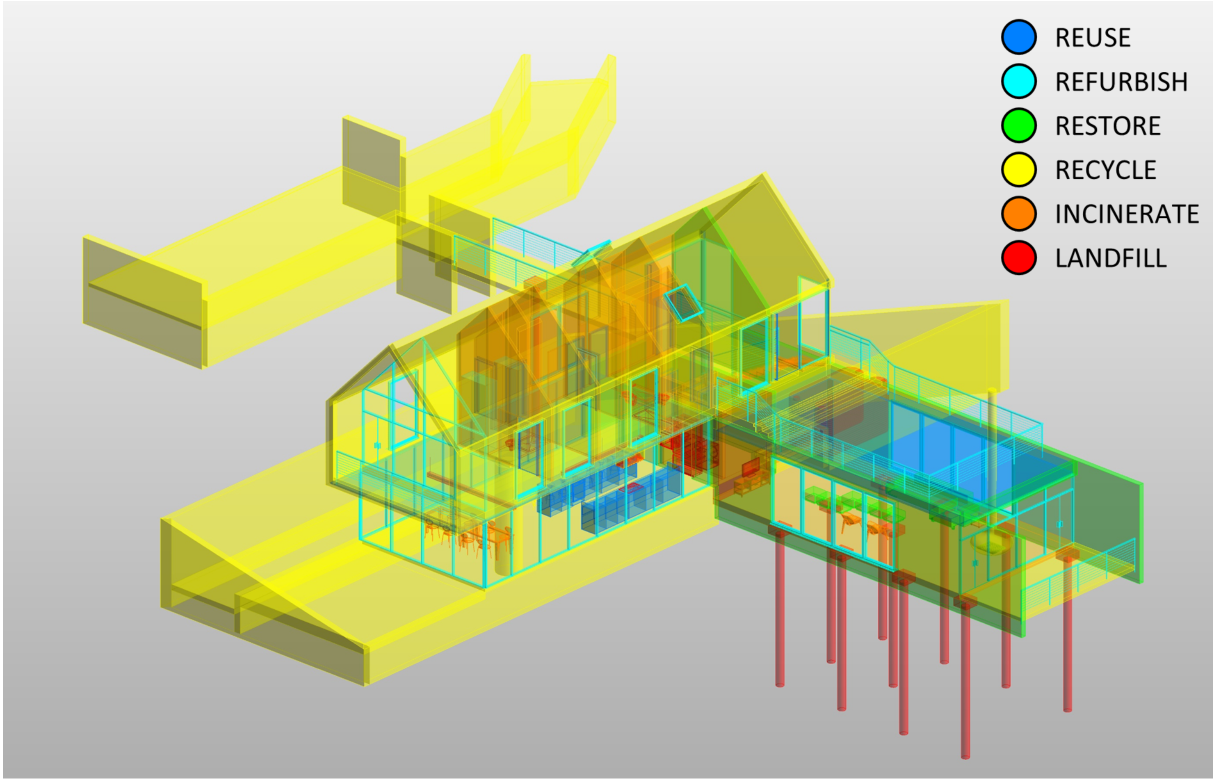


Figure 34 – Proposed graphical result of the future destiny analysis of the building's elements

As it can be seen from the, the analysis relies on a colour coding of elements based on data chosen in specific material passports. This is the functionality of all the previously-mentioned analyses – which results into simple and easily readable solution.

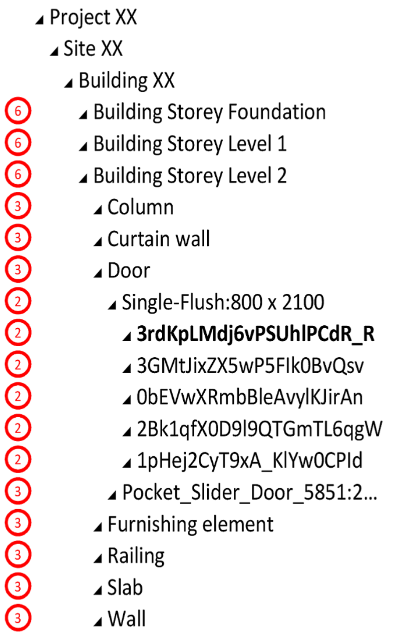
The merge of models by different stakeholders for the purpose of previously-mentioned analyses is expected at the end of phases or as specified by the client in BIM execution plan. Individual phases are connected to the level of detail (LOD) of BIM model. LOD was introduced in the theory chapter about BIM. It is expected, that LOD 200 would be enough for the initial circularity analyses and a subsequent alternation plan. However, as LOD 200 does not require precise size, shape, orientation, location or quantity, it is not suitable for the creation of material passports. These above-mentioned attributes are accurately defined from LOD 300, which is, thus, the minimal requirement for level 1 material passport. To fully cover the connections with other elements, which is a prerequisite for the design for disassembly, LOD 350 is required, as it provides information about interfaces with other building elements. To completely document a building, LOD 400 is necessary, as it includes detailing, fabrication, assembly and installation information. Even though it is desirable to document the building as thoroughly as possible, LOD 400 is better suited for level 2 material passports which will be introduced later. Nevertheless, LOD 350 is a great starting point for the implementation of both the circular economy and the design for disassembly principles into BIM model and as it was already said, the implementation should be gradual.

As the main goal of this solution is to reduce the level of construction and demolition waste, it should be pointed out that in the case study by Jensen & Sommer (2018), they found that focusing only on superstructure and the envelope of a building normally covers ¾ of materials by weight, resulting in a significant decrease of CDW generation, if rules of circularity are applied. In the other words, even small progress might result in a positive change, so the proposed way of the implementation is to start small and build up in detail.

The cost related to the web-based storage and the acquirement of the web-based application for both BIM model and the database is the financial responsibility of the client. Currently, the project group is not aware of a working solution with the proposed functionality for the circularity assessment and material passports. However, there are already some products available, that include the combination of a web-based application for open BIM model and a database. There are both paid and free options available. Some examples with such functionality are: Assemble, Autodesk BIM360, BIManywhere, Dalux Field and Tekla BIMsight.
From the mentioned applications, BIManywhere, which is paid, seems to be close to the intended functionality of the proposal of this report. It allows users to select BIM objects based on their types in a web-based application and then users can insert additional information, as report issues, which are then saved in a database, or upload COBie datasheets. BIManywhere is a solution for facility managers, but with small changes, it could be used for the proposed purpose of circularity assessments and material passports. However, as it was already touched upon in the theory chapter about material passports, there is also free, open-source alternative of BIMserver, on which this proposal could be built - Dankers, et al., (2014) demonstrated a solution featuring a web-based open BIM tool with the connection of other databases through Drupal content management system. To connect the database entity with BIM objects, globally unique IDs (GUIDs) are used.

It is not expected, that a client is going to be responsible for a development of the solution. However, it is foreseeable that BIM software developers could be interested to add the functionality of the proposal of this report, once awareness of CDW and circular economy increases, just as the support for COBie is being implemented into their BIM environments and tools, for example.

Apart from a geometry and few attributes necessary for the element identification that are kept in a model after the trim, there is no additional information stored directly in BIM model. Data that are part of material passports (example for level 1 MP in the Figure 33) are stored separately from the model – in a web-based database. This is due to the fact that the scope of all three levels of material passports defined for each BIM element would become too comprehensive for the processing power available. This will also ease the updating process, as it is easier to update just parts stored in a database, rather than attributes stored directly in BIM model. The only direct connection between elements inside BIM model and the database are GUIDs. GUID is created together with each BIM object and it is permanently attached to it. Once the model is uploaded to the web-based solution, BIM structure is transferred into a database structure (see left part of the Figure 35) and an entry is created for each object (see the right part of the Figure 35). The database entry for one material passport with information necessary for level 1 MP is illustrated in the Figure 35. The empty rows (21 and further) will be filled with information necessary for level 2 and level 3 MPs. Therefore, the final product is an aggregate of data for all the material passports for each element – single flush door in this example.



Entry for Single-Flush:800 x 2100:3rdKpLMdj6vPSUhlPCdR_R

	#	Attribute	Value
1	1	Name	Single-Flush:800 x 2100
2	2	Globally unique ID	3rdKpLMdj6vPSUhlPCdR_R
3	3	Object class	Door
4	4	Object type	800 x 2100
5	5	Quantity	5
6	6	Building storey name	Level 2
7	7	Geometry	Link to module desribing geometry
8	8	Dimensions	Link to module desribing dimensions
9	9	Life-cycle duration	XX
10	10	Kind of main material	Solid oak wood
11	11	Separability of main material	Pure
12	12	Regularity	Standardised element
13	13	Type of connections	Dismountable
14	14	Future destiny of the element	Reuse
15	15	Explanation of the destiny	Further explanation...
16	16	Additional links	Links to further documentation...
	21		
	22		

Figure 35 – Proposal of database structure and an entry for one element (example of a door)

To get a better understanding of the connection between BIM elements and the database entry through GUID connection, this is illustrated in the Figure 36:

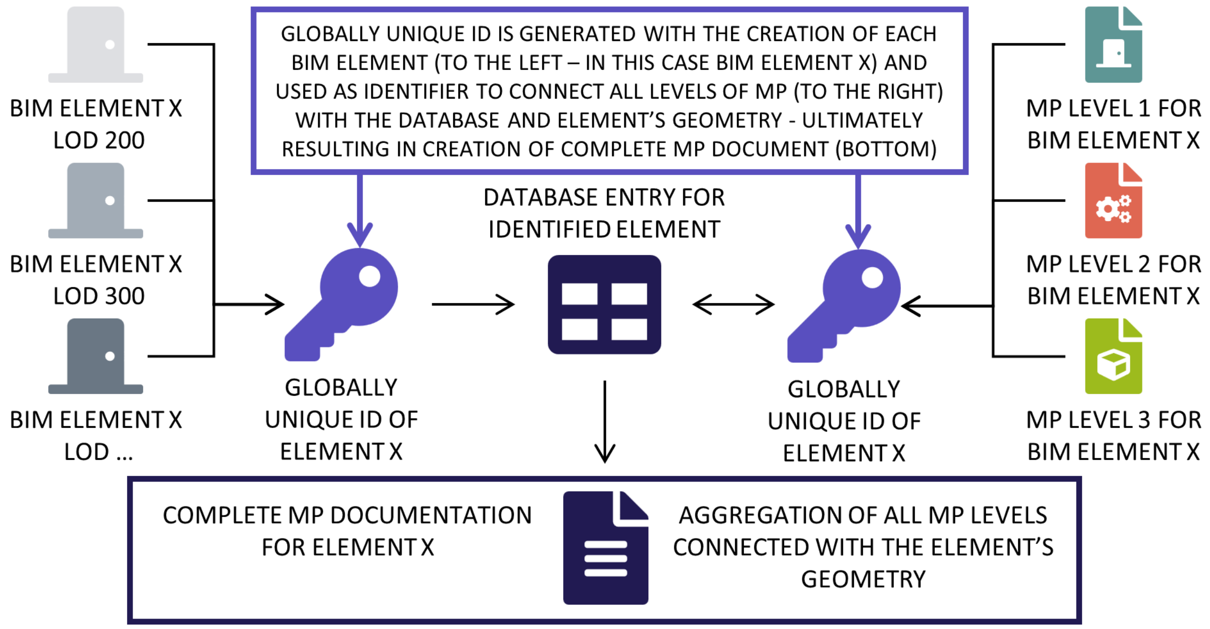


Figure 36 – The connection between elements' and material passports' updates

The major point of the Figure 36 is to show that BIM elements and information saved in the database for the purpose of material passports are two separate parts of the solution. The only connection between the BIM element and the database entry is the GUID, which is directly attached to each BIM object created. This way, both sections can be updated independently of each other – if there is a geometrical change (for example increase in LOD), the geometry is updated in the BIM model; if there is an update to information for material passport (for example when level 2 MP becomes available for specific element), only this information is updated in the database – without any interfering with BIM model. In the case the information would be directly connected to elements (for example directly stored as object attributes), it would be necessary to always update both the geometry and the information to obtain the same result. This would result in redundant work, as the update would always have to go through the trimming and the validation step as it was illustrated in the Figure 30. The GUID as a mean of a connection was chosen, as it is permanently connected with the element, no matter what LOD is used, and it also allows for timestamps and history log, together with the log of a stakeholder who makes the last update.

Although the ideal solution would be to have all elements documented through all three levels of MPs, it is foreseeable, that it will take significant time until level 2 and level 3 MP are available for usage. This is why level 1 material passports are proposed as a separately functional solution. Level 1 MPs do not cover all principles of the circular economy, but could significantly decrease the level of CDW generated – which is the main goal of this report. Once level 2 and level 3 MPs are available, they can be connected with level 1 MP and cover all principles of the circular economy – as it was demonstrated, this proposal is ready for the aggregation of the information. Even if level 2 and level 3 MPs are available from the project initiation, there will always be a situation when level 1 MPs are used solely.

Since it is not usually legally possible to define a manufacturer and specific product during the tender phase, level 1 material passport is well suited for this task, as it allows to specify expected characteristics of the element, yet the element remains generic. Once specific products are known, which is normally after the tender phase, material passports might be connected with these specific products and their material passports. These are covered in the following section of level 2 MP.

The most of the thought was given to Level 1 MPs in this part of the discussion. This is mostly due to the fact that the proposed solution is very similar for level 2 and level 3 MPs, as there are only few differences. Therefore, it showcases foreseeable solutions not only for the first level MP. Additionally, this solution can be used in the near future, since nearly no adjustments need to be done to the available technology. Therefore, it only requires a client to make the decision whether the cost associated to the adjustments is worth it or not. The first level can work individually as a system and lead towards significant minimisation of levels of CDW generated. However, when connected with the second level of material passports, most of the principles of the circular economy can be obtained.

Level 2 material passport:

As it was already illustrated in the Figure 29, material suppliers (manufacturers) are responsible for the creation of the second level of material passports. The first level material passports demonstrate the functionality of the system without “too much” of information. This, as a gradual step towards the circular economy, makes sense. However, if the circular economy is to be fully implemented into the construction industry, then more detail is going to be needed. Who else better knows what a product consists of than the manufacturer? This idea is inspired by the cosmetics industry, in which every manufacturer must put an ingredients list on a packaging, provide a wholesaler with a detailed content of a product, and the product must be approved to be safe for usage.

Level 2 material passport is a combination of product specifications with a visual representation of the element in a form of a BIM object. These MPs are not made especially for each project. Instead, products a manufacturer produces and intends to follow circular economy principles with, are stored in a web-based product library/libraries (such as bimobject.com, smartbim.com or mepcontent.com in the present). At the moment a designer, a contractor or a facility manager needs level 2 MP for a certain element, they pull data from the library, just as illustrated in the Figure 37. This results in the update of the geometry of a specific BIM element in the merged BIM model and enrichment of a database entry of the element.

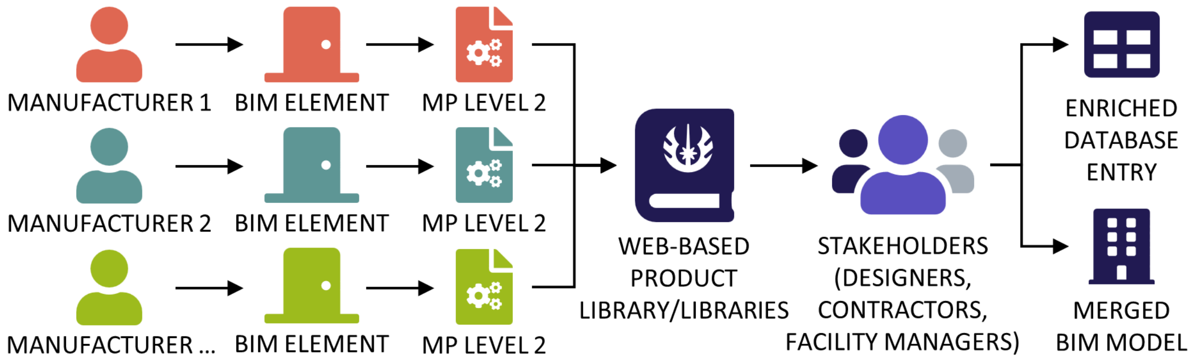


Figure 37 – Level 2 material passport workflow

The result is, in a perfect scenario, a representation of all used elements connected with material passports and merged together in BIM model. As a manufacturer is usually known only after the tender is over, a person to collect these objects from product libraries and put them into BIM model is most probably the main contractor and/or subcontractors – apart from circularity reports, they can also use the model for the construction phase and as a basis for the virtual design and construction. In the case a turn-key contract or similar is used, it might be designers to pull and use information already in the design phase. After the hand-over of a building, it will be facility managers to keep the model and information connected to elements up to date. Nevertheless, the requirement to use MPs must be specified by a client in BIM execution plan and employer information requirements – so connected costs can be calculated by stakeholders. In case a manufacturer does not provide level 2 material passports, level 1 material passport for the specific element is used solely, without the connection to the second level.

Since level 2 MP is a full representation of elements, LOD 400 is required to completely cover all necessary information. LOD 400 is also the highest level of detail expected to be uploaded to the merged BIM model. In case a manufacturer has a more detailed model of a product, it can be linked instead. This limitation is in place to avoid the overfill of BIM model with unnecessary geometry, which could lead to the scalability issue and problems connected to it. Since the functionality of this level is almost identical to the first level, the main differences are, that it is produced by manufacturers and the product is the focus, instead of a building. Therefore, graphical examples provided for level 1 MP are deemed to be sufficient to get the idea of the solution.

As for the content of level 2 material passport, what matters the most is to provide a way to identify a product, fully document dimensions of the element and to define all materials used. This is due to the expected connection with level 3 material passports and to bring the industry closer towards the ultimate goal of circular economy – to use materials' parts up to atoms. The proposed content of the second level of material passport is:

1. Name
2. EAN (or another identifier in case EAN is not available)
3. Object class
4. Object type
5. Geometry
6. Dimensions
7. Weight
8. Life-cycle duration (in years)
9. Materials (with links to level 3 material passport, if available)
10. Composition of the materials (Pure; Separable; Inseparable)
11. Future destiny of the element (Reuse; Refurbish or Renovate; Restore or Repair; Recycle; Incinerate; Landfill) with explanation
12. Links to further documentation

To fully cover a product – including both a visual and a specification part, might sound as a tedious and overwhelming work. However, it could bring the manufacturer many advantages, such as:

- Improvement of a company's corporate social responsibility.
- Analyses of level 2 MP can be used to create the circularity rating of elements, just like there are energy ratings at the moment for white goods. This might be a criterion for a client to choose a certain product.
- In the beginning, availability of level 2 MP might increase a demand for specific product, as circularity savvy clients will prefer well documented elements to unidentified ones.
- The possibility to manage the destiny of a product, materials might be returned back to a manufacturer after a product's life-cycle is over and be reused, which results in a minimisation of waste and most importantly for a manufacturer – cost savings, as the need for raw materials is minimised.

The complexity of the specification should actually play in a favour of the circular economy. There are four main principles of the circular economy, these are transparency, trackability, regularity and simplicity. To reduce the need to document too many products, this should lead towards two of the main principles of the circular economy, which are regularity and simplicity. More regular and simple the product is, easier it will be for a manufacturer to describe it and to reuse a product in the future. The transparency is assured through complete documentation of a product and trackability through an identifier, which can be attached, apart from in a material passport, also physically to a product for a later identification.

With the current development of the circular economy in the construction industry, it is understood that level 2 MP is a topic of the future. Therefore, the above-mentioned proposals should be taken as an inspiration as how the system could work, not as a finite solution. The technology progresses so fast, that it is difficult to predict possibilities in only few years later. To fully cover principles of the circular economy, individual materials need to be documented, which is the task for level 3 material passports.

Level 3 material passport:

This is the third and the final level of material passports. As illustrated in the Figure 29, this level of material passports is the responsibility of the government. Government is the stakeholder who is ultimately responsible for the way the waste disposal is treated. With the tightening of legislative requirements in regard to waste minimisation and the movement of EU towards the circular economy, this level could prove rather useful for governments, as it will be explained later. The main purpose of level 3 material passport is to provide a documentation for materials, instead of elements. Just like the other levels of MPs, all information about materials is stored in a web-based database and it is connected with the remaining levels of MP. The main difference is, that this level does not have any visual representation in BIM model.

The main reason the government is chosen to be responsible for the material documentation is the objectivity issue. If manufacturers were to document materials, it would be a subjective rating, as they could try to convince other stakeholders that their material is superior to others, yet have no proofing about it.

The proposed information to be part of each level 3 material passport is:

1. Name of the material
2. Identifier of the material
3. Category of the material (Positive; Neutral; Dangerous, but without a substitute; Banned; Not yet inspected)
4. Origin of the material (Biological; Technical; Hybrid)
5. Future destiny of the material (Reuse; Refurbish or Renovate; Restore or Repair; Recycle; Incinerate; Landfill) with explanation
6. Links to further documentation

Even though a government is responsible for the creation, the control and the storage of information, a manufacturer is still the one to be financially responsible for the task when new material is developed. When new material is developed, a manufacturer is the one to submit necessary information, such as specifications, to a governmentally controlled laboratory, for an objective analysis and an inspection. It is expected, that to convince manufacturers to be part of such system, a regulatory action will have to be taken into practice and make this testing mandatory – the inspiration might be taken from the cosmetics industry, where such practice is common.

With the increasing level of information about a product and materials that make up a product, it will become a possibility to create advanced analyses for an entire building, once all data are merged together both in BIM model and in the web-based database. The ultimate goal is to fully implement the circular economy into the construction industry. This will also allow for the creation of a circularity rating certification for a building, just as energy tags, that are currently part of the construction industry. This way, a client will be able to choose not only the energy consumption of a building, but whether it is safe for both the occupants and the environment or not. A client might even aim for a building which is positively healthy for the occupants to stay in.

However, why should the government be motivated to inspect and classify all the construction materials? These are the main motivational aspects the group members collected:

- It is the interest of a government to have safe indoor environment for occupants to live/work in. With the amount of time people spend indoors, many costs related to unhealthy indoor environment (such as allergies and respiratory problems to name a few) can be avoided – and a productivity increased.
- Classification of materials allows for full implementation of the circular economy. This, firstly, brings the benefit of CDW decrease. Secondly, it brings the benefit of increased GDP and the creation of new working positions connected to the circular economy.
- With tightening environmental regulations, a government can gain control over construction materials and how they are treated after their life-cycle. Since the proposed solution relies on a web-based database, the recommendations and regulations for the future destiny of the material might be changing as needed to comfort to specific regulations and to a research and development.

When it comes to the future destiny of a material, however, this should be taken as the last solution, as the future destiny should have already been specified in either level 1 or level 2 MPs which discuss the future destiny of elements. Preferably, elements are either reused, refurbished or renovated, or restored or repaired. In the case neither of these is possible, this is the moment the future destiny of the material comes into play in which the government gains the control of the material destiny based on regulations and needs.

As with the level 2 MP, the level 3 MP is also a thing of a future. However, it is partly based on currently working practice of another industry – the cosmetics industry. To currently analyse the entire building, down to LOD 400 and level 3 MP, might be too demanding for current processing power of common computers. However, the trim of the model and valid modelling techniques should help this, and it is foreseeable that the rapid development of the processing power will soon close the gap between possibilities of the present and the needed processing power.

8. Conclusion

This report has been focused on the global problem connected to construction and demolition waste in the area of EU. In order to analyse the case, the project group conducted first four steps of the LFA approach. The aim of this analysis was to localise the focal problem and possible solutions of it.

In regards to the progress of the report, before the semester started, the project group handed a brief description about the topic the group members were interested in. This was used for a selection of supervisors. In the beginning of this semester, the project group further developed this description into the thesis contract, which was approved both by supervisors and the head of studies. This contract served as a basis for the report. At the beginning of the report writing, the project group created the research design and the methodology, which were gradually updated according to the project development. In order to understand the basis of the problem, the project group started with the initial analysis of EU situation in regards to CDW. The analysis followed first four steps of LFA approach and resulted in the creation of the final problem tree and the objective tree. Based on these problem trees, the project group proposed the problem formulation:

"How can implementation of the circular economy through BIM minimise the CDW generation during the project's life-cycle?"

In order to assure the mutual understanding of some terms, inside and outside the group, the project group adapted definitions used in the literature about defined terms. Furthermore, in order to better understand desirable actions localised by the objective tree, the project group conducted an extensive literature review about these topics. The selection of the topics was further extended by additional topics, which were found to be necessary to achieve these desirable actions. Reviewed topics were the circular economy, the design for disassembly, material passports and the building information modelling. Results of the literature review were finalised in the theory chapter. The project group further discussed these results in the discussion chapter. In this chapter, the project group developed the concept of the problem solution. The concept is divided into the theoretical and the practical part.

In the theoretical part of the concept, the project group propose the implementation of the circular economy into the construction industry. This is due to the group's understanding that the circular economy might bring a positive result in the fight against CDW generation. Reason for that is behind advantages connected to the switch from the linear way of the production into the closed loops of the production in the construction industry. These advantages are: definition of stakeholder responsibility for waste; improved financial results of the construction industry; increased awareness about waste; technological and theoretical development in fields of CE practices; and governmental motivation to avoid landfilling and to implement CE. All these advantages are directly linked to causes of the focal problem localised in the final problem tree. The project group advises to implement the circular economy through the design for disassembly. This is due to the ability of DfD to implement CE into the construction process in the early stage of the design. This allows to fully develop the circularity potential of future structures. In order to fully implement the circularity into DfD, it is necessary to store comprehensive information about the circularity of a project. Therefore, the project group advises to use material passports as a system for the storage of circularity data.

In the practical part of the concept, the project group proposes the possible application of circularity data into the construction projects. This is done by the implementation of material passports into the process of the building information modelling and BIM models. The idea is based on the need to decrease the fragmentation of the industry and to assure the responsibility of a stakeholder for the creation of material passports. The need to decrease the fragmentation of the industry is satisfied by the implementation of a web-based solution for material passports implemented into BIM models. This allows a wide range of stakeholders to access data about the circularity during the whole building's life-cycle. The need to assign responsibilities of stakeholders to create material passports is satisfied by the implementation of material passports levels. This allows for a gradual implementation of the circular economy into the construction industry, where the proposed responsibility for the creation of such documentation is divided between clients (represented by designers, engineers, contractors and facility managers), manufacturers and governments.

Combination of both the theoretical part and the practical part of the concept demonstrates the ability of solving the focal problem by the implementation of the circular economy into the construction industry. In this case the project group advises to use the design for disassembly as way to transfer circularity into a design of a structure. Material passports are a form to store data about the circularity and BIM is a tool to implement circular economy into the construction industry. This is mostly due to the understanding of the group that these processes might simplify the implementation of the circular economy into the construction industry and, therefore, make the whole process viable.

While the nature of the case study makes the final result valid only for the location of case study, in this case EU, the attributes of the instrumental case allows for a wider generalisability. In this specific case, this is valid due to the choice of topics used in the final concept, as all four topics are globally acknowledged and used. Therefore, the application of the concept, with minimal or no adjustment, should be possible even outside the location of EU.

Based on the project group's understanding, gained during the process of the research, the project group believes that successful implementation of the concept might have a positive impact on the CDW generation and the construction industry in general. These impacts might be: a decrease of landfilling; improved recycling and reusing rate of materials used in the construction industry; lower waste generation by the construction industry; and a lower cost of construction processes. While the first three impacts represent environmental impacts, the last impact shows a reason why the construction companies would opt for a wider implementation of the concept. Lastly, these partial improvements might result into the ultimate goal of the creation of a more sustainable environment.

9. Further studies

This report presented the idea and principles, which can be used in order to solve the problem with increasing generation of construction and demolition waste. However, the research is not validating the concept provided by the project group. This is, mostly, due to the project's limitations.

Therefore, further validation of data and the concept provided in this report presents a suitable topic for further studies. This can present a validation of data by external validators from groups of clients, architects, contractors and other stakeholders which are connected to CDW.

Another option for the further study might be presented by a case study of the proposal's application. This can provide necessary data for the movement in the field of the circular economy and further validate the model presented by the project group.

10. Reflections

While the project group is satisfied by the result of the report, it is also aware of a need for a constant improvement. Therefore, at the end of the project, both members of the project group reflected on the process of the semester:

During the semester and writing of this master thesis, the project group members have to deal with a long-distance relationship. This is because of different places of living of both group members, where one lives in Aalborg and the other lives in Copenhagen. Overcoming of this obstacle helped project group members to improve their skills in teamwork and to develop new abilities of working remotely.

They agreed, that more efficient usage of information technologies could improve the remote process of the collaboration. As an example can serve a usage of Trello platform, which is supposed to allow for a better time management. The project group intended to use Trello throughout the project, however, it disappeared from the process later during the semester.

Another possible improvement is connected to the academical writing and the ways of conducting the academical research. Here, the project group feels the space for the improvement. However, as students, the project group members still lack the experience necessary to improve their conduct of such a report.

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