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Environmental impact assessment of building materials in BIM models

Computation of embodied carbon in building materials with the use of Industry Foundation Classes and Semantic Web technologies

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Preface

Before you lies the report of the process undertaken during my graduation research at the Eindhoven University of Technology over the past six months. After a period of intense work, knowledge growth and scientific as well as personal discoveries, I am proud to present the outcomes through this thesis, which concludes the Masters of Science Construction Management and Engineering.

Inspired by the innovative vibes of TU/e and my supervisors' devotion, I selected a topic, that combines my interest in contributing to the planet's sustainability with my academic background in the built environment and my aspiration towards continuous learning and development. Throughout my graduation project, I gained great insight into the environmental aspects of building activities, BIM practices and Semantic Web applications.

The final outcome of this research is the fruit of my efforts, towards which a number of people contributed in different ways. Significant part of this contribution belongs to my three supervisors. I would like to thank Jakob Beetz for his help in the decision of my thesis topic, his practical guidance and constructive feedback during the whole process, but also for his conceptual support and motivation towards creative thinking and possible tool applications. Furthermore, I am sincerely thankful to Thomas Krijnen, who was always willing to help me with my tool development both content and technical-wise, through discussions about the use of the tool and its potential, as well as through assistance on what I considered as difficult to implement from a programming perspective. I would further like to express my special thanks to Nicole Segers, who played one of the most inspirational roles in the research process, through her knowledge and expertise on environmental issues and the state-of -art of relevant initiatives, but also through her passion and belief in material and resource reuse.

Last but not least, I would like to thank my university colleagues, friends and family, for their support, either practical or moral, which holds a great share in the performance of my thesis. I am grateful to my parents and brother, who despite being physically far away, they have always been on my side, supporting me, believing in me and sharing both my happy and stressful moments. My special thanks goes to a number of colleagues and friends, who had the patience to listen to my problems, brainstorm for my research and often helped me to solve technical difficulties in my development. Although, I am not including their names, as the list would be long, I am certain they are aware of how much I appreciate their help and that without their contribution the result would not have been the same.

I hope you find this report interesting, as much interested as I was while performing the research.

Maria-Niki Kravari

Eindhoven, September 2017

Summary

The construction industry entails severe environmental effects accounting for a yearly 30% of the green house gas (GHG) emissions in a global scale (United Nations Environment Programme, 2009), while 24% of the total material extractions from the lithosphere are used for building purposes (Zabalza Bribián, Valero Capilla, & Aranda Usón, 2011). The need to assess these impacts has steered the development and implementation of tools and policies, whereas such assessment is documented as a rather challenging task. Adopted policies and measures so far concentrate mainly on the operational phase of the building, since this phase accounts for most of the life cycle energy (Pomponi & Moncaster, 2016a). Whatsoever, embodied impacts of buildings have been proven to contribute to global emissions, with a quantified share of more than 50% of the whole life impacts of buildings (Crawford, 2011).

At the same time, Building Information Modelling (BIM) has been gaining grounds of adoption, with multiple of its users supporting the idea that BIM has great potential in enabling increase in sustainability (Bynum, Raja R. A. Issa, & Svetlana Olbina, 2013). One of the sources of this potential is the ability of BIM to simulate the building in a 3D environment, along with all the geometric and non-geometric information associated with it, such as spatial, geographic, quantities and properties (Azhar, 2011), enabling the analysis of different sustainability parameters, such as energy and daylight (Krygiel & Nies, 2008). Establishing object-oriented design, and introducing vendor-independent standards, as the Industry Foundation Classes (IFC), where objects are well defined and semantically rich, BIM can contribute to sustainability decisions already during the design phase.

The introduction and application of the Semantic Web with the shift from document linking to data linking has established different structures for data publication that allow machine readability and processing (Horrocks, 2008). One step further of publishing raw data in a computer-processable manner is creating links between the data, connecting multi-domain concepts in order to retrieve information, which results in the Linked Open Data cloud. Therefore, potential is documented in generating links between building data existent in BIM models to external multi-disciplinary data, such as environmental, cost, requirement or sensor data.

Following an attempt to capture and reduce the environmental impact of buildings, this research proposes an ontology-based approach where embodied carbon data of building materials is linked to actual BIM data for conducting the impact assessment. The objective of the research is to develop an application, as a decision-support tool starting from the early design phase, based on the environmental impact of the materials used in a building project. This application aims to influence the designer’s choice of building materials, by creating awareness and visualization of their environmental impacts. The adopted approach included integration of environmental impact data and BIM, in order to facilitate automation in calculations and visualization of results. This integration is realized through the use of Semantic Web technologies and formats, in an attempt to implement Linked Data.

An embodied carbon database of building materials is used, which is connected to the IFC model. This connection occurs via semantic datasets generation and query construction, after the development of two ontologies. The ontology engineering enables the establishment of the entities, the relationships between the entities and their properties in the created

datasets. The selected database contains embodied impact coefficients, namely embodied energy (EE – MJ/kg), embodied carbon (EC – $kgCO_2/kg$) and embodied carbon equivalent (EC – $kgCO_2e/kg$) for a great variety of building materials. Firstly, a data selection process is conducted, in order to create a mapping file between the entities in the database and the entities in a design software basic material library. Following the data selection, the new dataset is transformed, with the elaboration of a Python script, into a semantic dataset based on Resource Description Framework (RDF) principles.

The calculation of the embodied impacts of materials existent in a design requires awareness of the material quantities. Such information is attained via the development of a Python script, which iterates through the elements of the model and calculates the quantities of their constituent materials. The model-associated information dataset is then converted into RDF, in order to support the connection to the environmental impact dataset.

The application is integrated into a user interface, enabling the user to calculate the embodied impacts of the chosen materials in a design model. This tool links the produced semantic datasets, through the use of SPARQL Protocol And RDF Query Language (SPARQL), by matching the materials that appear in both datasets. Subsequently, for these materials, the SPARQL queries calculate the different embodied impacts. The interface offers the capability to visualize the results numerically, as well as graphically in a 3D environment. By accessing such information in the virtual building model, the user is able to gain insight into the allocation of critical components within his/her design. Finally, the application provides the user with the possibility to export the results into table format, that can be used for design alternative comparison. The tool is validated in practice and theory, through syntax validation, building model case studies and calculation verifications for the former, while for the latter, the results of a reference literature study are employed so as to guarantee that the tool results are realistic.

The formulation of the environmental impact dataset as Linked Data unravels tangible benefits. First of all, interoperability issues across software can be overcome, due to the practice of non-proprietary standards, as supported by the Semantic Web formats. Second, data extensibility is well feasible with the dataset being on the web and available for editing. Such extensibility can occur for the whole dataset or even individual data instances, since Semantic web structures allow for relationships between entities and data in a one-to-many base. Next to data extensibility, the linked dataset or partial information in it can be applicable and useful in multi-domain contexts, ensuring this way data reusability. Finally, efficient data consumption is a Semantic Web advantage, since through the use of standards, such as SPARQL queries, it is possible to call for specific information and receive more accurate results than when keyword search is applied. In what concerns the BIM implementation for assisting the environmental impact assessment, the research reveals the potential of object-oriented design, via ability of material quantification, use of semantic content in building models, and more efficient use of resources due to early awareness of the end-stage of the building. Finally, the research depicts the potential of linking BIM models to external datasets. From this perspective, even though validation of the tool proved to be successful and the tool can be considered working and functional, linking of entities is achieved through matching of string labels. This connection, however, does not constitute a sustainable solution for linking concepts, bearing in mind the absolute lack of standardization that outlines a string.

Abstract

The construction sector accounts for a yearly 30% of the green house gas emissions in a global scale, while 24% of the total material extractions are used for building purposes. This thesis addresses the problem of sustainability in construction through an attempt to influence designers to make more environmentally friendly choices with regards to building materials. The objective of the research is to develop an application, as a decision-support tool starting from the early design phase, based on the environmental impact of the materials used in a building project. The followed approach includes integration of environmental impact data and Building Information Modelling (BIM), enabling automation in calculations and visualization of results. The integration is implemented using Semantic Web technologies and structures, as an attempt to apply Linked Data. An embodied impact database of building materials is used, while necessary information for the assessment is retrieved from the Industry Foundation Classes (IFC) model. Both information sources are converted into Resource Description Framework (RDF) datasets, based on the development of related ontologies. Information retrieval and RDF conversion is done with the use of Python programming language. These datasets are linked to each other through application of SPARQL Protocol And RDF Query Language (SPARQL) queries, for the estimation of the embodied impacts of materials existent in the model design. The implementation is incorporated into a user interface, creating a simple tool, able to calculate the embodied impacts of the materials in a model, visualize the critical components in a 3D environment and export the results into table format. Syntax validation, model case studies, calculation verifications and a reference literature study are employed in order to validate the tool in practice and theory. The conversion of the environmental impact dataset as Linked Data reveals the benefits of interoperability, data extensibility and efficient data consumption through employment of Semantic Web standards. The integration of Building Information Modelling and embodied impact information enables automation in the calculation process and exposes the potential of object oriented design towards sustainability.

List of Abbreviations

3D	: Three Dimensional
AEC	: Architecture, Engineering and Construction
BIM	: Building Information Modelling
CAD	: Computer Aided Design
CO_2	: Carbon Dioxide
CSV	: Comma-Separated Values
EC	: Embodied Carbon
EE	: Embodied Energy
EIA	: Environmental Impact Assessment
FM	: Facility Management
GUID	: Globally Unique IDentifier
IAI	: International Alliance for Interoperability
ICE	: Inventory of Carbon and Energy
IFC	: Industry Foundation Classes
GHG	: Greenhouse Gases
MEP	: Mechanical, Electric and Plumbing
OWL	: Web Ontology Language
RDF	: Resource Description Framework
RDFS	: Resource Description Framework Schema
SPARQL	: SPARQL Protocol And RDF Query Language
TTL	: Turtle
UNEP	: United Nations Environment Programme
URI	: Unique Resource Identifier
XML	: eXtensible Markup Language
SI	: System International

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1. Introduction

1.1. Problem definition

1.1.1 Environmental Impact of construction industry

The construction industry worldwide, though responsible for the development and transformation of the built environment, following the technological advances and meeting the modern needs, is also one of the industries that entails serious environmental effects. The impacts on nature originating from the construction sector include resource reduction, greenhouse gas emissions, noise, dust, and construction waste (Weisheng Lu, 2017).

According to UNEP (United Nations Environment Programme, 2009), the building industry accounts for 30% of the green house gas (GHG) emissions globally per year, as well as is responsible for the consumption of 40% of all global energy. Emissions generated by buildings are distributed over a long life cycle starting from the material production, construction processes, operational and maintenance stage until the end of life (Pöyry, Säynäjoki, Heinonen, Junnonen, & Junnila, 2015). Material usage within building and construction activities has a significant contribution to environmental decay. Specifically, in global scale, building construction is responsible for 24% of the total material extractions from the lithosphere (Zabalza Bribián et al., 2011).

The impact of the construction sector on the environment is not a novel insight; on the contrary it has been rather extensively researched (Bates, Carlisle, Faircloth, & Welch, 2013; Green Building Council, 2015; Marijn Bijleveld, Geert Bergsma, & Marit van Lieshout, 2013; Pomponi & Moncaster, 2016a, 2016b; Pöyry et al., 2015; WRAP, n.d.; Zabalza Bribián et al., 2011), taking into consideration all the different phases of a construction project, from conceptual design to demolition and refurbishment. Consequently, the various studies have proposed solutions and suggestions depending on their vantage point and aims, which led to the development and implementation of several tools and policies to assess this impact. The complexity of such assessment is stressed in Kohler and Moffatt's (2003) study, where they emphasize that conducting a Life-Cycle Analysis of a building project entails the formulation of several assumptions and even so tends to be a rather difficult assignment. This, due to the fact that a single building consists of several materials, each one with a different lifetime and manufacturing, reparation or disposal processes, while certain local impacts have to be taken into account. All this complicates the gathering of information and data, as well as allocation choices on behalf of designers (Niklaus Kohler & Sebastian Moffatt, 2003). In addition to the task complexity, an Environmental Impact Assessment (EIA) of a building project, due to being a manual process, may face issues due to the great volume of quantitative and qualitative data that need to be handled by the end users (S. Selvakumar & R.K.C. Jeykumar, 2016).

The policies taken so far and the measures proposed by states, organizations and industries, focus almost exclusively on the operational stage of the building, as this is the stage which holds the greatest share of life cycle energy of a building (Pomponi & Moncaster, 2016a). Nevertheless, embodied impacts of buildings have been proven to contribute to a great extent to global emissions, accounting even for more than 50% of the whole life impacts of buildings (Crawford, 2011).

1.1.2 Building Information Modelling and Sustainability

With the emergence of Building Information Modelling (BIM), a great amount of BIM users considers sustainability to be the most important benefit generated by the use of BIM (Bynum, Raja R. A. Issa, & Svetlana Olbina, 2013). One of the reasons behind this is that BIM offers the possibility of simulating the building in a virtual environment, along with all the information associated with it, such as geometrical, spatial, geographic, quantities and properties (Azhar, 2011). This is also supported by Krygiel & Nies (2008), who point out that use of building geometry from the model in other applications enables faster analysis for sustainable design, as for instance energy or daylight analysis. The particular functionality allows for the verification of the performance of alternative design proposals and thus design optimization (Liu, Meng, & Tam, 2015). Therefore, the growing adoption of BIM by the Architecture, Engineering and Construction (AEC) stakeholders, with the benefits associated with it, can contribute to the decision making when it comes to several aspects of a building project; such aspects include increase in sustainability and reduction of environmental footprint, through support of more automated processes.

1.1.3 Application of Semantic Web and Linked Data

These processes can be further implemented using Semantic Web technologies and Linked Data, two relatively recent concepts, envisioning the creation of a web of distributed and interconnected data, described in a machine readable format (Allemang & Hendler, 2011). As Abanda, Zhou, Tah, & Cheung (2013) identify, even though BIM was developed to assist the building sector, whereas Linked Data development was not, they both share a common objective; that is to improve the use and applications of domain-specific information and knowledge. Within this notion, building information models can be linked to environmental impact data, ensuring awareness of the construction's footprint and as a next level taking action towards a more sustainable construction. According to Lee et al. (2016), linking BIM applications with external data sources based on linked data structures, enables searching for specific information when required, as well as sharing of this information with different participants or stakeholders (Lee, Chi, Wang, Wang, & Park, 2016).

On the basis of the background introduction of facts and theories, regarding the environmental impact of the construction sector, as well as the potential of the integration of BIM and Semantic Web technologies, the research problem can be defined. This is how to reinforce sustainable construction, through early information of the environmental impact of the building materials chosen in a design, by linking the BIM model to environmental impact datasets.

1.1.4 Objectives and limitations

In this research, the focus lies on the embodied impacts, which take place long before the start of the life of the building itself, with the initiation point being the extraction of raw materials, the factory processing, until their transportation to the factory gate.

The objective of the research is to develop an application, as a decision-support tool starting from the early design phase, in regards to the environmental impact of the materials used in a building project. The research constitutes an attempt to influence the choice of materials aiming to support a more sustainable construction. The application will enable the estimation of the embodied carbon of the chosen building materials, the visualization of the most critical components and the possibility to export the results in table format, in order to reinforce sustainable construction. A key attribute of the tool is that it integrates impact assessment information and design software tools. In fact, this integration is done using non proprietary data models, thus complying to the rules of the Semantic Web and Linked Data, while also enabling interoperability, flexibility and use of more automated processes, which constitute some of the benefits of open standards (Open Standards). Industry Foundation Classes (IFC), which is the standard non-proprietary data model for 3D building representation is used in order to connect the environmental impact data with the building objects.

Regarding the level of analysis of the research, two boundaries should be considered, namely location and system boundaries. In what concerns the former, the range of application is considered not to be bounded to local context. This is due to the fact that the environmental impact data of building materials is taken from a database created in the UK, which uses measurements both from the UK and globally. However, in terms of the latter, this research assesses the impact of building materials only within the system boundary cradle-to-gate; and so not the whole life cycle is taken into account. More information about the data used is given in section 3. In what concerns the interests served through the application developed for this research, the so-called potential users can be designers, architects, structural engineers or contractors. In addition, people working for environmental certifications, could also benefit from the application when it comes to the assessment of embodied carbon of materials for calculating certificate points.

1.2. Research Questions

The principle research question to be addressed in this study, based on the problem definition and objective described above is as follows:

How can 3D Building Information Models and Semantic Web technologies be used to assess the selected building materials during the design phase, seeking to reduce environmental impact?

The main research question will be supported through the following sub-questions:

- What is the added value of publishing an environmental impact dataset as Linked Data?
- How can BIM contribute to the environmental impact assessment of a building project during the design phase?
- How can BIM models be linked to external datasets adopting Semantic Web principles?

1.3. Research design

Following, an overview of the research design is given in Figure 1, in which it is shown how the research and development process was conducted. The research is divided into three different stages, each and every consisting of distinct actions and topics. The three stages are Literature Review and Data Collection, Tool Development, and finally Conclusion.

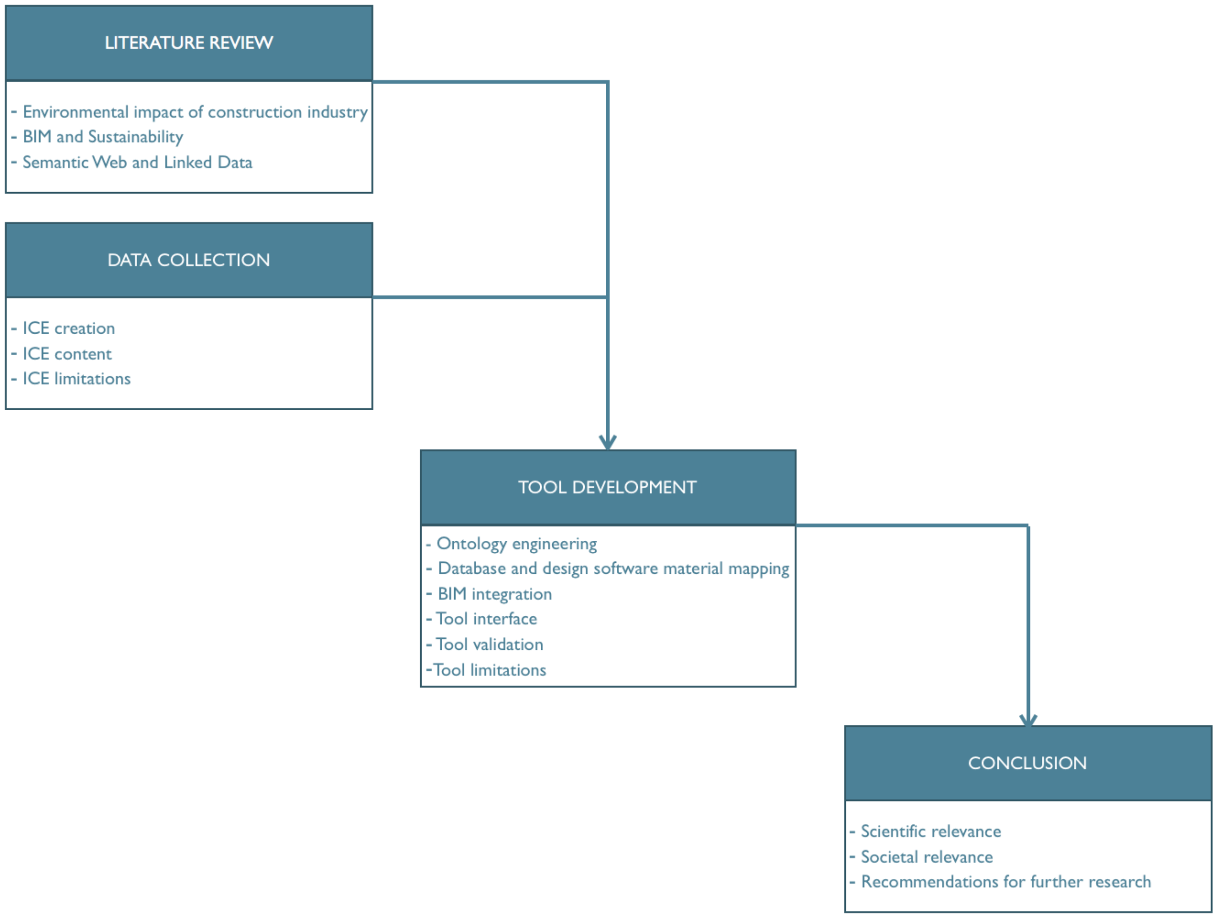

Figure 1: Research design

1.3.1. Literature Review

Initially, the fields of literature that need to be examined are established, in order to reach the research objectives. The literature review is divided into three main topics, namely the environmental impact of the construction industry, the use of Building Information Modelling, especially in what concerns the theme of sustainable construction, and finally recent developments in the field of Semantic Web and Linked Data, in particular related to the AEC industry.

1.3.2. Data Collection

In parallel to the examination and assessment of the state-of-art on the topic under research, another milestone is being realized; that is data collection. An environmental impact database with embodied carbon coefficients for a great variety of building materials is selected in order to serve the assessment purposes of the research. The context in which this database was created is presented together with the database content and limitations.

1.3.3. Tool Development

Based on the literature findings and the selection of data, the tool is developed. The first step is ontology engineering, where ontology development takes place, in order to assist the Semantic Web structures that are followed by the implementation. Next, the selected database is mapped to a design software material library through a data integration process.

Accordingly, BIM integration comes in place, through the IFC data model examination, in order to investigate the kind of information that can be retrieved, with reference to material representation. Certain codification is conducted, for the extraction of this information and both data sources are converted in a format which complies to the Semantic Web principles. The transformation of the datasets enables Linked Data implementation. The development of the tool is represented through a user interface. Finally, the application is tested on a number of existing 3D building models for verification and the tool limitations are exposed.

1.3.4. Conclusion

As a final step, conclusions are drawn, in regards to the process, but also to the tool itself, by reflecting on the research questions. This leads to the formulation of the scientific and societal relevance and future research recommendations.

1.4. Social and scientific importance

1.4.1. Social importance

The social importance of this research stems from the fact that the building industry entails serious consequences for the environment through the different activities taking place along the process of a construction project; in fact, building operations have a share of approximately 40% of global energy and carbon dioxide emissions (Schlueter & Thesseling, 2009). In this case, estimation of Greenhouse Gas (GHG) emissions from building materials is the spotlight of the research, and more specifically communication of these impacts to early design participants and decision-makers. Changing the established processes and creating opportunities to assess such factors is now more feasible than ever, if we take into account the technological advancements, as well as the accumulated and detailed knowledge at our disposal over all the aspects involved regarding a certain topic.

Additionally, the reduction of the environmental impact of construction projects would definitely lead to further long-term social benefits, as for example the improvement of life conditions, through a cleaner and healthier atmosphere.

1.4.2. Scientific importance

Within the scientific and theoretical context of the research, the optimization of processes is an important factor. Having in mind the complexity of an environmental assessment analysis as outlined in section 1.1.1, this research attempts to make such process more automated, to decrease manual input and use modern technologies and concepts. Generally, it should be noted that building materials are in the centre of attention for the particular research and this is a field not extensively researched, since it contains high level of local influence, and therefore generic use is hard to be implemented. The result of the development aims to facilitate and encourage the potential users to account for the environmental impact of their design and identify ways to optimize it, in relation to sustainability increase. This is achieved via direct integration of 3D building models and environmental impact assessment data, which is an important scientific accomplishment.

The scientific importance, thus, lies on the fact that application of new theories takes place and a modern approach is adopted, in which linking environmental impact data with design alternatives is the main goal. Finally, there is currently little research that addresses the topic using the particular methodology of linked data, and especially with direct connection to 3D building models.

1.5. Reading guide

The following chapters outline the implementation of the research model. Initially, the findings of the literature analysis are given in section 2. Three parameters are taken into account for conducting this literature review, namely the environmental impact of construction industry, along with the existing assessment standards and tools; second the use of Building Information Modelling, its benefits and challenges, as well as the open standard used and the association to sustainability; and finally, introduction to the Semantic Web and Linked Data technologies and concepts, along with applications within the AEC industry. Section 3 presents the environmental impact data collection, referencing the creation, content and limitations of the database used for the research. Having introduced the foundation data source, section 4 offers a detailed description of the tool development, which aims to integrate the building design and environmental impact data, in order to provide an estimation of the embodied carbon of materials. The development process is followed by the tool validation and limitations. Finally, in section 5, conclusions are presented, on the basis of the research questions established in section **¡Error! No se encuentra el origen de la referencia.**, and following the scientific and societal relevance. The end of this section provides a number of recommendations for further research, in regards to the environmental assessment, extensibility of the model and possibilities of the linked data approach.

2. Literature Review

This section presents a summary and evaluation of contemporary literature and state-of-the-art studies related to the research problem. The research problem concerns how one can influence designers to make environmentally friendly choices with regards to building materials. Insights into the different approaches adopted by the scientific community, such as assessment standards; state regulations; and computational data handling, identify important findings of the advantages and disadvantages related to each one. This literature review helped in motivating the methodology used along with the results and applications generated from past methodologies, which lead to call for optimized actions and solutions.

This section is divided into three different topics in relation to the problem definition; Environmental impact of the construction industry, Building Information Modelling, Semantic Web and Linked Data.

2.1. Environmental impact of construction

The first point is to show the impact of the construction industry on the environment during the different phases of the construction process, with reference to all the aspects that contribute towards this impact. Special importance is given to the building materials usage, since it is the basis of the tool. The impact of the construction activities on the environment leads to revising the initiatives taken so far on behalf of governments, states and organizations in order to reduce this impact. Finally, certain environmental targets of the Dutch state are included, so that to set the context of the research and make it more tangible, in terms of the movements towards sustainability.

2.1.1. Environmental impact of building materials

Amongst all the industrial areas, the construction industry is the one, which burdens the surroundings the most. Within the European Union, the built environment is responsible for half of the total material extraction, 42% of the final energy consumption and 35% of greenhouse gas (GHG) emissions (EC, 2011).

The core of every building and infrastructure project is the building materials used in order to pass from paper or computer aided design to a solid new construction. One of the aspects when considering the environmental impact of the built environment is the embodied impacts of building materials, also known as embodied carbon.

Embodied carbon is defined as the amount of CO_2 emissions related to the production of a building. In detail, embodied carbon includes the GHG emissions, generated through the energy used in the processing, manufacture and distribution of the materials, products and components needed to erect a building. The maintenance, repair, replacement and disposal or reuse of these materials and products also contribute to emissions, however these emissions are treated separately (WRAP, n.d.). The factors that influence the embodied carbon of materials include: a) the type of the raw material constituents, b) the site of material quarries and transport mode needed, c) carbon intensiveness of the processes for extracting, manufacturing, constructing and installing; and d) recycling and reuse after the building lifetime and distance travelled for disposing the subsequent waste (Hammond & Jones, 2008).

The production of building materials is responsible for a large share of carbon footprint; in detail, approximately 10% of global energy supply is used for material manufacturing (United Nations Environment Programme, 2011), while production of specific materials, for instance, manufacturing of steel and cement account together for about 15-20% of worldwide CO_2 emissions (Yellishetty, Ranjith, & Tharumarajah, 2010). According to the results of a case study conducted by Pöyry et al. (2015) concerning the embodied and construction phase greenhouse gas emissions of a low-energy residential building in Finland, concrete is the single greatest contributor to GHG emissions, with the production of cement to be the main source. The above figures reveal the importance of the embodied impacts of materials, while stress the need to increase sustainability in construction. Insight into the terms and context of sustainability in construction is given in section 2.1.2.

Pomponi and Moncaster (2016) present 17 embodied carbon mitigation strategies, with the first one being the use of materials with less embodied energy and carbon. Some of the other recommended strategies include better design; reduction, reuse and recovery of embodied impact intensive materials; refurbishment of existing buildings; greater use of local materials; building lifetime extension. In their study, they mention that the use of materials with less embodied energy and carbon has been a quite typical approach. In some cases it involves alternatives such as natural materials, for example timber, bamboo, hemp-lime composites, while different studies conduct comparative analysis between commonly used materials, as for instance steel-concrete structures versus masonry-concrete structures (Pomponi & Moncaster, 2016b). An example is a multi-story residential construction in Hong Kong, which achieved embodied carbon savings of magnitude of 34.8% by using alternative building materials instead of traditional ones (Cui, Sham, Lo, & Lum, 2011).

Taking into consideration the above points and the fact that carbon embodiment cannot be changed across building phases, the solution is to intervene during the design phase. The importance of acknowledging the environmental impact in terms of the embodied carbon of materials during the design stage is discussed in section 2.1.3.

2.1.2. Sustainable construction concepts

The concept of *Sustainability* is concerned with the sensible use of the planet's natural resources. Therefore, sustainability in construction is meant to reinforce application of this concept to construction-related activities (Farzad Shahbodaghlou & Arjun R Pandey, 2015). Niklaus Kohler & Sebastian Moffatt (2003) define sustainable development of the built environment essentially as the transformation of the built environment in such directions so that to enable our enduring survival on the planet.

Some of the principles that can classify a construction project as sustainable include applications of concepts such as reduction, reuse, recycling of building materials; reduction of toxic substances; life-cycle economics consideration; aesthetics and durability application, and all these using the least amount of resources (Farzad Shahbodaghlou & Arjun R Pandey, 2015). Therefore, what arises as a fundamental point is making considerate use of available natural resources, avoiding abuse of it and waste generation.

Circular Economy is another term used to refer to efficient use of resources. In recent years, it is regularly utilized and associated with the above mentioned concepts, such as sustainability, zero waste, material reuse, renewable energy and efficiency. By definition, "a circular economy is restorative and regenerative by design, and aims to keep products, components and materials at their highest utility and value at all times. The concept distinguishes between technical and biological cycles" (Ellen Macarthur Foundation). Within the construction sector framework, the significance of the circular economy derives amongst other things from the fact that it results in fewer use of resources (e.g. less materials are extracted) and lower costs for taking care of waste (Schut, Crielaard, & Mesman, 2016). An innovative example of resource and material reuse and recycle, considering the time it was realized, is the Heineken WOBO (World Bottle); a wall made of beer bottles, designed by the Dutch architect John Habraken in 1963. Heineken's and Habraken's conception of the idea to convert used products that would be disposed otherwise to something new and different continues to be an example for reference even today (Kriscenski, 2012).

In contrast to other sectors, scarcity of resources does not constitute a principle cause for the built environment sector to adopt circular economy processes. On the contrary, the environmental impact of building materials plays an important role and is one of the driving forces towards circular economy application (Schut et al., 2016). Even so, Dutch architect Thomas Rau takes into consideration both factors; in the renovation of the office building of Liander, the first circular building in Europe on this scale (DeVorm, 2015), his company *RAU architects* was the main architect. For this project, 80% of the materials used was recycled from existing buildings, which resulted in reduced energy consumption. As a result, surplus energy was shared with surrounding companies and the rainwater collected by the roof was used for cooling and toilet rinsing (Rau, 2015; DeVorm, 2015). All of Rau's buildings include a resources passport that keeps record of the origin of the materials and the potential use of them for recycle and reuse after demolition (Rau, 2015). An aspect to consider regarding the use of recycled materials is that increasing the amount of them in a construction project, results in decreasing the embodied carbon of the whole building (Akbarnezhad & Xiao, 2017), since recycled products are less carbon intensive in terms of processing compared to raw materials. For example, for the metals, the percentage decrease of embodied carbon when using a recycled product is approximately 85% (Hammond & Jones, 2011).

Apart from the environmental impact of materials, there are of course other factors to be considered as beneficial in opting for sustainable designs. These include for example economic and social affairs, such as lower costs or investments through efficient designs, but also more comfortable and engaging living spaces (Bragança, Vieira, & Andrade, 2014). A social benefit for instance of a sustainable design would be that by creating an energy efficient building, the thermal conditions within the interior improve and so users are more satisfied in terms of comfort. Furthermore, economic benefits of an energy efficient building include lower annual fuel and electricity costs for the users/owners, but also lower costs for governments due to decreased necessity for new energy infrastructure (Federal Energy Management Program, n.d.).

Having exposed that one of the aspects to consider when deciding on a sustainable design is the environmental impact of materials, the next step is how to approach this aspect. A calculation method for quantifying these impacts would be to consider the embodied energy and carbon. And since the choice of materials takes place during the design phase, accounting for such impacts can and should take place during the design phase (Bates et al., 2013). An insight on the importance of considering the embodied energy and carbon during the design phase is given in the following section 2.1.3.

2.1.3. Accounting for environmental impact during design phase

This section provides evidence, based on scientific literature research, about the significance of accounting for the environmental impact of building materials within the development of the design.

Bragança et al. (2014) pointed out the importance of early stage design decisions towards sustainable buildings, as through efficient design, the buildings' environmental impact is decreased. They considered the factors that can be taken into account during the conceptual phase of the project and selected eleven indicators, based on three categories, as in environmental impact, energy impacts and life cycle costs. Amongst these indicators was the global warming potential (GWP), which constitutes a factor for measuring the environmental effect of materials in CO_2 equivalent.

However, both Bates et al. (2013) and Liu et al. (2015) emphasize that no building rating system exists with certain design criteria or no complete application has been developed and been integrated to existing design tools (such as BIM), for the assistance of the designer during the design phase to assess the environmental impact (Bates et al., 2013; Liu et al., 2015).

T. Häkkinen et al. (2015) also concentrate on the design phase of a construction project, supporting the statement that sustainability decisions should start from the initial stage. This due to the fact that low-carbon design belongs to one of the most important factors towards sustainable construction. They additionally make reference to the lack of tools for accounting the embodied carbon and energy during the design and construction phases, compared to the existence of several methods for assessing the energy use during the operation phase (Häkkinen, Kuittinen, Ruuska, & Jung, 2015). Hence, amongst the decisions taken during the design phase and which can determine the project's sustainability level, is the choice of building materials. An important step towards constructing sustainable buildings is the choice of materials with lower embodied carbon content. Figure 2 shows the amount of influence that decisions have towards the environmental impacts and costs and the actual impacts and costs within the different project phases. It is made quite clear that initial decisions can have the greatest effect, while the biggest share of impacts and costs take place during the use phase and maintenance. Therefore, by intervening in the initial design process, it is possible to achieve great environmental impact reductions in later stages, with lower costs.

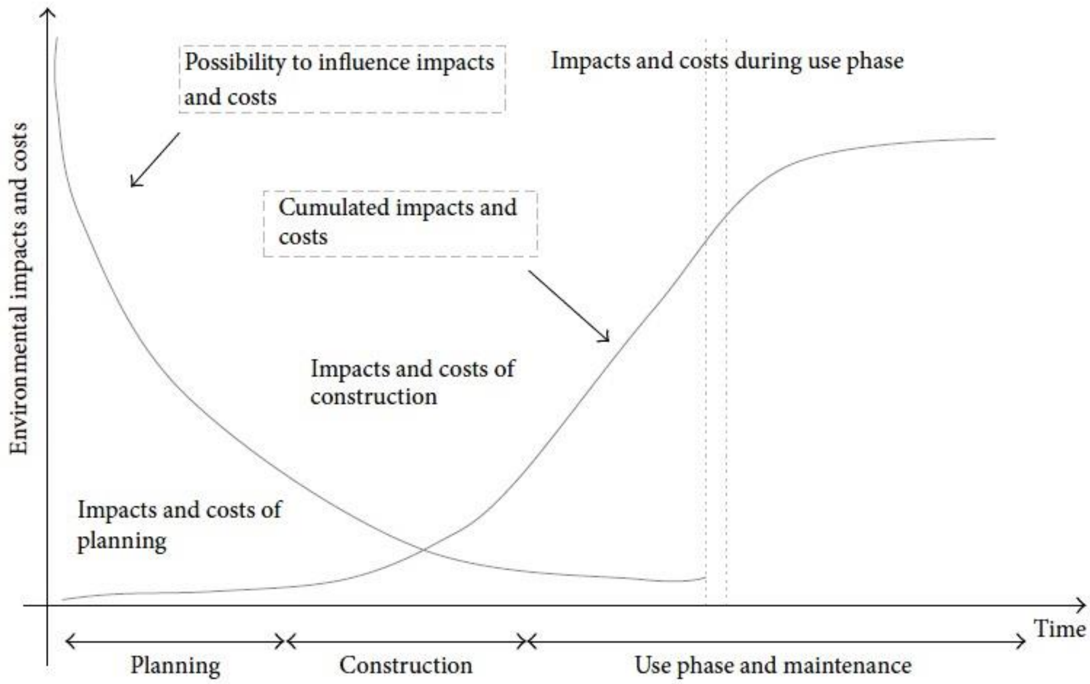

Figure 2: Power of design choices on life cycle impacts and costs (Niklaus Kohler & Sebastian Moffatt, 2003)

Nevertheless, within the existing tools for embodied carbon assessment, Ariyaratne & Moncaster (2014) identify three main issues; these are a) quantification methods, b) handling design alterations and c) acquiring updated data for executing the analysis. Likewise, Bates et al. (2013) indicate that due to continuous review and revision of the material and system requirements, during the various design stages, real-time and constant update of environmental impacts of the design alternatives is essential. Therefore, even though taking decisions regarding the embodied carbon should be done during the design phase, in practice the carbon footprint estimation can be very trivial in case of multiple design modifications and lack of material quantities. A solution to the latter is the use of Building Information Modeling (BIM), which is thoroughly examined in section Building Information Modelling and Sustainability.

When estimating embodied carbon, it is important to place it within a certain context, since there are different boundaries of the material life-cycle for which the carbon footprint can be calculated. Tah et al. (2010) propose a holistic framework of embodied carbon and waste in the building lifecycle, and point out that during the design stage the embodied carbon in the building materials can be calculated precisely in the system boundary of cradle-to-gate (Tah, Zhou, Abanda, & Cheung, 2010). Cradle-to-gate system boundary, as shown in Figure 3 includes the initial stages of extraction and manufacture of the raw materials, as well as transportation to the gate of the factory. It is apparent that this accounts only for just a part of a whole life cycle assessment, however it is considered very important as mentioned above due to the fact that it is irreversible. The embodied carbon of the materials once chosen for a construction of a building cannot change, whereas there are several ways to influence the emissions during the following stages. Tackling these emissions is an issue, which has been very extensively addressed, as described in section Environmental impact assessment standards.

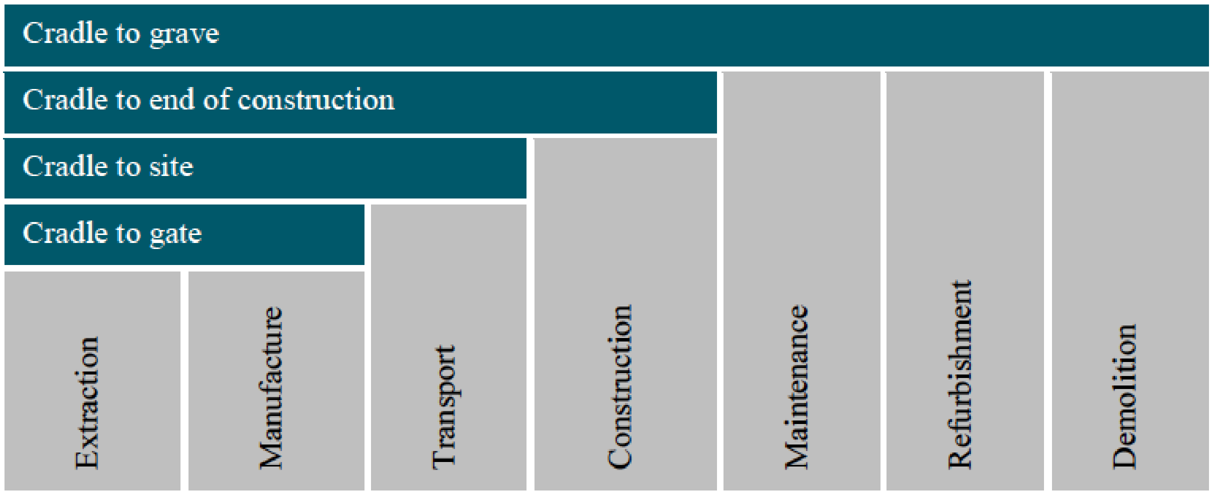

Figure 3: Life Cycle Assessment Stages (Ariyaratnea & Moncaster, 2014)

Summing up and evaluating the points described above, three main conclusions can be made; the importance of attempting to influence the environmental impact of building materials, in order to achieve sustainable construction; secondly, the need to do that during the initial phases of conception and design, in which the choice of building materials takes place; and finally, the scarcity of existing tools, which address the issue and help the designer.

2.1.4. Environmental impact assessment standards

In regards to the environmental assessment of buildings, there have been introduced various rating systems worldwide, with states developing their own guidelines and standards, such as *BREEAM*, *LEED, HQE, CASBEE, Green Globe, Green Star, GBC* (Häkkinen, Kuittinen, Ruuska, & Jung, 2015). The mentioned systems, also known as voluntary standards help to assess the performance of a finished construction, while the impacts of embodied carbon are not being considered (Ariyaratne & Moncaster, 2014).

The *GPR Gebouw* developed in the Netherlands measures the sustainability of residential and non-residential buildings. It is an online application, which can be used for all project phases, from design to renovation, and is performance oriented suitable for all the different teams of the project. *GPR Gebouw* also offers the possibility to get certification through testing of the building or design by an independent GPR Building assessor. It is developed for municipalities, corporations, real estate stakeholders, architects, consultants, project developers and care institutions and measures sustainability on five different themes (Energy, Environment, Health, Usage quality and Future value) (GPR) as shown in Figure 4. In the second cluster for the *Milieu* (Environment), the first point (Milieuprestatie) involves the embodied carbon of the materials.

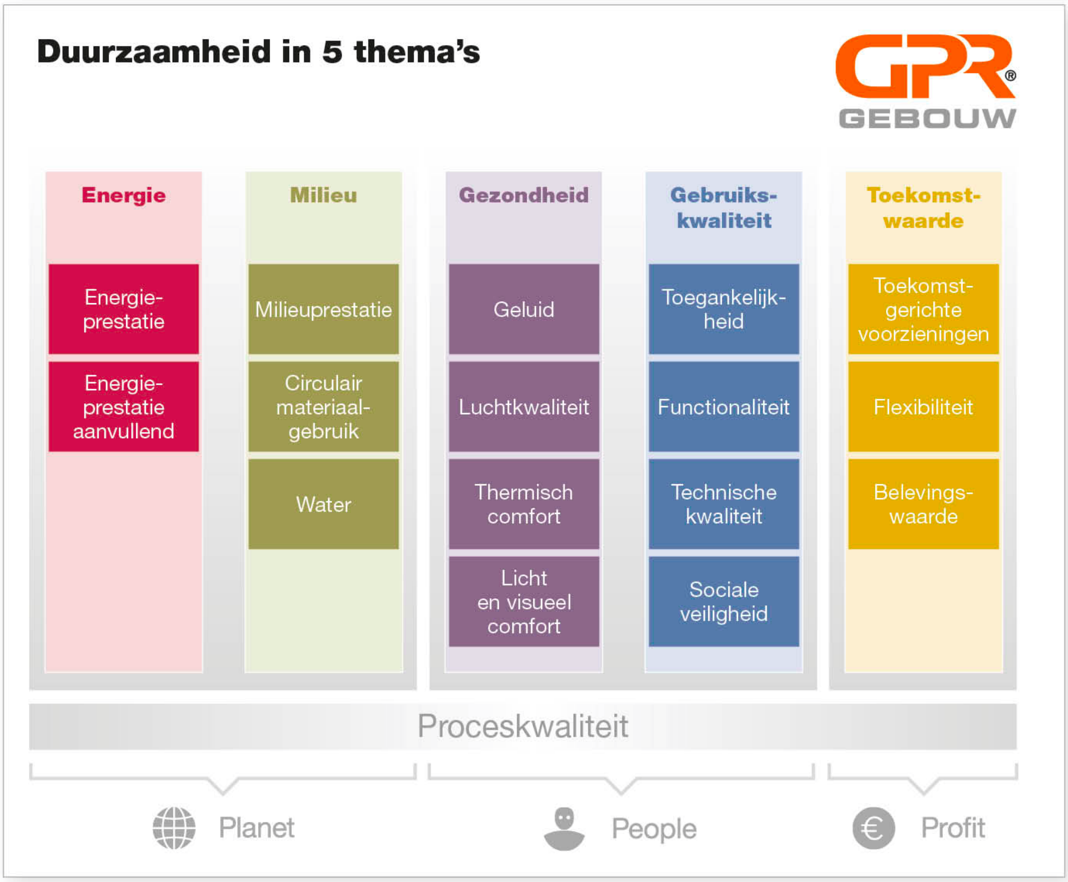

Figure 4: GPR Gebouw, Sustainability in 5 themes (GPR, 2016)

An interesting green building certification program is the *Living Building Challenge*, which "visualizes the ideal for the built environment", depicting this ideal as a flower, which functions cleanly and efficiently. Unlike other standards, *Living Building Challenge* demands for actual, instead of anticipated, performance validated over a period of twelve months. Additionally, it includes occupants' interaction with the spaces and all the functions associated with them, such as light, air, food, nature and community. For the particular certification, low impact and and non-toxic materials is a requirement (International Living Future Institute).

According to Bates et al. (2013), the tendency of focusing on the operations energy consumption through the aforementioned voluntary standards and through very tight rules and restrictions, will result in the continuous reduction of the energy used during operation, while the impacts related to the life cycle of building materials will keep on increasing, perhaps to an extent at which they become the primary source of the environmental impact in construction related context.

Regarding building materials, in the Netherlands, *DUBOkeur* is a certification for products, including products for construction. For a product to gain the *DUBOkeur* ® tag, a life-cycle analysis is conducted by the Dutch Institute for Building Biology and Ecology (Nederlands Instituut voor Bouwbiologie en Ecologie - NIBE) and compared to similar products. A *DUBOkeur* certified product is classified to the top of the market in terms of sustainability and it should also not cause any negative effects to the users, harmful emissions or washouts during the use phase (DUBOkeur).

2.1.5. Embodied carbon tools

Apart from the environmental impact standards for whole buildings or for individual products mentioned in the section por encima de, there exists a number of embodied carbon tools, for buildings, specific materials or infrastructure projects. This section gives an insight to these tools.

Currently, in comparison to carbon emissions during the operational phase, which are controlled through building regulations, embodied impacts are not yet regulated. Nevertheless, the latter tend to become the centre of attention in the European Union, with embodied energy being characterized as one of the suggested core indicators for the EU Framework for Building Assessment (Green Building Council, 2015).

In order to calculate the carbon footprint of buildings, a very extensive analysis is required, since large amounts of materials, products and assemblies need to be assessed. At the moment, there are different publicly available carbon footprint and embodied carbon assessment calculators, which however are not integrated with design software tools (Circular Ecology). The existing carbon footprint calculators, which are available online to use or download for free are presented Table 1.

Table 1: Existing carbon footprint calculators (Circular Ecology)

Name	Use	Source	Type
AggRegain	Primary or recycled and secondary aggregates	WRAP	Excel
asPECT	Asphalt	Highways Agency, Mineral Products Association, Refined Bitumen Association and TRL Limited	Excel
Build Carbon Neutral	Structures and sites	Mithun, Lady Bird Johnson Wildflower Center, University of Washington	Online
Environment Agency Carbon Calculator	Sustainability performance of design choices	Environment Agency	Excel
PAS 2050	Stoneworks	Forest Pennant, Natural Stone Specialist	Excel
Highways Agency Carbon Calculator	Highways	Highways Agency	Excel
Carbon Management System	Road and rail schemes	Transport Scotland	Excel
Klimagassregnskap	GHG emissions of buildings	Statsbygg	IFC file, data input

As it becomes clear from Table 1, most of the existing tools are Excel based. In practice, this means that manual input is needed by the designer, which might lead to higher probabilities of error. Furthermore, it reduces potential use to an extent, due to being quite time consuming, making the process less attractive to follow, unless strictly required to do so. The detection of the availability of these tools further stresses the need to explore different ways for the environmental impact assessment, with more automated processes and integration with design tools.

2.1.6. Dutch environmental targets and movements

In the Netherlands, environmental issues are taken into serious consideration and there is continuous effort to resolve them. Nevertheless, the country has low scores in attempts to decrease carbon dioxide emissions. In 2016, carbon dioxide emissions from fossil fuels increased by 0.4 percent, whereas the EU average emissions decreased by 0.4 percent since 2015 (Jos G.J. Olivier, Marilena Muntean, Greet Janssens-Maenhout, & Jeroen A.H.W. Peters, 2016)

The Dutch State is bound to a goal of a 30% decrease in GHG emissions compared to 1990, by 2020. The new buildings should be energy neutral on that year, while the consumption of energy of the existing buildings should be reduced by 50% (Royal BAM, 2008). According regulations to reach those goals include implementations of EU directives (e.g. Eco-design directive, Energy Performance of Buildings Directive), as well as national initiatives (Nachmany, et al., 2015). Already since 2002, the Netherlands Agency for Energy and the Environment (Novem) developed the Strategic Framework for the Market Implementation of Energy Efficiency within the Dutch Built Environment (SFBE), as a governmental tool to achieve goals in Kyoto Protocol and European Union GHG decrease (Kool, Jenniskens, Leeuwen-Jones, Rijn, & Poolen, 2002). In 2012, the Dutch government signed the 'Green Deal' with the organisation MVO Netwerk Beton, constisted of 21 companies and 6 trade associations involved in the supply chain of concrete. The goal was to achieve 100% sustainable concrete by 2050 (Marijn Bijleveld et al., 2013).

According to Rijkswaterstaat's (department of the Dutch government responsible for infrastructure projects) 2015 report, named "Circular economy in the Dutch construction sector", the building industry consumes large amounts of materials; in fact, more than half of the total quantity of materials used within the country are reserved for construction purposes. Regarding the waste, a large amount (more than 95%) of all construction and demolition waste is recycled (Spijker & van der Grinten, 2014)) and used for foundation material in infrastructure projects. This process has been established as *downcycling* as it entails total reprocessing for production of a new material of usually lower quality (Sassi, 2002). There are actually hardly any new residential areas, business parks or roads that are produced without the use of recycled materials (e.g. aggregates). On the other hand, recycled products are almost never used for the construction of buildings, with figures indicating only a 3-4% of all new materials for (non)-residential buildings to be made of secondary materials (Schut et al., 2016).

According to the same report, suggestions include the collaboration of Rijkswaterstaat with the construction industry, in order to develop means for supporting circular construction. These means should be integrated with already existing ones for Life Cycle Assessment and Life Cycle Cost Analysis, as well as BIM and be incorporated in the Buildings Decree regulation (Schut et al., 2016).

2.2. Building Information Modelling and Sustainability

The second topic reviewed, is the advancement and use of Building Information Modelling (BIM). This section gives a background on BIM origins and definition, while then the benefits and challenges associated with it are discussed. Following this, a detailed introduction of the Industry Foundation Classes (IFC) data model is given, which was extensively used in the development process and finally, BIM implementations are presented, especially within the context of environmental assessment and sustainability.

2.2.1. BIM background

The AEC industry has always looked for ways to improve project efficiency, in terms of cost reduction, productivity and quality boost, as well as shortening of delivery time, and BIM has the potential to accomplish these goals (Azhar, Nadeem, Mok, & Leung, 2008)

The concept of Building Information Modelling (BIM) first appeared in the early 2000s, as a result of field research on the development of new collaborative data exchange methods and standards (Penttilä, Rajala, & Freese, 2007). With the introduction of BIM, the line-based Computed Aided Design (CAD) was converted to object-based CAD, adding the concept of building elements representation, not only with respect to their 3D geometric data, but also other non-geometric, for example functional characteristics (Ghaffarianhoseini et al., 2017).

The main difference between BIM and traditional 3D CAD is that the building in the latter, is described in 3D, as well as in separate views (i.e. plans, sections, elevations), and any modification in one of those views would need update of all of them. This is not a sustainable and efficient procedure, not to mention the error prone probability. The most important difference though is that and as mentioned before, the entities in these views are not explicitly defined, but rather represent just geometrical shapes. On the other hand, a BIM model consists of well-defined objects (e.g. beam, wall, slab etc.) with extra semantic information associated with them (e.g. time plan, suppliers, operation and data information etc.) (Cooperative Research Centre for Construction, 2008). Figure 5 gives an example of a BIM model about how objects are represented with extra semantic information.

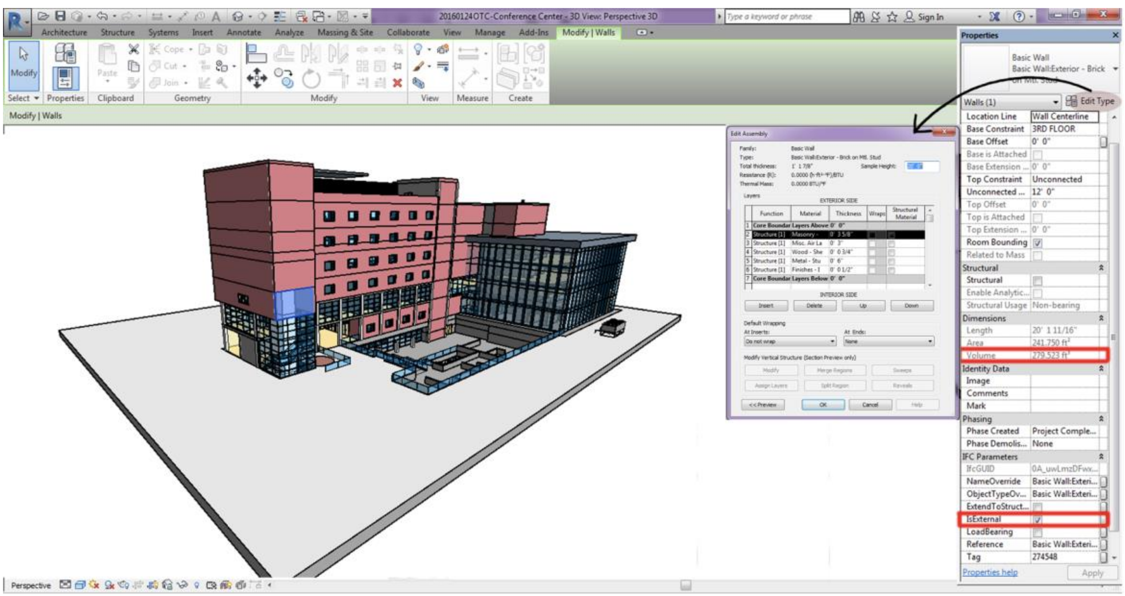

Figure 5: Example Building Information Model

As it is evident from the figure above, BIM offers the ability to visualize a construction project in a virtual 3-dimensional environment. A precise model is created with all the explicit geometry and other applicable data required to facilitate the construction, fabrication and procurement processes (Eastman, Teicholz, Sacks, & Liston, 2008).

2.2.2. BIM benefits and challenges

In their review, Ghaffarianhoseini et al. (2017) introduce a number of actual BIM benefits for the AEC industry, namely technical; knowledge management; standardization; diversity management; integration; economic; planning/scheduling; building LCA; decision support benefits.

An important aspect of the construction process is the ability to attain an accurate quantification of building components, materials and spaces. In the past and sometimes even today, the so-called quantity takeoff was done manually, based on taking measurements of elements using 2D documents. Human involvement in this process makes it, therefore, prone to errors (Monteiro & Poças Martins, 2013). With the introduction of BIM, the model is represented as an assembly of objects as mentioned before, with explicit properties, such as their geometric attributes. Thus, the above manual process can be now achieved automatically with the quantity takeoff feature, available in most of the existing BIM tools (Monteiro & Poças Martins, 2013). The extraction of exact quantities of building materials contributes to the management of the procurement process during the design and construction stages (Grilo & Jardim-Goncalves, 2011), as well as the more accurate ordering of materials well in advance, achieving delivery on site without delays (Ghaffarianhoseini et al., 2017).

A strong advantage resulting from the use of BIM is in the field of knowledge management, enabling the sharing of detailed information regarding the building, already within the design phase. This information might concern individual building elements and their relationships with each other, while integrating data such as light analysis, geographic information, quantities and properties of the components, carbon content, costs and many more (Ghaffarianhoseini et al., 2017).

BIM adoption involves along with numerous benefits, certain challenges that need to be overcome. One of the most important ones is issues regarding the intellectual property of the results generated by the BIM tools (Solihin & Eastman, 2015). Due to the fact that project information is available to be accessed by different members, there might exist matters of unauthorized access and copyright infringement (Chien, Wu, & Huang, 2014). Moreover, since, the BIM models can be used and reused by the team, which produced them, but also by others, this might result in making the level of responsibility between the different members quite vague (Azhar, Khalfan, & Maqsood, 2012). However van Berlo's et al. (2015) conclusions of their study on collaborative engineering in the Netherlands seem to differentiate on that; they argue that the legal matters of using BIM appear to stay the same as before the use of it; they explain that information is maintained separately between the different project participants, as in there is no central model archive (van Berlo, Derks, Pennavaire, & Bos, 2015).

There are of course other reasons for resisting the adoption of BIM technologies, and these can be technical or financial. Regarding the technical possible causes, often interoperability difficulties, due to lack of suitable software or use-friendly interfaces and absence of required skills and previous experience, play an important role for not embracing BIM. In terms of the financial aspect, it is often the case, BIM users (especially smaller companies) suffer from low return of investment, which is seen as an obstacle in the decision to engage its technology (Ghaffarianhoseini et al., 2017). Regarding experience levels, van Berlo et al. (2015) support that inexperienced BIM users tend to believe that there are problems, which in reality are not there, and so collaboration with advanced users becomes difficult.

2.2.3. Industry Foundation Classes (IFC)

As mentioned, interoperability issues can often obstruct the implementation of BIM technologies. The definition of interoperability as expressed by Venugopal et al. (2012) is the ability of various systems and organizations (domains) to collaborate, as in interoperate (Venugopal, Eastman, Sacks, & Teizer, 2012). The big range of software used in the AEC/FM (Facility Management) industry by the different stakeholders creates difficulties in communication; Figure 6 illustrates the various "partial" models, generated by different programs, each one representing a particular aspect of the building project (Torma, 2013). Since the native files of these software programs can normally open within the same program, integration of information between the different domains was not possible. Some neutral formats (e.g. DXF, IGES, SAT etc.) were developed to enable file exchange across different systems, nevertheless the exchanged files contained only geometric information(Venugopal et al., 2012).

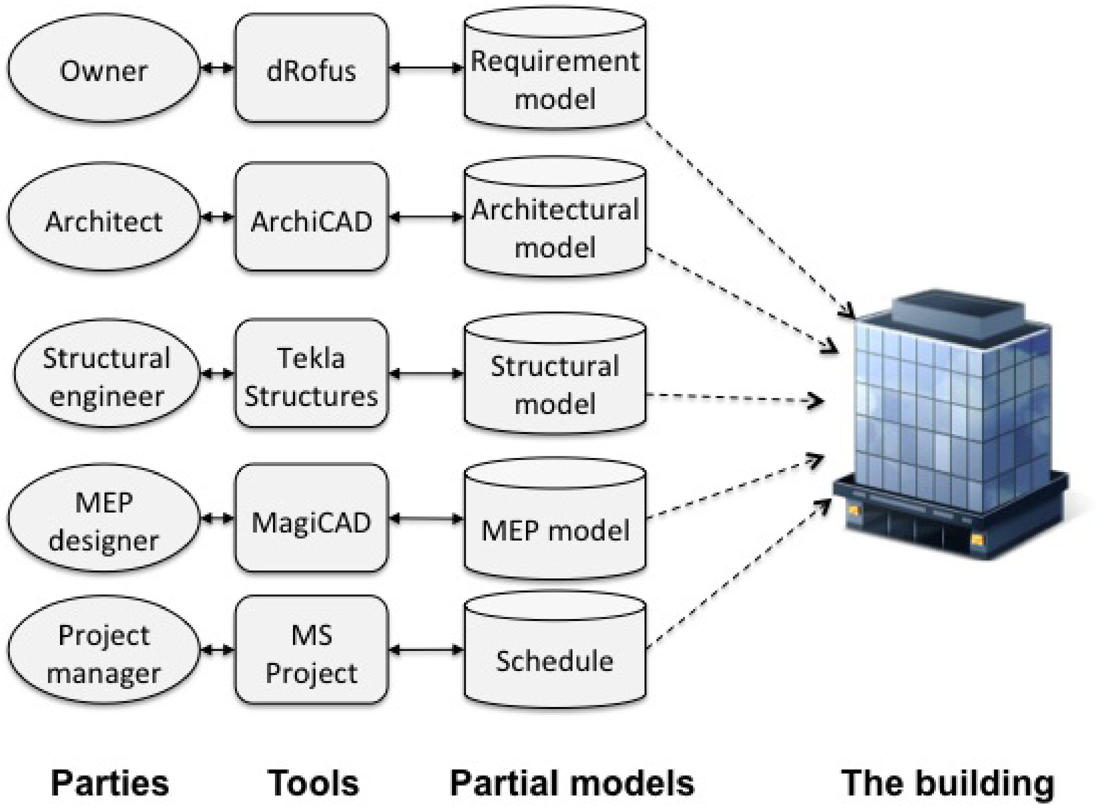

Figure 6: Partial models of a building (Torma, 2013)

To overcome interoperability issues and introduce non-proprietary building data models, the former International Alliance for Interoperability (IAI), now named BuildingSMART International developed the Industry Foundation Classes (IFC) data model (Dimyadi, Spearpoint, & Amor, 2008; Jakob Beetz, J. P. Van Leeuwen, & B. de Vries, 2005; Pauwels, Zhang, & Lee, 2017). The IFC specification uses the EXPRESS data definition language, while the IFC exchange format is the IFC STEP Physical File Format enabling the exchange of IFC among various applications, through import and export features (BuildingSMART)(Pauwels et al., 2017).

The IFC data model is an open vendor-independent file format, which contains geometrical, and semantic properties of building objects, as well as how these are related with each other in the building information models (Volker Thein, 2011) (Borrmann, Beetz, Koch, & Liebich, 2015). Despite its ability to represent not only non-geometric, but rather domain specific properties, exchanged files in practice, mostly contain geometric information as for example clash detection and quantities extraction (Dankers, van Geel, & Segers, 2014).

Being a vendor-neutral format with zero monetary cost of use, it has resulted in that multiple vendors (more than 160 in 2015) have incorporated the IFC model in their design software, with the most extensively used version being IFC2x3; this version is slowly substituted by IFC4 (Borrmann, Beetz, Koch, & Liebich, 2015) and as of beginning of 2017, there is the latest specification for the IFC4 Add2 Release (Library of Congress, 2016).

The IFC format, due to its generic structure and neutrality, is used by the majority of public sector building projects, which require the use of BIM, with countries such as Singapore, Finland, the USA and Great Britain being amongst the greatest implementers (Borrmann, Beetz, Koch, & Liebich, 2015). According to a recent article (April 2017), about the adoption and implementation of BIM in some of the major nations in the world, 72% of the construction firms in the US are thought to use BIM technologies, while in the UK BIM adoption has gotten to the level of 54% (Singh, 2017).

Its model structure contains four layers namely Resource; Core; Shared (or Interoperability); and Domain Layer. Supertypes and Subtypes of entities and their relationships are defined by the inheritance hierarchy of the IFC data model as shown partially in
Figure 7. Building elements are defined in the shared layer and are subclasses of entities that belong to the core layer (i.e. *IfcElement*, *IfcBuildingElement*). The building materials that the building elements consist of, are included in the resource layer; classes in this layer do not derive from *IfcRoot* (basic abstract class of the core layer) and so cannot exist as independent objects, but need to be referenced by other objects which are derived by *IfcRoot* (Borrmann, Beetz, Koch, & Liebich, 2015).

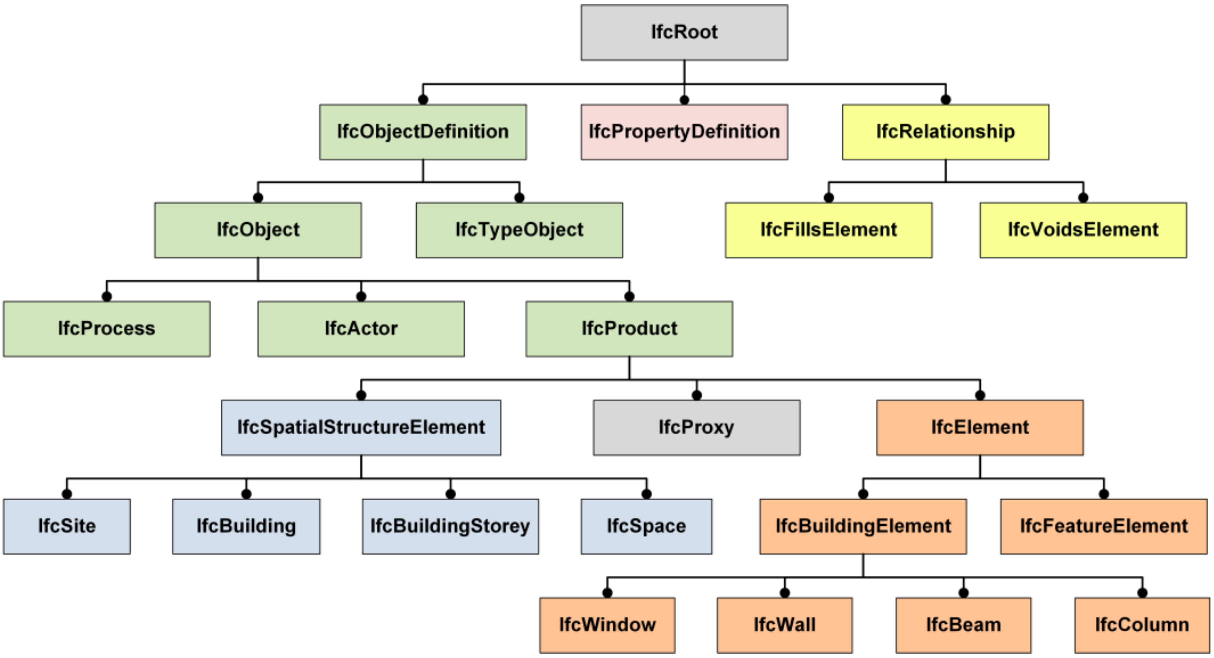

Figure 7: Part of inheritance hierarchy of the IFC data model (Borrmann, Beetz, Koch, & Liebich, 2015)

In the IFC data model the relationships between the different entities are not represented as direct links, but instead they constitute separate entities and function as intermediary objects. The relationship entity for defining a material is the class *IfcRelAssociatesMaterial*, which is associated to a building element. The way this relationship works is given in Figure 8. A wall is a layered element, defined by the *IfcMaterialLayerSet*, which consists of *IfcMaterialLayer*(s) with certain thickness and each layer uses an *IfcMaterial* (Borrmann, Beetz, Koch, & Liebich, 2015). In IFC2X3 version, the entity *IfcMaterial* has only one attribute, which is the material *Name*. However, in the more recent IFC4 version, apart from the *Name* attribute, it is also defined by two more, which are the *Description* and *Category* attributes (BuildingSMART). The attribute *Category* provides an extra level of specification to the *IfcMaterial*, making it less generic than before, where there was no attribute for classification. The entity definition in the previous version, but also in the newer version to a certain extent does not enable standardized material definitions with specific properties and types.

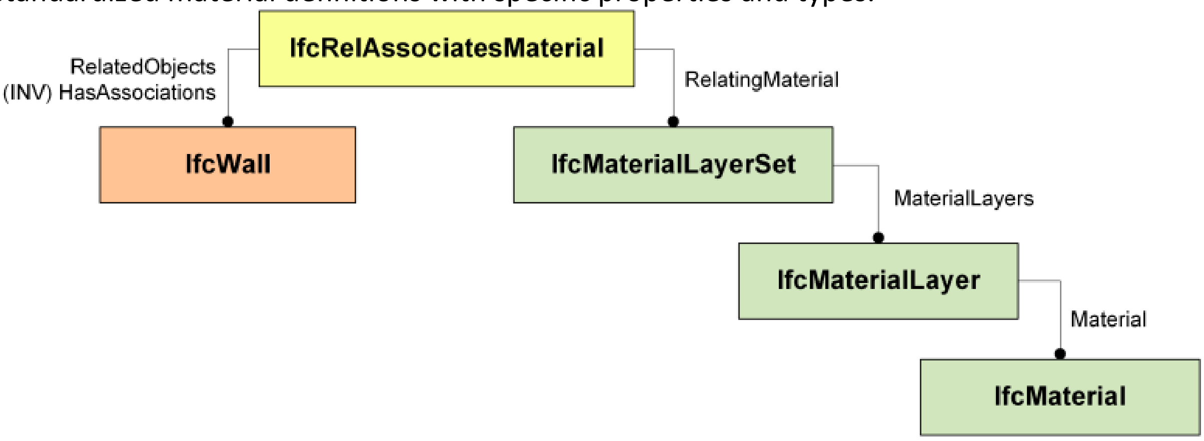

Figure 8: Linking of an IfcWall to its materials (Borrmann, Beetz, Koch, & Liebich, 2015)

An aspect of the IFC data model which can sometimes be considered as a drawback is the fact that it is very flexible, as in it allows for different ways to express things; for example different ways to specify properties and this might sometimes impede compatibility (Borrmann, Beetz, Koch, & Liebich, 2015). An example is the specification of the elements' volumes. Even though normally volumes are described under the quantity entities (e.g. *IfcElementQuantity*), there exist models, which contain element volumes under the property set entities (e.g. *IfcProperty*). This is something that should be given the necessary attention, especially in cases where certain properties or quantities need to be extracted or manipulated.

An additional limitation of the IFC is the conversion process from-to native software; basically the design software tools can export building models in the IFC format, nevertheless the backward route (i.e. when the IFC is imported back to the native software, as depicted in Figure 9) is usually not effective, as a lot of information is lost, making remodeling and development of the new model very difficult. Thus, modification should be implemented to the native model and then be exported again to IFC (Torma, 2013).

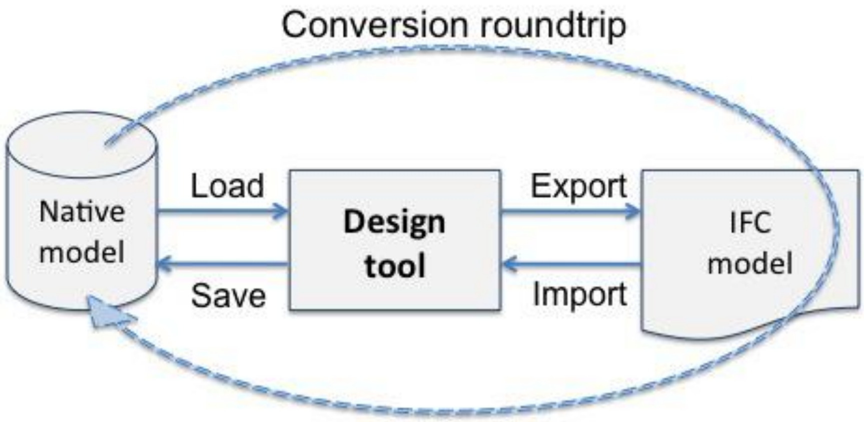

Figure 9: Conversion roundtrip: native-IFC-native(Torma, 2013)

In terms of the environmental impact, in the IFC4 version, it is possible to add environmental impact indicators and values to elements and element types (Liebich, 2011). This is done with a property set called *Pset_EnvironmentalImpactIndicators*. Indicators values can include the whole life cycle or a particular phase, which can be specified with the *LifeCyclePhase* property. The specific property set consists of 19 properties, only five of which have been formally established at an international level (BuildingSMART). One of the properties is the total primary energy consumption (*TotalPrimaryEnergyConsumptionPerUnit*), which could be the embodied energy, when the boundary set was cradle-to-gate.

2.2.4. BIM applications for sustainability

The use of BIM to encourage and enable sustainable construction has been extensively researched by the scientific community (Chong, Lee, & Wang, 2017; Farzad Shahbodaghlou & Arjun R Pandey, 2015; Liu et al., 2015; Motawa & Carter, 2013; Tajin Biswas, Tsung-Hsien Wang, & Ramesh Krishnamurti, 2008). It is recognised that multiple features coming from the implementation of BIM technologies can facilitate the simulation and estimation of the building performance, energy efficiency, carbon footprint and other aspects of environmental impact.

In order to accomplish sustainable designs, certain analyses and design optimization need to take place so as to increase building performance. These analyses require coherent and reliable data, such as building geometry and orientation, associated loads, ventilation, surroundings, etc. which however is not traditionally accessible at early design stages, resulting in the realization of the analyses at later stages. As a consequence, optimizations based on such analyses that could have been done at early stages are obstructed. On the other hand, BIM can offer solution to this problem, by acting as a multi-domain digital database accessible during the whole lifecycle of the building through just a single building representation. Therefore, information related to structural, MEP, lighting are collected in this representation, enabling faster and more precise building analysis (Kamaruzzaman, Salleh, Weng Lou, Edwards, & Wong, 2016). This ability of early analysis and assessment allows for intervention earlier in the process, already during the design phase, which can have a greater effect on the impacts and building performance, as explained in section 2.1.3.

The last decade, there have been several attempts to integrate sustainability concepts into Building Information Modelling (BIM), during all the different stages of a building project, as described in the review of (Chong et al., 2017). The most important findings of their review were that amongst all the construction phases, demolition and refurbishment were the least developed, while most BIM standards and guidelines concerned mainly the design phase. In fact, design, manufacturing and use of products and materials, as well as energy efficiency were the likely topics within the research of BIM for sustainable construction (Chong et al., 2017).

The usefulness of BIM towards sustainability in the AEC industry has further been discussed by (Ariyaratne & Moncaster, 2014). In their review it is suggested that adding environmental impact data of building elements to the BIM model could facilitate the calculations by making use of the quantities extracted directly from the design; and thus, enable the comparison of design alternatives (Ariyaratne & Moncaster, 2014), while further reinforce the information transfer in regards to modern applications of for example embodied carbon analysis (Rachael Luck, 2007).

In addition to the focus on individual building elements, research has been conducted in integrating BIM with building rating systems for a whole building performance rating model. Biswas et al. (2008) developed the sustainable building information model (SBIM) application, in order to assist designers to which factors they should take into account early in the design, for achieving credits, according to the LEED sustainable building rating system. Their application is built on Revit design software and amongst other assessments, includes the calculation of the embodied carbon of the materials. They conduct this calculation with the use of the quantities of the model mapped to emission factors from the Inventory of Carbon and Energy (ICE) database, and consider only basic building materials (not composite elements) (Tajin Biswas et al., 2008). Ilhan & Yaman (2016) also propose the development of a tool, which integrates BIM and sustainable data based on BREEAM certification. As a first step, they introduce new property sets in the IFC model, extending the material properties (e.g. reused materials, responsibly used materials etc.), which have to be inserted by the user; the enriched IFC is imported into the developed application, where based on the quantities and information on sustainability, a report is generated with the ratings of each basic element (i.e. wall, window, roof etc.). These tools assist the designers and policy makers to decisions they need to make during the design phase when a certification for sustainability is needed. This way, the potential process for getting a sustainability certificate requires less effort on behalf of the assessor, while otherwise it is considered a long and tedious procedure (Kamaruzzaman et al., 2016; Rasekh & McCarthy, 2016).

Mousa et al. (2016) propose the development of a tool for BIM visualization of building carbon emissions during the operation phase, after identifying a research gap on picturing carbon data in real time and localizing this data in the building. They believe that such features could help operation managers to spot emission issues and manage more effectively the carbon emission levels of the building. Their research model includes collecting sensor data from the building, using IFC objects to attain necessary information from the model combined with the sensor data and importing the managed data set to the carbon calculation method. The result of the calculations is then imported back to the BIM model, in order to create the carbon emission data representation; thus by color-coding it is possible to check which areas of the building have the greatest environmental impact in terms of real time carbon emissions (Mousa, Luo, & McCabe, 2016). An important suggestion that comes out of this study is that visualization of data -here environmental impact related data- can have a greater influence on the decision making; picturing data enables the more efficient view of the situation and thus better judgment can be made in terms of measures to be taken.

Other implementations include the use of energy simulation programs next to the building information model, in order to assess different aspects of environmental impact. Chen and Li (2014) propose the integration of BIM (Revit) and eQuest to calculate the lifecycle costs and carbon dioxide emissions of building materials. The boundary they consider includes the material production, transportation to the site and operation phases. According to their approach, initially cost and emission data is input into the BIM model, which is then translated to gbXML and imported to Green building studio, in order to convert the data such way to be processed by eQuest. The results from eQuest are exported into an Excel file, which can be used by developers to make more environmentally conscious choices of construction materials (Po-Han Chen & Yu-Chieh Li, 2014). Taking into consideration alternative design solutions, this study shows how the choice of different materials can have a strong impact on the environmental behavior of the whole building. However, Motawa & Carter (2013) mention there are certain difficulties in the use of BIM with energy simulation tools, which can disable adoption and implementation. More specifically, they point out that importing the BIM model to such tools is done easily using IFC and gbXML, while the opposite route might require significant manual input when changes in the building model are needed for achieving optimal performance.

All in all, literature has shown that using BIM technologies within sustainability and environmental impact assessments can be of great advantage. It enables more automated processes, while manual input can be diminished, which as a result can reduce error generation and create more accurate evaluations. Finally, it seems beneficial to create tools, which have an influence on the design phase, especially when the choice of building materials is the examined aspect.

2.3. Semantic Web and Linked Data

2.3.1. Semantic Web and Linked Data definitions

The *Semantic Web* is a relatively new term, a concept introduced by Tim Berners Lee, the inventor of World Wide Web, in 2000, who defined it as “a web of data that can be processed directly or indirectly by machines” (Berners-Lee, 2000).

The traditional web, as we know it so far is a set of distributed hypertext and hypermedia that can be retrieved through search of keywords and page linking; something which in fact causes certain difficulties when it comes to complicated searches of information, for instance, searches which require the combination of more than one sources. This is where the Semantic Web arises, in which the data is structured in such format that becomes readable by computers, and as such can be processed automatically by machines, as well as humans (Horrocks, 2008).

Following the introduction of the Semantic Web, the concept *Linked Data* was proposed in 2006 again by Tim Berners-Lee. He came to recognize that even though there is a lot of information published on the web, complying to the semantic web principles, it is not linked to external data, which was the essence of the semantic web concept (Berners-Lee, W3C, 2006). In his inspirational TED talk in 2009, Tim Berners-Lee stresses the need for raw data publication, as there is huge potential in relation to data usage. He emphasizes though that the most important is connecting the data and creating links between all different concepts (Berners-Lee, 2009). Linked Data refers to the implementation of systems for linking data from various sources that may belong to very different domains (Christian Bizer, Tom Heath, & Tim Berners-Lee, 2009). Figure 10 depicts the Linking Open Data (LOD) cloud diagram (Abele, McCrae, Buitelaar, Jentzsch, & Cyganiak), which is a presentation of the datasets that have been published in Linked Data format. The lines between the datasets suggest the existence of links between entities of the two datasets (Christian Bizer et al., 2009).

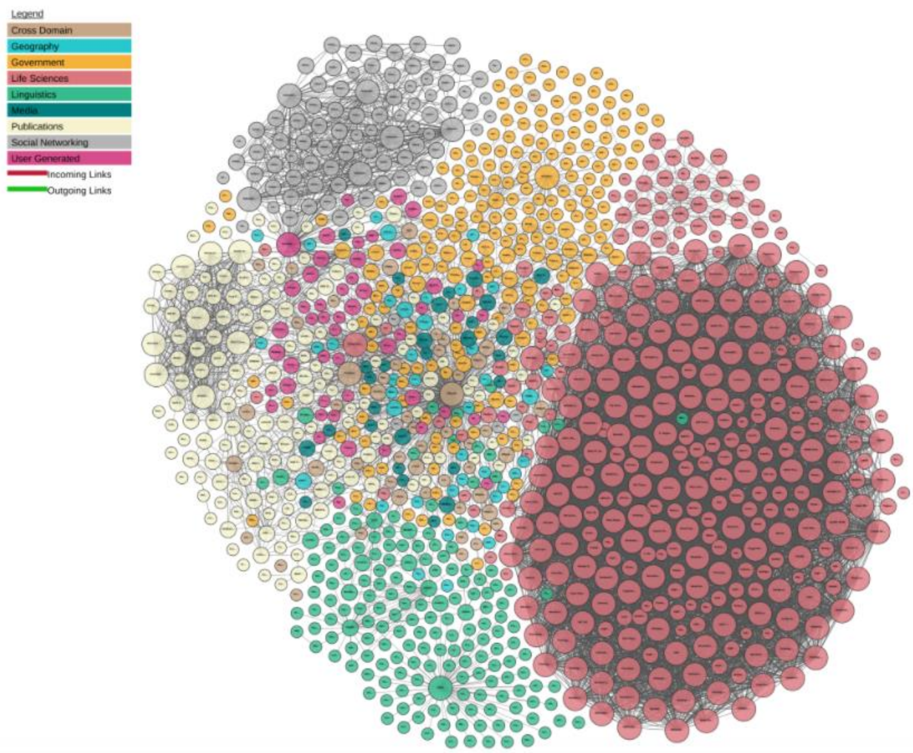

Figure 10: The Linking Open Data cloud diagram (Abele, McCrae, Buitelaar, Jentzsch, & Cyganiak)

There are four rules, developed by Tim-Berners Lee, which if followed, the result can be considered true linked data. These four rules (Berners-Lee, W3C, 2006) are:

1. Use of URIs to name things
2. These URIs should be HTTP, so that people are able to track the names
3. Use of standards (RDF, SPARQL) for providing meaningful information to the URIs
4. Add links to other URIs, so that more information can be discovered

The following figure (Figure 11), illustrates the 5-stars of linked data, which portrays what it takes for published data to be considered Linked Open Data.

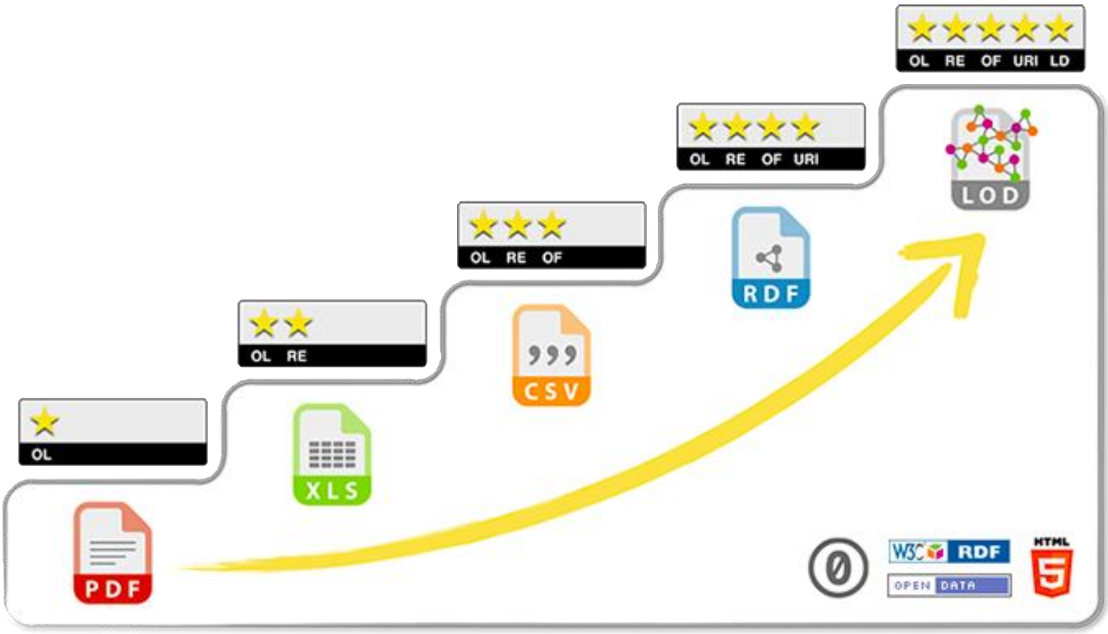

Figure 11: 5-Star Deployment Scheme for Open Data (5 Star Open Data)

2.3.2. Resource Description Framework

In the Semantic web, things are referred to as *resources*, and a resource can basically represent anything that someone is interested in talking about (Allemang & Hendler, 2011). Resource Description Framework (RDF) is the standard followed by the World Wide Web Consortium (W3C) for governing the data existing in semantic web applications (Klyne, Carroll, & McBride, RDF 1.1 Concepts and Abstract Syntax , 2014). W3C is the international community, led by Tim Berners-Lee and CEO Jeffrey Jaffe with a mission to lead the Web to its full potential (W3C).

The RDF standard consists of graphs, in which each node is a concept or an object in the world, defined by its own global ID, in this case what is called a Unique Resource Identifier (URI) (Pauwels et al., 2017). The RDF graphs are modelled as triples, each triple being composed by a subject (s), a predicate (p) and an object (o). The first two items, as in subjects and predicates need to be URIs, while the object can either be a URI, a literal or a blank node (Horrocks, 2008). The syntaxes used to serialize an RDF graph are RDF/XML (eXtensible Markup Language) and the Notation 3 (N3) language, as well as the subsets of the latter namely, NTriples and Turtle (Berners-Lee & Connolly, 2011). In order to model RDF data, a semantic extension to the RDF vocabulary has been developed, named RDF Schema (RDFS), which specifies the mechanisms for describing groups of related resources (e.g. rdfs:Class, rdfs:Datatype) and their relationships (e.g. rdfs:subClassOf, rdfs:subPropertyOf) (Brickley, Guha, & McBride, 2014).

2.3.3. Ontologies

The RDF language, however, cannot depict important relationships, such as cardinality constraints, that is why in 2004, the OWL ontology language was published by W3C, as the standard for a Web ontology language.

Ontologies function as vocabularies, in which terms are described with explicit meanings and specifications (Horrocks, 2008). An ontology is essentially a set of axioms; each of the axioms is a statement, declared to be true and says something about classes, properties and instances (Bock, et al., 2012). In terms of the structure of the ontologies, classes are used to group resources with similar features, and each class is related to a number of individuals; individuals are linked to each other via object properties, while they are linked to data values via datatype properties (Bechhofer, et al., 2004).

Thus, ontologies are the ones that enable the determination of cardinality restrictions, property hierarchies, inverse properties (Horrocks, 2008) and so contribute to the development of complete and well-defined datasets, often within a specific domain. With the use of ontologies and creation of RDF graphs, the emerging question is how to actually take advantage of these graphs, how to retrieve information existed within them, as well as how to manipulate them. Interaction with RDF graphs is achieved with employment of query languages.

2.3.4. SPARQL Query Language

A query language is a programming language that enables the searching and modification of the contents of a database. Modern query languages are able to interact in different ways with databases and graphs, such as by altering the schema, searching, populating and updating the contents, while they have many more capabilities (Vassilakopoulos & Tzouramanis, 2009).

The recommendation of W3C for query language of RDF is SPARQL 1.1. With SPARQL, it is possible to express queries across various data sources, as well as query graph patterns together with their associations. The results of SPARQL queries can be result sets or RDF graphs (W3C, 2013). SPARQL stands for SPARQL Protocol And RDF Query Language. SPARQL queries can be used to query one kind of data or merged data, in order to obtain information or to convert a graph to a new form (Allemang & Hendler, 2011).

A typical example of a simple SPARQL query is given below, taken from the official W3C SPARQL tutorial website, in order to show the structure:

```
SELECT  ?country_name ?population
WHERE { ?country a type:LandlockedCountries ;
           rdfs:label ?country_name ;
           prop:populationEstimate ?population .
        FILTER (?population > 15000000) .
}
```

Initially the result clause *SELECT* is used, which in this case contains two variables, namely *?country_name* and *?population*. With this clause, the required result is determined, which in this case is countries and their population. Then the query pattern *WHERE* is used, which contains the conditions and constraints of the query. In particular, the countries to be selected here should be of type Landlocked Countries, with a property for estimating the population and a filter to include only the ones that have population more than 15 million.

2.3.5. Semantic Web in the AEC industry

The concept and use of semantic web technologies for the AEC industry was introduced by the scientific community in the early 2000s. This was partly due to the need for combining different information sources and data, in order to achieve better results in terms of availability and efficiency of the information. Gradually, more and more experts from the AEC industry resort to the establishment of semantic web and linked data technologies (Pauwels et al., 2017).

One of the driving forces to integrate Semantic Web technologies within the framework of the AEC industry, has been the ability to link across domains. Using semantic web technologies, it becomes possible to associate information from various domains, such as BIM; GIS; sensor data; and smart cities with the the web of linked building data (Pauwels et al., 2017). Even though the AEC/FM industry is generally quite divided and stays behind when it comes to adopting new technologies (Jakob Beetz et al., 2005), the scientific community in a number of studies has pointed out the benefits from the potential integration of Semantic Web technologies into the construction sector practices; such benefits include interoperability solutions, enrichment of BIM models with external useful information/data and cross-domain applications. To that end, integration of environmental impact data and geometric data would facilitate the environmental assessment of a building design and its alternatives, in order to opt for the one that is more “environmentally friendly”.

BuildingSMART has also inclined towards the use of Semantics, and for that the Linked Data Working Group has been initiated, as a support to the use of semantic web applications within the context of the construction industry, with a focus on the development and maintenance of the ifcOWL ontology (Pauwels et al., 2017) (BuildingSMART International, 2015). This ontology is built upon the IFC to serve the building and construction sector (Beetz, Leeuwen, & Vries, 2009). After a period of approximately 7 years (2005-2012) and a number of research and implementation proposals of an OWL from an EXPRESS schema (Schevers and Drogemuller, 2005; Beetz et al., 2009; Krima et al., 2009; Barbau et al., 2012), there was an increased interest in creating an ifcOWL, so since 2012 several attempts made their appearance. In 2014, Pieter Pauwels and Walter Terkaj recommended one conversion procedure from an EXPRESS schema to an ontology, combining the previous developments, so that to establish a more standard process (Pauwels & Terkaj, 2014). The latest version, as published in January 2016, is automatically created from the EXPRESS schema 'IFC2X3_Final' with the use of the 'IFC-to-RDF' converter and can be found in the buildingSMART website, under the Linked data file.

In (Abdul-Ghafour, Ghodous, Shariat, & Perna, 2007), an ontology-based approach has been proposed in order to overcome the existing heterogeneities which often obstruct the attempt of product data integration with 3D geometric information and reinforce interoperability during product data exchange for instance design intent and domain-specific product attributes.

There has also been a number of recent research efforts within the scientific community, in regards to the use of Semantic Web and environmental impact assessment of the construction sector. Niknam & Karshenas (2015) developed a knowledge based system, using semantic technologies, which is able to access different sources of information regarding energy and input this information into an energy analysis program. Hou et al. (2015) developed a system called OntoSCS (Sustainable Concrete Structure Ontology), to support optimization of structural design options and supplier selections for concrete, using embodied energy and CO_2e to assess the sustainability level of the structure (Hou, Li, & Rezgui, 2015).

In regards to the use of Semantics for building materials, Bilal et al. (2017) proposed a repository of standardized building materials in order to support Building Waste Analysis (BWA) for designing out waste. They recognized the need for detailed description of materials and the lack of product ontologies and classification systems for explicit modelling of the building materials, and so suggest the creation of a database of building materials complying to standards such as RDF and OWL. In this database the materials are classified with properties, using names; as well as synonyms to capture the diversity of material expressions along the globe; dimensions; price; and a list of alternative materials (Bilal et al., 2017).

A very extensive and publicly available dataset is the BauDataWeb, which represents the Austrian building and construction materials market as Linked Data. With the aid of this dataset, it is possible to search for products, providers and warehouses for all kinds of construction-related needs, while even distance values between warehouses and consumption sites are available. The dataset is built upon the FreeClassOWL ontology and constitutes an exhaustive tool for the construction sector market, accessible on the Semantic Web (Radinger, Rodriguez-Castro, Stolz, & Hepp, 2013).

2.4. Conclusion literature review

The literature analysis has shown that the key phase for taking decisions associated with the sustainability of a building project is during the design phase; that is when the building materials are chosen and since they account for a great share of the total environmental impact of the building, they need to be chosen mindfully. Additionally, the literature review has indicated the significant potential in the use of BIM for sustainability, for example since the quantities of the materials can be extracted accurately from the BIM model. Moreover, the use of Semantic Web is highly recommended, especially for linking BIM with external semantic information, as in this case with environmental impact data. This constitutes a very sustainable way of connecting different domain information without having to deal with interoperability issues, while, Semantic web technologies continue acquiring different implementations, making Semantic web one of the key instruments of the future data web. Finally, it is suggested that data representation in the 3D virtual environment can have a great impact on the potential users' behaviour, as in the particular case encouraging further sustainability decisions.

3. Data Collection

For the realization of the research, it was necessary to find a valid source of data with the embodied impact of the building materials. The environmental impact database is an essential aspect of this research for being able to generate results based on real figures. The selected source used here is a database named Inventory of Carbon & Energy (ICE). It was created by Geoff Hammond and Craig Jones as the Sustainable Energy Research Team (SERT) of the University of Bath, department of Mechanical Engineering. The first version was published in 2005 and the second updated version was released in 2011 in Excel format (Hammond & Jones, Inventory of Carbon & Energy (ICE), 2011). The reason behind the choice of the particular database is that it is publicly available and construction-sector oriented, offering a vast range of building materials, while it is given in such format that enables easy handling and retrieval of information. Additionally, it contains a detailed reference list of the data sources making it possible to verify and explore these sources. The following sections describe how the database was created, how it is structured, as well as its limitations.

3.1.1. ICE creation

Figure 12 below displays the process of the database creation (Circular Ecology). Lifecycle Carbon Inventory (LCI) and Lifecycle Carbon Analysis (LCA) contributions were selected from scientific sources, such as published journal papers, technical reports and monographs. These contributions were then evaluated in terms of the quality of the energy coefficients they provided. Following the publication of the first version of the database, professional feedback was received by participants from the material industry, which was used to optimize the energy coefficient values and the boundary definitions, as well as include values for recycled materials.

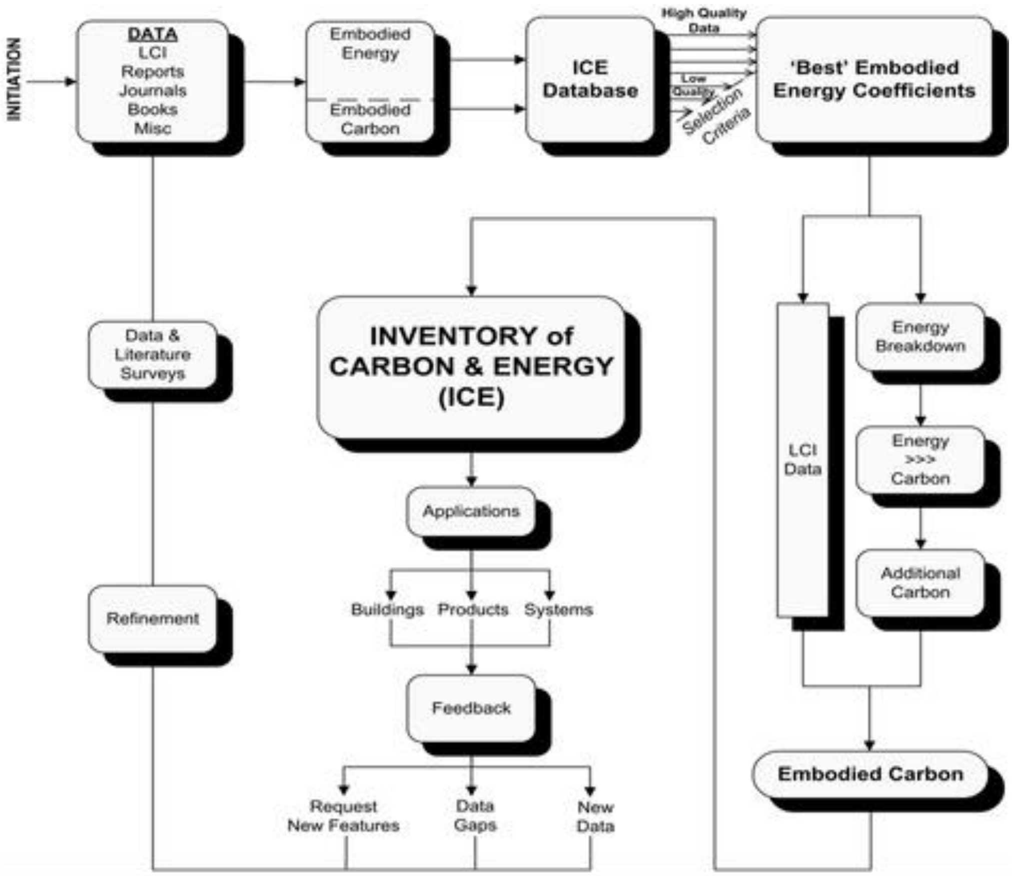

Figure 12: How ICE database was created? (Circular Ecology)

3.1.2. ICE content

ICE is very extensive and construction sector oriented as well as free to download and use; interested users can download it after completing a short form. It includes figures for a great amount of building materials (more than 200), which are divided into 30 basic material categories. According to the official website, it has been downloaded by more than 20,000 professionals and has been used as reference in numerous reports, journals, books, carbon footprint calculators, and more (Circular Ecology). Figure 13 illustrates the default format of the database after download from the official online source.

On one hand, the particular format provides a clear and well-ordered information system in a user-friendly environment, enabling the easier understanding of the data. However, what should be noted is that manipulation of this data, as in usage of it as input to different tools and applications can be quite time-consuming, while manual input is essential. For example, for an architect or engineer to use this Excel sheet for the calculation of the carbon footprint, implies a lot of manual effort and possible error generation; first the quantities of the materials should be generated from the design, then units have to be converted if needed and as the final step the mapping with the database coefficients should be done to proceed to the calculation. Consequently, this seems as a long and tiresome procedure, while design alternatives would possibly slow it down more.

INVENTORY OF CARBON & ENERGY (ICE) SUMMARY

Materials	Embodied Energy & Carbon Coefficients			Comments
	EE - MJ/kg	EC - kgCO2/kg	EC - kgCO2e/kg	EE = Embodied Energy, EC = Embodied Carbon
Aggregate				
General (Gravel or Crushed Rock)	0,083	0,0048	0,0052	Estimated from measured UK industrial fuel consumption data
Aluminium	Main data source: International Aluminium Institute (IAI) LCA studies (www.world-aluminium.org)			
General	155	8,24	9,16	Assumed (UK) ratio of 25.6% extrusions, 55.7% Rolled & 18.7% castings. Worldwide average recycled content of 33%.
Virgin	218	11,46	12,79	
Recycled	29,0	1,69	1,81	
Cast Products	159	8,28	9,22	Worldwide average recycled content of 33%.
Virgin	226	11,70	13,10	
Recycled	25,0	1,35	1,45	
Extruded	154	8,16	9,08	Worldwide average recycled content of 33%.
Virgin	214	11,20	12,50	
Recycled	34,0	1,98	2,12	
Rolled	155	8,26	9,18	Worldwide average recycled content of 33%.
Virgin	217	11,50	12,80	
Recycled	28	1,67	1,79	
Asphalt				
Asphalt, 4% (bitumen) binder content (by mass)	2,86	0,059	0,066	1.68 MJ/kg Feedstock Energy (Included). Modelled from the bitumen binder content. The fuel consumption of asphalt mixing operations was taken from the Mineral Products Association (MPA). It represents typical UK industrial data. Feedstock energy is from the bitumen content.
Asphalt, 5% binder content	3,39	0,064	0,071	2.10 MJ/kg Feedstock Energy (Included). Comments from 4% mix also apply.
Asphalt, 6% binder content	3,93	0,068	0,076	2.52 MJ/kg Feedstock Energy (Included). Comments from 4% mix also apply.
Asphalt, 7% binder content	4,46	0,072	0,081	2.94 MJ/kg Feedstock Energy (Included). Comments from 4% mix also apply.
Asphalt, 8% binder content	5,00	0,076	0,086	3.36 MJ/kg Feedstock Energy (Included). Comments from 4% mix also apply.
Bitumen				
General	51	0.38 - 0.43 (?)	0.43 - 0.55 (?)	42 MJ/kg Feedstock Energy (Included). Feedstock assumed to be typical energy content of Bitumen. Carbon dioxide emissions are particularly difficult to estimate, range given.
Brass				
General	44,00	2.46 (?)	2.64 (?)	Poor data availability. It is believed that the data may be largely dependent upon ore grade. Poor carbon data, making estimate of embodied carbon difficult.
Virgin	80,00	4.47 (?)	4.80 (?)	
Recycled	20,00	1.12 (?)	1.20 (?)	

Figure 13: Inventory of Carbon and Energy (ICE)

The available data includes (when applicable) values of embodied energy (EE – MJ/kg), embodied carbon (EC – kgCO_2/kg) and embodied carbon equivalent (EC – kgCO_2e/kg). "The embodied energy (carbon) of a building material can be taken as the total primary energy consumed (carbon released) over its life cycle" (Geoff Hammond & Craig Jones, 2008). That would ideally take into account extraction, manufacturing, transportation, operation and disposal; which is referred as *cradle-to-grave* boundaries. However, it has widely been established to determine the embodied energy in the boundaries *cradle-to-gate*, which involves the primary energy up to the transportation to the factory gate (Geoff Hammond & Craig Jones, 2008). CO_2 equivalent or CO_2e is a metric measure for the comparison of the different greenhouse gas emissions in terms of their global-warming potential (GWP). This is done by translating amounts of other gases to the equivalent amount of CO_2 with the same Global Warming Potential (GWP) (Eurostat).

Energy data involves the energy consumed, in order to produce a building material, which then results in carbon emissions, contributing to global warming and climate change. Even though the ICE database has been fitted to UK standards when possible (e.g. by using typical material mixtures of the UK), it has used data figures from all over the world, hence it can be applied in cases where there is lack of local explicit information. In terms of EE and EC boundaries in a global framework, usually EE is more relevant than EC. For example, it is possible for two materials to have similar EE and different EC; this could be due to differences in the national fuel and electricity mixtures, which will result in significant variance of the EC (Circular Ecology). One of the essential factors to consider when measuring the environmental impact of building products is the boundaries of the measurements; the ICE database has a boundary *cradle-to-gate*, which as explained before takes into account the extraction of the raw material, the factory processing and the transportation to the factory gate.

3.1.3. ICE limitations

The limitations of the ICE database are presented below:

- System boundary only cradle-to-gate
- No manufacturer specific data incorporated
- Last update was in 2011
- There are values extracted from very old studies
- There are values determined, based on only a few or just a single source
- Often diverse methodologies have been used by the sources for boundary definition or allocation

Despite these limitations, the ICE database still constitutes the most consistent embodied carbon dataset for the UK (Anderson). It is a very powerful tool on the hand of those interested to calculate the environmental impact of construction materials. This assertion can be based on the following motivations: a) variety of materials that it contains, b) well-structured layout, c) it has been created based on several literature sources, as well as optimized along the years. It is worth mentioning, that building materials all around the globe are very customised, meaning they are of many different specifications, types and properties. Thus, it is quite difficult to find a repository with reliable data compared to the magnitude of existing construction materials, which offers extra valuable credits to the particular data source.

4. Tool Development

This section describes the methodology used for the tool development. The adopted approach and the detailed working processes are explained within every step of this development. The aim of this tool is to facilitate the designer to calculate the environmental impact of his/her design, via direct links between the existing building materials within the BIM model and their environmental impact values from an external database. Such an instrument is useful as it encourages sustainability in construction by supporting decision-making towards more environmentally-friendly materials. The examined literature has indicated the importance of being able to interfere during the design phase for environmental impact decisions, especially with BIM integration. Furthermore, usage of linked data for the connection of the BIM model to an external database, provides greater efficiency since update and enrichment of the database values will be available for use in future projects, without having to modify the values in the native software in case of built-in properties. BIM integration, which enables practice of open non-proprietary standards, such as the IFC format, in combination with the adoption of Semantic Web structures, allows for a tool independent of vendor-based software.

The chapter is structured as follows: first, the resources used for this development are enumerated (4.1), followed by a short overview of the tool (4.2). Next, the ontology engineering is presented, describing the ontology development (4.3) and the two following sub-sections explain the methodology adopted to build the tool, which includes the material coordination between the database and the IFC model (4.4) and the BIM integration (4.5). Finally, section 4.6 is an illustration of the tool interface, followed by the tool validation (4.7) and limitations (4.8).

4.1. Resources used for the development

The tool development required the use of numerous resources, namely programming software, building models and information on the environmental impact of building products. The used resources are shown in Table 2.

Table 2: Resources used for tool development

Programming software	Building models (IFC)	Environmental Impact information

- Python 2.7
- Python modules
  - Python OCC 0.16
  - IfcOpenShell 2.7-0.5.0
  - PyQt4
  - RDFLib 4.2.2
	- Duplex_A_20110907
	- Clinic_A_20110906_optimized
	- 20160124OTC-Conference Center
	- 20160125Trapelo - Existing-Trapelo_Design_Intent
	
	Version: IFC2X3
		- ICE Database Version 2.0

4.2. Overview of the tool

The aim of this tool's function is to support the decision-making of the designers or other potential users, during the design phase, in what concerns the choice of building materials. The decision factor will basically concentrate on how environmentally friendly are the materials selected, in terms of their embodied carbon (EC) and embodied energy (EE). The tool will consider system boundaries of building materials for their environmental impact to be *cradle-to-gate*. The designer will be able, by using the tool, to check the amount of EE and EC that will determine the environmental impact of the construction materials of their design. The EC or EE will be given for the whole construction or per building component (e.g. wall, beam, floor etc.) or per material (e.g. concrete, insulation, brick etc.). Furthermore, visualization of the most critical building elements will be one of the tool features, offering the designer a more complete overview of the localization of construction elements with major environmental impact. Finally, the tool will provide the possibility to export the results in table format (CSV). Figure 14 portrays the tool design, indicating the input data, the processes taking place during the execution and the output results. Detailed explanation over each aspect is given in the following sections.

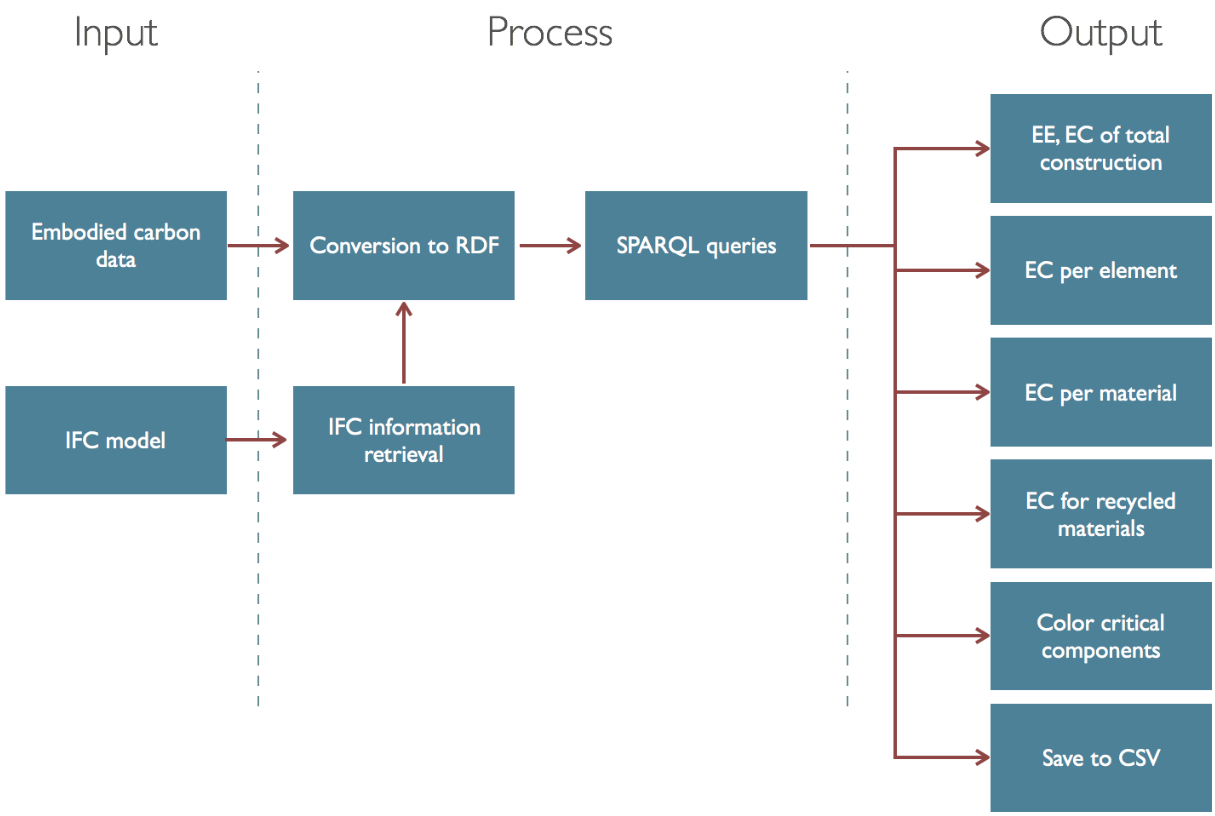

Figure 14: Visualization of tool input-process-output data

4.3. Ontology engineering

The development of ontologies has been established aiming to accomplish different tasks concerning interoperability, such as communication optimization between humans and software, data model and knowledge schema reusability (Roussey, Pinet, Kang, & Corcho, 2011). This chapter initially introduces the concept of ontology engineering, as the mechanism used for the ontology development within the framework of this research, and then the creation of the subjective ontologies is explained and presented schematically.

Ontology engineering aims to "provide a basis of building models of all things in which computer science is interested" (Mizoguchi & Ikeda, 1998). It is basically the course for examination of principles, approaches and instruments of ontology building and maintenance. Ontology engineering provides the standards and actions to be followed when developing an ontology (Staab & Studer, 2009).

For the purpose of the specific research, the OWL Web Ontology Language (OWL) was used, as a W3C recommendation. OWL is intended for use by applications, which require information processing rather than data presentation for human interpretation. Furthermore, it enables machine readability of Web information to a greater extent than XML, RDF and RDFS, since it offers an extended vocabulary together with formal semantics (Roussey et al., 2011).

OWL determines the language for the description of concepts and relationships amongst these concepts. The use of OWL language includes (Roussey et al., 2011):

- Definitions of concepts, which are named classes, as well as definitions of the properties of these classes
- Definitions of instances, named individuals and assignment of properties to these instances
- Reasoning over the above, for retrieval of interesting information

Following the above principles, two ontological vocabularies were developed. One to support the environmental impact information provided in the ICE database and a second one to establish the information needed to be retrieved from the 3D building model. The creation of these ontologies provides formalization of the concepts described in the two RDF datasets, in order to conduct concept matching and extract required information for the calculation of the embodied impacts of building materials. The RDF datasets are explained in sections 4.4.2 and 4.5.2.

4.3.1. ECOM Ontology

The ontology created to define concepts, properties, and individuals for the embodied impacts of building materials was named ECOM, which stands for **E**mbodied **C**arbon **O**ntology of **M**aterials. Protégé software was used to build the ontology and express the classes and properties associated to them. The default base Unique Resource Identifier (URI) http://www.sementicweb.org/ generated from Protégé is adopted here. The prefix used is :ecom. The whole ontology URI is as follows:

http://www.semanticweb.org/marianiki/ecom#

Figure 15 is a schematic representation of the ontology. ECOM consists of two classes: *Material* and a subclass of this, *ICEMaterial*. The *Material* class defines the material as generic concept, while *ICEMaterial* indicates the material concept specifically as expressed in the ICE database. There are 7 data properties attached to the instances of this class, which are the different embodied impact coefficients, material densities and language tags. The ECOM Ontology is given in Appendix I.

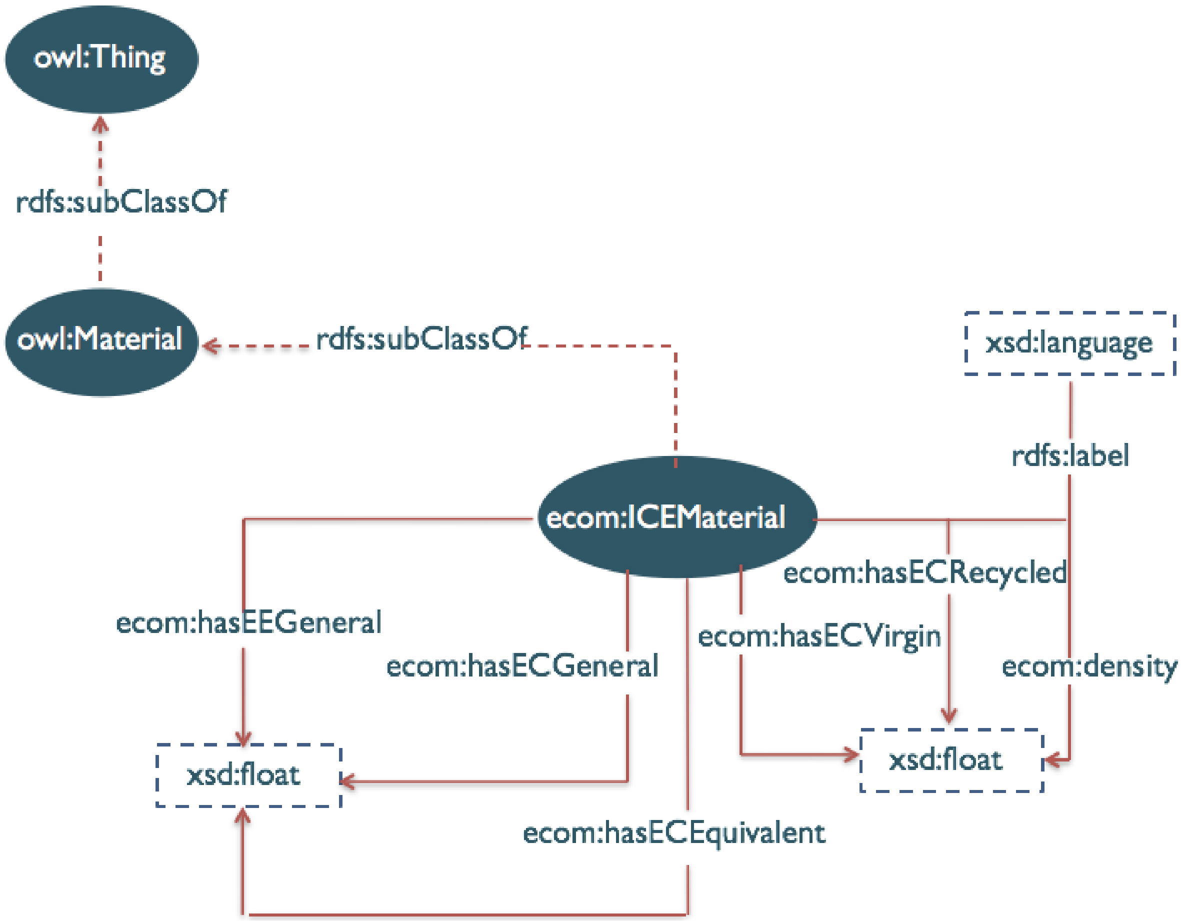

Figure 15: ECOM Ontology

4.3.2. IFCMAT Ontology

Accordingly, the IFCMAT (IFC Material) ontology is developed, in which the concepts retrieved from the IFC model are determined. The prefix used is :ifcmat and the whole ontology URI is set as follows:

http://www.semanticweb.org/marianiki/ifcmat#

The ontology in question (Figure 16) consists of 5 classes, based on the IFC schema, for representing building elements (IfcBuildingElement) and their constituent materials, following possible material entities (i.e. IfcMaterial, IfcMaterialLayer, IfcMaterialList). Detailed explanation of the material usage in the IFC model for this development is presented in section 4.5.1. The existing object properties relate the building element to its constituent materials (i.e. isAssociatedTo) or the entities IfcMaterialList and IfcMaterialLayer to individual materials (i.e. hasMaterial). Finally, amongst the data properties, one determines the GlobalId of the building element (i.e. hasGUID), which will be used as the element identity; another one is used to label the material (i.e. label), while the rest of the data properties define the element volume (i.e. elementVolume), the thickness of each material layer (i.e. layerThickness) and the material fraction within the total volume of the element (i.e. fractionOfVolume). The IFCMAT Ontology is given in Appendix I.

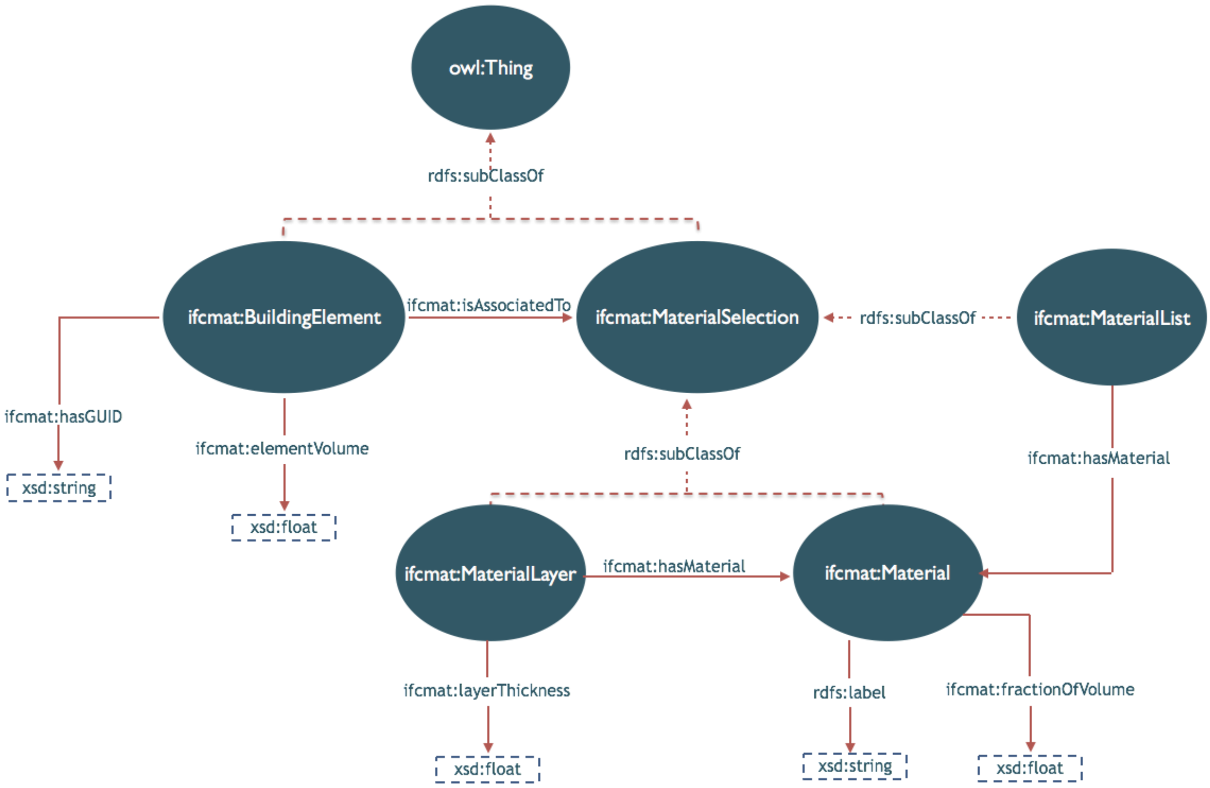

Figure 16: IFCMAT Ontology

4.4. ICE and design software material coordination

This fragment describes the approach adopted in order to create a mapping between the materials represented in the ICE database and the material entities represented in the model design. The result of this mapping is a CSV file, which is then converted into RDF, based on the concept definitions set in the ECOM ontology described in section 4.3.1.

4.4.1. Design of material mapping

The use of the ICE database described por encima de will be the instrument, based on which the IFC models will be enriched with environmental impact data. With the use of the native state of the ICE database, appending EE and EC coefficients to the building materials coming from the IFC model is not an automatic process, due to lack of direct matches between the entities from the two sources. To overcome this issue, a mapping procedure has to be developed. This is a necessary process, since a way needs to be identified so that the IFC materials are recognised as materials given in the database. The practice of joining data hosted by different sources and offering an integrated view of this data to the user is called *Data integration* (Lenzerini, 2002).

An example of such mapping is given in Listing 1: Material representation in IFC Schema (above) and in ICE database (below). The material representation as illustrated in an IFC model is shown first, following by the way the same material is represented in the ICE database.

```
#3875=IFCPROPERTYSET('37jaIcMfrD2ffdsL2W8PC_',#33,'PSet_Revit_Type_Other',$,(#3834,#
3835,#3836,#3837,#3838,#3839,#3840,#3841,#3842,#3843,#3844,#3845,#3846,#3847,#384
8,#3849,#3850,#3851,#3852,#3853,#3854,#3855,#3856,#3857,#3858,#3859,#3860,#3861));
#3876=IFCMATERIAL('Masonry - Brick');
#3877=IFCCOLOURRGB($,0.666666666666666,0.392156862745098,0.411764705882353);
#3878=IFCSURFACESTYLERENDERING(#3877,0.,$,$,$,$,IFCNORMALISEDRATIOMEASURE(0.00
390625),IFCSPECULAREXPONENT(128.),.NOTDEFINED.);
```

Brass				
General	**44,00**	**2.46 (?)**	**2.64 (?)**	Poor data availability. It is believed that the data may be largely dependent upon ore grade. Poor carbon data, making estimate of embodied carbon difficult.
Virgin	80,00	4.47 (?)	4.80 (?)	
Recycled	20,00	1.12 (?)	1.20 (?)	
Bricks				
General (Common Brick)	**3,00**	**0,23**	**0,24**	
EXAMPLE: Single Brick	**6.9 MJ per brick**	**0.53 kgCO2 per brick**	**0,55**	Assuming 2.3 kg per brick.
Limestone	**0,85**	**?**	**-**	
Bronze				
General	**69.0 (?)**	**3.73 (?)**	**4.0 (?)**	Average of the only two references

Listing 1: Material representation in IFC Schema (above) and in ICE database (below)

In this basic example, materials are represented with very similar name tags. Nevertheless, during the whole process, correlation of same materials can be much more complicated, as building materials can be quite custom-made. Therefore, quality, composition, strength, and other features may differ in different local contexts or manufacturing processes, making the mapping more difficult and sometimes not entirely accurate.

Apart from the lack of industry standardization, as mentioned in the literature, the representation of materials in the IFC data model is not very exhaustive, meaning that detailed attributes of materials can be missing, disabling standardized classifications and mapping. Therefore, for plotting the materials generated from the IFC model, their *Name* attribute was used, as retrieved from the native software. This might not constitute a very "sustainable" way of mapping, since string name tags of materials can differentiate for same materials along different design software programs or even different software versions. Nevertheless, since it is the established way of IFC material representation, it is adopted in this development.

Additional possible difficulties, which may create lack of material standardization can be caused due to the way the designer is using materials in his/her native design software. The following ways were identified:

- The designer makes use of the basic material library of his/her native design program. In that case, even though materials are more standardised, as they have default characteristics (i.e. strength, heat capacity, density etc.), there might be the case of materials being too generic. This implies that no elaborated attributes are given to each material, making it hard to draw conclusions about which material category it should be placed in, to select the correct environmental impact coefficient.
- The designer might use his/her own library of materials, with specific features according to project requirements or company standard libraries. In that case, mapping becomes difficult, unless there is manual input on part of the designer to insert the material properties and attach the right environmental impact values.

Taking into consideration the facts given above, the detailed mapping process is explained in the following fragment. The goal of the material mapping is, through data integration theory, to create a "dictionary" between the materials of the database and the IFC materials.

The material library used for the creation of the mapping within the possible boundaries of this study, is the Revit library, named *Material browser*. Revit material library is selected in this research as a case study, because Revit has many applications worldwide as a design software, while diverse IFC models are accessible from online sources. Figure 17 shows the activity diagram of the process aiming to create a unified data file, with the matched materials.

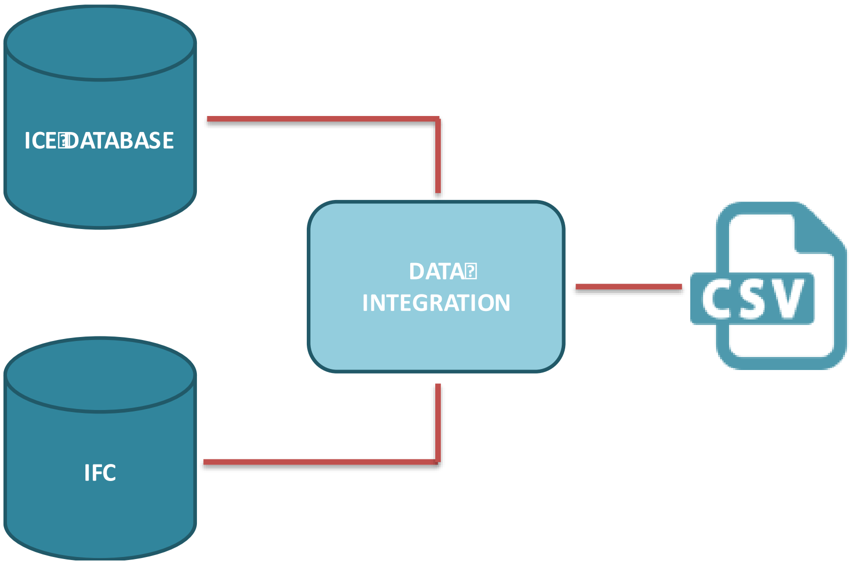

Figure 17: Material mapping process

Data integration included examination of both sources (i.e. ICE database and Revit material browser) to identify corresponding material entities between the two. This was achieved through inspection of the material properties given in Revit material browser and the material compositions in the ICE database. Even though the ICE database is rich in terms of types and variety of materials, during the data integration the extensiveness was narrowed down, on the basis of the material availability in Revit library. For this data contraction, certain assumptions had to be made:

- Average coefficients values were taken when material types were limited in the Revit library compared to the ICE database.
- Existing materials from the ICE database that did not appear at all in the Revit library, were not considered.

For example, under the category *Concrete*, there are multiple material types available in the database, depending on the concrete strength, cement content, reinforcement, prefabrication etc. These types have different embodied impact values. However, in Revit material browser, the material concrete appears more generic, meaning that less types are available. Hence, based on the material characteristics in Revit about the material concrete, average coefficients are chosen, to correlate them with the values that have the best fit according to these characteristics. This might result in a certain deviation from the real result, however it is still considered a good estimation within an acceptable variance.

The variance and standard deviation was calculated for a sample set of values of embodied carbon coefficients for the material concrete, with variations depending on the strength. Table 3 shows the results of the calculation, displaying the quantified standard deviation, which is small as expected, due to the values being very close to each other.

Table 3: Calculation of variance and standard deviation for concrete EC coefficients

Concrete	EC - kgCO2e/kg	(X-μ)²
16/20 Mpa	0,100	0,00042025
20/25 MPa	0,107	0,00018225
25/30 Mpa	0,113	5,625E-05
28/35 Mpa	0,120	2,5E-07
32/40 Mpa	0,132	0,00013225
40/50 Mpa	0,151	0,00093025
Mean (μ)	0,1205	
Variance (σ²)	$\Sigma(X-\mu)^2/N$	0,000286917
Standard deviation (σ)	$\sqrt{\sigma^2}$	**0,016938615**

The result of this material mapping is a CSV file, which contains material names, along with properties, such as the different coefficients of the environmental impacts and the density of the materials. The density is needed for later conversion of the volume coming from the IFC file to attain $kgCO_2/kg$ of material. The file created is in CSV format, as considered to be a standard format, easy to parse and compliant with linked data concepts. Part of the created CSV file is shown in Figure 18, while better visualization of the CSV file can be found in Appendix II.

ICEDatabase	RevitMaterialBrowser@EN	RevitMaterialBrowser@NL	EE_General	EC_General	EC_Virgin	EC_Recycled	EC_Equivalent	Density
Aluminium	Aluminium	Aluminium	155.00	8.24	11.46	1.69	9.16	2700
Asphalt	Asphalt Shingle	Asfalt Shingle	3.93	0.0678	0.0678	NotApplicable	0.075	1700
GeneralCommonBrick	Masonry Brick	Metselwerk Baksteen	3.00	0.23	0.23	NotApplicable	0.24	1920
GeneralCommonBrick	Brick Soldier Course	Brick Soldier Course	3.00	0.23	0.23	NotApplicable	0.24	1920
GeneralCarpet	Carpet	Tapijt	74.00	3.9	3.9	NotApplicable	NotApplicable	400
TimberGeneral	Cherry	Kers	10.00	0.71	0.71	NotApplicable	0.72	630
20/25Mpa	Concrete	Beton	0.74	0.100	0.1	NotApplicable	0.107	2400
20/25Mpa	Masonry Concrete Block	Metselwerk Betonblok	0.70	0.079	0.079	NotApplicable	0.084	1950
20/25Mpa	Concrete Cast In Situ	Beton Cast In Situ	0.74	0.1	0.1	NotApplicable	0.107	2400
25/30Mpa	Concrete Lightweight	Beton Lichtgewicht	0.78	0.106	0.106	NotApplicable	0.113	1750
PrecastConcrete	Concrete Precast	Beton Precast	1.19	0.127	0.127	NotApplicable	0.136	2400
Copper	Copper	Koper	42.00	2.60	3.65	0.80	2.71	8600
Asphalt	Damp Proffing	Vapor Proffing	3.93	0.0678	3.93	NotApplicable	0.075	1700
GeneralRammedSoil	Earth	Aarde	0.45	0.023	0.023	NotApplicable	0.024	1460
ExpandedPolystyrene	EIFS Exterior Insulation	EIFS Exterieur Isolatie	88.60	2.55	2.55	NotApplicable	3.29	328
PrimaryGlass	Glass	Glas	15.00	0.86	0.86	NotApplicable	0.91	2600
PrimaryGlass	Glass Clear Glazing	Glas Helder Glazen	15.00	0.86	0.86	NotApplicable	0.91	2600
Plasterboard	Plasterboard	Gipsplaat	6.75	0.38	0.38	NotApplicable	0.39	800
Plasterboard	Gypsum Wall Board	Gips Wall Board	6.75	0.38	0.38	NotApplicable	0.39	800
IronGeneral	Iron Ductile	Strijkijzer	25.00	1.91	1.91	NotApplicable	2.03	7870
SteelGeneral	Metal Deck	Metalen Dek	20.10	1.37	2.71	0.44	1.46	7800
SteelGeneral	Metal Furring	Metalen Furring	20.10	1.37	2.71	0.44	1.46	7800
SteelGeneral	Metal Stud Layer	Metaal Stud Layer	20.10	1.37	2.71	0.44	1.46	7800
SteelGeneral	Metal Steel 345MPa	Metaal Staal 345MPa	20.10	1.37	2.71	0.44	1.46	7800
SawnHardwood	Wood Flooring	Houten Vloer	10.40	0.86	0.86	NotApplicable	0.59	720
Paint	Parking Stripe	Parkeerstrip	70.00	2.42	2.42	NotApplicable	2.91	1000
Plywood	Wood Sheathing plywood	Hout Schede Multiplex	15.00	1.07	1.07	NotApplicable	1.10	540
PlasticsHighDensityPolyethylene	Polyvinyl Chloride Rigid	Polyvinyl Chloride Stijf	76.70	1.57	1.57	NotApplicable	1.93	950
ExpandedPolystyrene	Insulation / Thermal Barriers Semi-rigid Insulation	Isolatie / Thermische barrieres Halve stijve Isolatie	88.60	2.55	2.55	NotApplicable	3.29	328
ExpandedPolystyrene	Insulation / Thermal Barriers Rigid Insulation	Isolatie / Thermische barrieres Stabile Isolatie	88.60	2.55	2.55	NotApplicable	3.29	328
ExpandedPolystyrene	Rigid Insulation	Rigid Insulation	88.60	2.55	2.55	NotApplicable	3.29	328
Rubber	Roofing EPDM Membrane	Dakbedekking EPDM Membraan	91.00	2.66	2.66	NotApplicable	2.85	1500
SawnSoftwood	Wood Dimensional Lumber	Naaldhouthout	7.40	0.58	0.58	NotApplicable	0.59	510
SawnSoftwood	Wood Flooring	Houten Vloer	7.40	0.58	0.59	NotApplicable	0.59	510
StainlessSteel	Stainless Steel	Roestvrij Staal	56.70	6.15	6.15	NotApplicable	NotApplicable	7850
SteelGeneral	Steel ASTMA992	Staal ASTMA992	20.10	1.37	2.71	0.44	1.46	7800

Figure 18: CSV file for material mapping

ICEDatabase	RevitMaterialBrowser@EN	RevitMaterialBrowser@NL	EE_General	EC_General	EC_Virgin	EC_Recycled	EC_Equivalent	Density
Aluminium	Aluminium	Aluminium	155.00	8.24	11.46	1.69	9.16	2700
Asphalt	Asphalt Shingle	Asfalt Shingle	3.93	0.0678	0.0678	NotApplicab	0.075	1700
GeneralCommonBrick	Masonry Brick	Metselwerk Baksteen	3.00	0.23	0.23	NotApplicab	0.24	1920

4.4.2. CSV to RDF conversion

Lack of structure of the information available on the Web is one of the reasons for which sharing and processing of such information can be problematic. Semantic annotation provides proper structure, in order to conceive the meaning of the content, depict relationships between concepts and be able to incorporate content originating from different sources (Horrocks, 2008). RDF language is an instrument, with which it is possible to designate Web resources, as well as relationships with each other (Klyne & Carroll, 2004).

As shown in the 5-star Linked Open data schema in Figure 11 of the literature review, CSV format acquires 3 stars of Linked Data, with the next level being RDF with 4 stars. Hence, the CSV mapping file created is translated into RDF triples, in order to comply with semantic web principles and become a file able to be queried using SPARQL Query Language. In order to design Linked Data, the four principles explained in **¡Error! No se encuentra el origen de la referencia.** are used. These principles are: a) use URIs for naming of resources, b) use HTTP URIs, c) use RDF, SPARQL standards, d) add links to other URIs.

The conversion of CSV to RDF is achieved with the development of a Python script, using the RDFLib and CSV libraries. It is worth mentioning that there are also tools available for the conversion of tabular data to RDF, such as Google Refine, Tarql, XLWrap etc. (W3C). However, the Python code offers flexibility and thus was chosen for the particular development. The script is given in Appendix IV, where the Python script for the whole tool is given. The function of the script includes going through the CSV document, and creating RDF triples with the material instances and their properties. An example set of triples from the resulting RDF graph, representing an individual of the ICEMaterial class is shown in Listing 2. Partial RDF dataset from the ECOM Ontology can be found in Appendix III.

```
ecom:Mat01 a ecom:ICEMaterial ;
    rdfs:label "Aluminium"@en,
        "Aluminium"@nl ;
    ecom:density "2700.0"^^xsd:float ;
    ecom:hasECEquivalent "9.16"^^xsd:float ;
    ecom:hasECGeneral "8.24"^^xsd:float ;
    ecom:hasECRecycled "1.69"^^xsd:float ;
    ecom:hasECVirgin "11.46"^^xsd:float ;
    ecom:hasEEGeneral "155.0"^^xsd:float .
```
Listing 2: Example RDF triple from material mapping graph

The RDF data structure enables more efficient interaction amongst the actual data, data updates as well as correlation of the data to external data sources. According to Ingwersen et al. (2015) adopting the RDF approach for LCA data representation, has several benefits over traditional data structures (e.g. lists, spreadsheets etc.). This is supported by the ability offered by ontology models and their computer-readability to integrate references and links from ontologies of different domains, share external data sources and facilitate integration with other tools (Ingwersen et al., 2015).

4.5. Integration with BIM

An essential aspect of the development of an embodied energy and carbon calculator is integration with the design software, which is a missing feature of the already available tools (Circular Ecology). Such integration is one of the objectives of this research, with attention to use of non-proprietary standards, as one of the rules for semantic web implementation. The IFC standard, the only BIM ISO standard is an exchange data model, in which buildings are defined with regard to their semantically represented building components (Bozic, Mendel-Gleason, Debruyne, & O'Sullivan, 2016).

To enable integration of building material environmental impacts and BIM, the IFC data model is used as the basis, due to its semantic structure and independence of vendor-specific design software. This section explains the steps followed in order to retrieve required information from the IFC Schema, the volumes of the elements in this case, as well as the conversion of the retrieved information to RDF.

4.5.1. Retrieval of required information from the IFC model

The integration of the environmental impact data and the design can occur under the condition of acquirement of particular information existing in the design model. More specifically, this information includes building element quantities, material constituents and measurement units. Having this information at our disposal, matching it with environmental impact coefficients becomes feasible, enabling the estimation of embodied energy and carbon.

The IFC model is a semantically rich file, containing all the information of the entities included in a design and their properties. In order to be able to calculate the environmental impact of the building materials selected by the designer, it is essential to know the quantities in which they appear in a building project. Volumes of the building elements can be retrieved from the IFC model, in cases when such volumes have been defined in the native software. For this development, the volume of the building elements is the quantity to be extracted and converted to weight using material densities. This due to the fact that the ICE database provides EE and EC values in kg units, therefore using volumes and densities is the most convenient way. Nevertheless, attention needs to be given to the units used in the 3D model. The database uses System International (SI) units; thus the volume quantities need to be in m^3.

Quantities are built-in the IFC file as mentioned in section 2.2.3 within the *IfcElementQuantity* or the *IfcProperty*. A python script is written, using IfcOpenShell library, in order to extract the element quantities from the BIM model. IfcOpenShell open source software library was initiated and is mainly led by Thomas Krijnen, with the aim to enable users work with the IFC file format, to retrieve and handle geometry within the IFC files (Krijnen).

Since the database contains EE and EC coefficients of materials and not whole building components, the volume quantities of the building elements (i.e. beam, slab, wall etc.) need to be translated into material volumes, based on the fraction of volume, that each material occupy within a particular element. However, the IFC schema does not provide directly material quantities or such fraction attributes, therefore certain calculations are required to get these amounts. Thus, the components are "fragmented" into their composite materials depending on the type of building element. The following cases are considered in order to attain the aforementioned volumes:

<u>Layered building element</u>

If the building component is a layered one, layer thicknesses is used to determine the percentages of each of the composite materials. The material amount within a specific building element in this case is calculated via the following equation:

$$Fraction\ Of\ Material\ in\ the\ Element = \left(\frac{Layer\ Thickness}{Total\ Thickness}\right)$$

$$Material\ Volume = Fraction\ Of\ Material\ in\ the\ Element\ \times\ Element\ Volume$$

The estimation of the material quantities in a particular layered building component was executed, with the assumption of linear building components. In case of curved elements, there would be a certain deviation in these quantities. In order to quantify this deviation, an example building wall element with two layers was chosen, and the quantities of the two constituent materials were calculated for a number of different curvatures (possible angles). The common point between the two scenarios (i.e. linear and curved), as shown in Figure 20 was assumed to be the wall length, which resulted in equal total element volumes. However, the volumes of each material within the element presented slight differences. As can be seen in Figure 20, the percentage of Material 2 within the element changes from 14.12% to 13.51% in the total element volume, which is translated into a 4.3% decrease in the volume of this material in a curved element, compared to the volume of this material in the linear element.

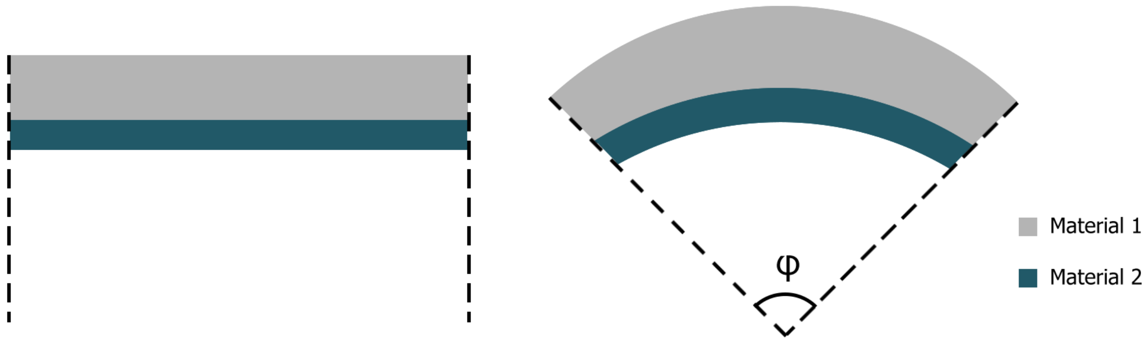

Figure 19: Section of inear wall element (left), curved wall element (right)

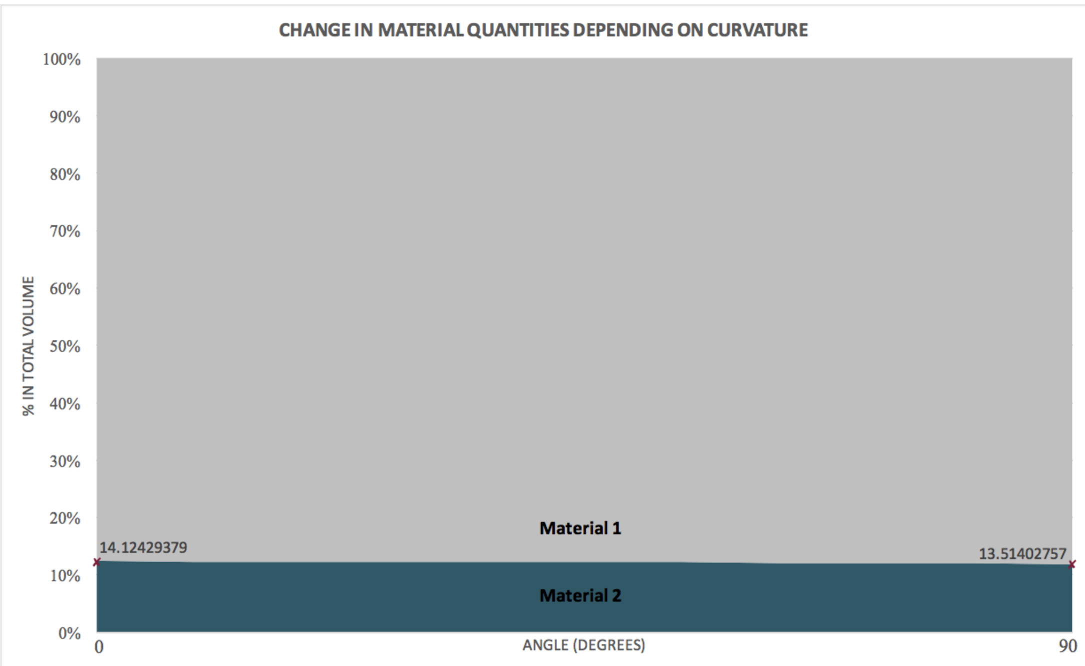

Figure 20: Change in material quantities depending on curvature

Single material element

If the building component is a single material element, then the material volume is equal to the element volume:

$$Fraction\ Of\ Material\ in\ the\ Element = 1$$
$$Material\ Volume = Fraction\ Of\ Material\ in\ the\ Element\ \times\ Element\ Volume$$

Element associated with *IfcMaterialList*

It is possible in the IFC model, an element to be associated to a material list, which is a list of materials that make up the building element. In this case, an estimation of the material quantities was done, by assuming equal volume of all materials within the element:

$$Fraction\ Of\ Material\ in\ the\ Element = Number\ of\ materials$$

$$Material\ Volume = \left(\frac{Element\ Volume}{Fraction\ Of\ Material\ in\ the\ Element}\right)$$

Apart from the material quantities, attributes such as material density is also needed, in order to translate the volume into weight and match the units of the EE and EC coefficients. In the IFC data model, density is represented as an attribute (i.e.MassDensity) of the entity *IfcGeneralMaterialProperties*. However, after inspection of several IFC models, it was seen that the particular attribute was not used, therefore the density of the materials will be incorporated in the environmental impact RDF dataset, as explained in section 4.4.1.

4.5.2. Conversion of IFC to RDF

In order to comply with the linked data concepts, the IFC model needs to be converted to a format that conforms with the semantic web principles and supports ontology-based structure. As mentioned in 2.3.5, for the conversion of the IFC, the ifcOWL ontology has been established. The conversion can be done online with an open web-based IFC-SPF convertor tool; after a simple upload of the IFC file, an RDF graph is generated on the server, available for download (Open BIM Standards).

For the development of the present tool, the available convertor was not used, but rather a Python script was elaborated, which was incorporated into the script described above for the quantities extraction. In detail, the results of the previous script were added into an RDF graph. The generated RDF graph was based on the IFCMAT ontology and consists of instances of building elements, their connection to the constituent materials, as well as the attached data properties and their values, needed to calculate the material quantities. The triples of an instance building element, from the Duplex model are shown in Listing 3 and the triples of an instance material in Listing 4. The element URI is defined from the Global ID of the element, as extracted from the respective attribute of the IFC model.

```
<http://www.semanticweb.org/marianiki/ifcmat#0dxE1Sy6nDqfpDb5vIMN_Z> a
ifcmat:IfcBuildingElement ;
    ifcmat:elementVolume "1.6408704"^^xsd:float ;
    ifcmat:hasGUID "0dxE1Sy6nDqfpDb5vIMN_Z"^^xsd:string ;
    ifcmat:isAssociatedTo ifcmat:Mat01_0dxE1Sy6nDqfpDb5vIMN_Z,
        ifcmat:Mat02_0dxE1Sy6nDqfpDb5vIMN_Z .
```

Listing 3: Example element instance in RDF triples

```
<http://www.semanticweb.org/marianiki/ifcmat#Mat06_202Fr$t4X7Zf8NOew3FNtn> a ifcmat:IfcMaterial
;
    rdfs:label "Plasterboard"^^xsd:string ;
    ifcmat:fractionOfVolume "0.0383693045564"^^xsd:float .
```

Listing 4: Example material instance in RDF triples

Since only very specific information is needed from the IFC model, conversion of whole file using the ifcOWL convertor is not necessary. On the contrary, it would create a much heavier file (24 x bigger for one of the tested use cases), with the rest of the information coming from the IFC being unused. With the Python script only the elements, their constituent materials and the fractions of these materials within the element volume are added to the RDF graph, creating a query-able file with only the required entities and attributes. This is considered as the most efficient way for converting the IFC to RDF in the particular case. Furthermore, in the scenario of the conversion of the whole file, the calculations for the materials volumes would have to be done through SPARQL queries, which is feasible but would complicate the process, considering how customized the IFC model can be.

4.6. Tool interface

The following section describes the function and interface of the tool, based on the built-in processes and methodologies described. This interface was developed, based on the previous thesis work of van de Riet (2016) and van de Ven (2017). It consists of two different tabs; Tab A for converting the CSV dataset into RDF and Tab B for visualization of the model and the calculations of the different embodied impacts of building elements and materials. The Python script developed for the tool interface is given in Appendix IV.

4.6.1. Tab A

The functionality of the RDF parser tab is built so the user can upload a CSV dataset with environmental impact information of building materials and convert it to an RDF graph. This way, the dataset's structure allows manipulation with the use of queries and linking with other datasets. Figure 21 illustrates the tab interface, and the incorporated features (i.e. Open CSV file, Write to RDF).

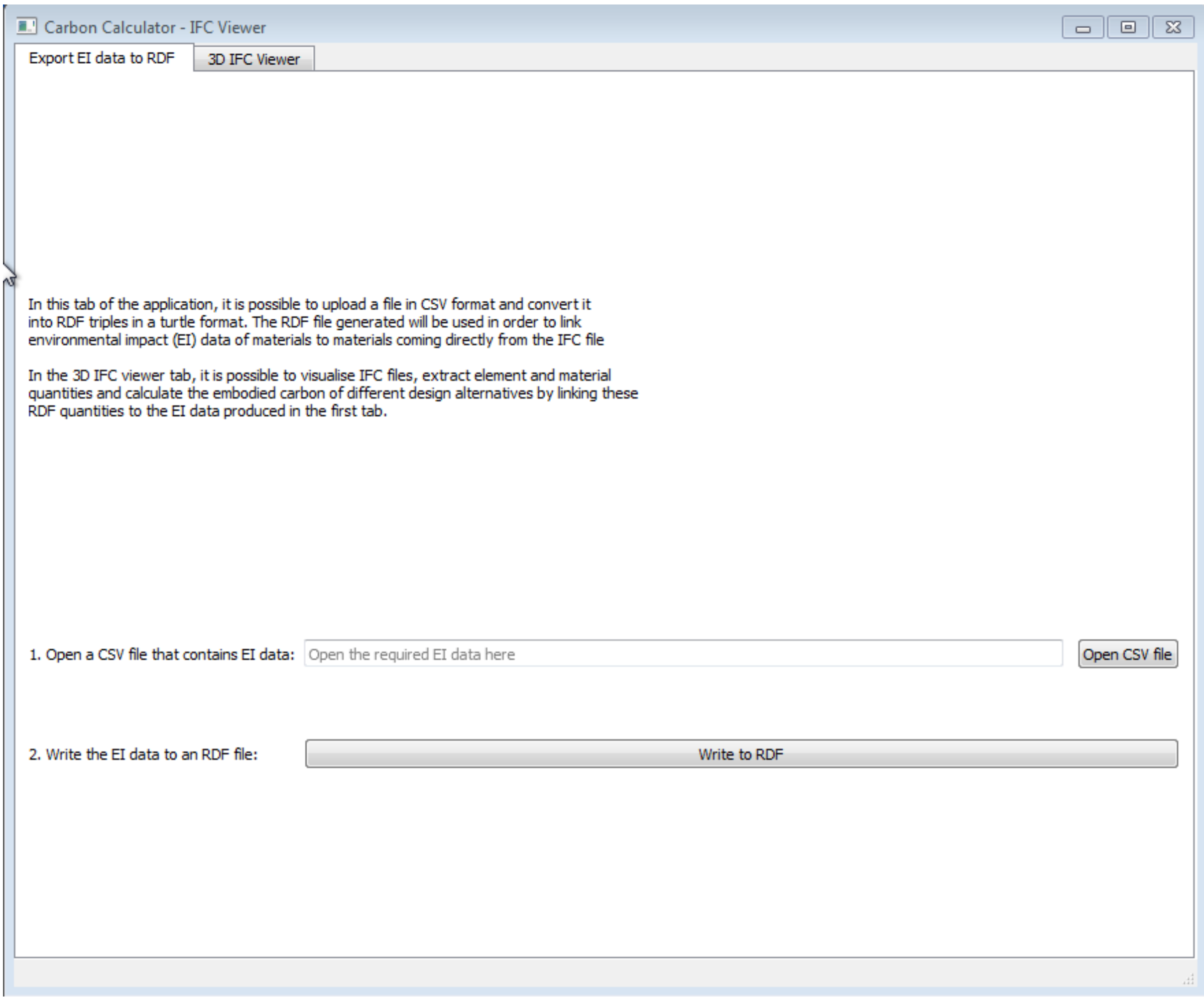

Figure 21: RDF Parser

4.6.2. Tab B

In the IFC viewer tab, the user is able to load and visualize their model. As explained in section 4.5.2, the Python script retrieves the relevant model information to conduct the assessment and converts this information into an RDF dataset. After both tabs have created the associated RDF graphs, the user is able to view, in the property boxes attached next to the 3D model, various results in relation to the embodied impacts of materials. More specifically, it is possible to check the results of the EE, EC and EC equivalent of the whole design project; the EC equivalent sorted per building material or per building element; and the EC for possible recycled materials. Furthermore, the user is able to have a visualization of the critical and non-critical components of their design, colored red and green respectively, facilitating the allocation of these components in the design. Finally, an export feature enables the user to save the embodied impact information of his/her design into a CSV file; the CSV filename contains by default the date and time of saving, in order to allow the user to structure the versions of the design alternatives. Figure 22 shows the results retrieved after loading of the Duplex IFC building model. The results are generated by executing SPARQL queries against the two RDF graphs for the matching elements. The content of these queries are given in the following section, 4.6.3.

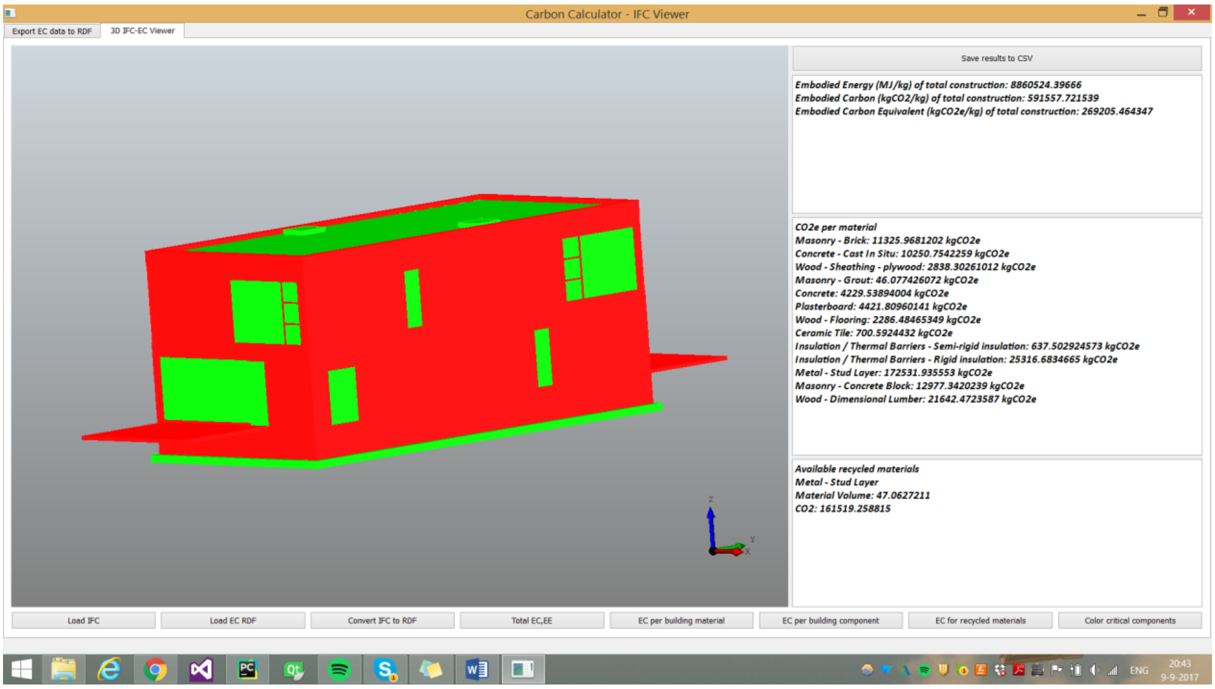

Figure 22: 3D IFC viewer

4.6.3. SPARQL Queries

The developed tool uses the RDF graphs created from the material mapping and the IFC model to retrieve information and calculate the embodied impacts of materials using SPARQL queries. More specifically, the IFC materials are mapped to the materials from the database, their volume is converted into weight using the density values of the database and finally the weights are converted into environmental impacts according to respective coefficients. A rough visualization of this process is given in Figure 23, while a detailed visualization graph of the SPARQL query is presented in Appendix VII.

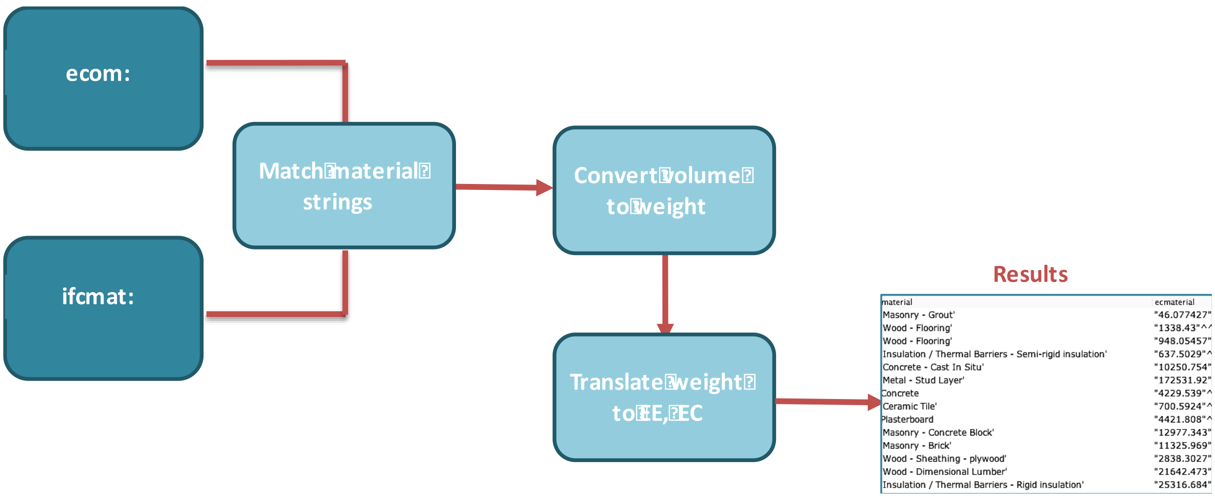

Figure 23: Visualization of the tool's SPARQL query

Two example queries of the ones incorporated into the tool are given in Listing 5 and Listing 6. As it is seen, the connecting link between the two RDF datasets is the labels of the materials, as generated from the environmental impact dataset and the IFC model.

```
SELECT (SUM(?ee) AS ?totalee) (SUM(?ec) AS ?totalec) (SUM(?equiv) AS ?totalequiv)WHERE {
        ?material a ecom:ICEMaterial .
        ?material rdfs:label ?label .
        ?material ecom:density ?density .
        ?material ecom:hasEEGeneral ?eegeneral .
        ?material ecom:hasECGeneral ?ecgeneral .
        ?material ecom:hasECEquivalent ?ecequivalent .
        ?element a ifcmat:IfcBuildingElement .
        ?element ifcmat:elementVolume ?elemvol .
        ?element ifcmat:isAssociatedTo ?mat .
        ?mat a ifcmat:IfcMaterial .
        ?mat ifcmat:fractionOfVolume ?fraction .
        ?mat rdfs:label ?label1      .
        BIND ( str (?label) as ?label2 ) .
        BIND ( str (?label1) as ?label3 ) .
        FILTER ( ?label2 = ?label3 ) .
        BIND ((?fraction * ?elemvol ) AS ?matvol) .
        BIND ((?density * ?matvol ) AS ?weight) .
        BIND ((?weight * ?eegeneral ) AS ?ee) .
        BIND ((?weight * ?ecgeneral ) AS ?ec) .
        BIND ((?weight * ?ecequivalent ) AS ?equiv) .
}
```

Listing 5: EE, EC, ECEquivalent of total project

```
SELECT ?label3 (SUM(?ec) AS ?ecmaterial) WHERE {
        ?material a ecom:ICEMaterial .
        ?material rdfs:label ?label .
        ?material ecom:density ?density .
        ?material ecom:hasECEquivalent ?ecgeneral .
        ?element a ifcmat:IfcBuildingElement .
        ?element ifcmat:isAssociatedTo ?mat .
        ?element ifcmat:elementVolume ?elvol .
        ?mat a ifcmat:IfcMaterial .
        ?mat ifcmat:fractionOfVolume ?fraction .
        ?mat rdfs:label ?label1      .
        bind ( str (?label) as ?label2 ) .
        bind ( str (?label1) as ?label3 ) .
        filter ( ?label2 = ?label3 ) .
        BIND ((?fraction *?elvol ) AS ?volume) .
        BIND ((?density * ?volume ) AS ?weight) .
        BIND ((?weight * ?ecgeneral ) AS ?ec) .
}
        GROUP BY (?label3)
```

Listing 6: EC per material

Apart from the queries with which the designer can attain the values of the environmental impact of the design, the transformation of the CSV dataset into RDF, containing environmental impact coefficients, can be used as a stand-alone tool. The applicability of the tool lies on the fact that without the use of special software, somebody can use the dataset, via query computation, in order to retrieve all sorts of information regarding embodied impacts of building materials in the existing dataset. Figure 24 is an example of a query, which retrieves the maximum value of embodied carbon existent in the database; with the results given below the query.

```
SELECT ?label ?maxec
WHERE  { ?material a ecom:ICEMaterial .
      ?material rdfs:label ?label .
FILTER langMatches( lang(?label), "EN" ) .
              ?material ecom:hasECGeneral ?maxec .
}
ORDER BY DESC (?maxec)
LIMIT 1
⍰
```

label	maxec
"Metal - Aluminum Polished"@en	"8.24"^^<http://www.w3.org/2001/XMLSchema#float>

Figure 24: Query for retrieving the maximum EC coefficient value and results of the query

Figure 25 is a different query example, with which the amount of existing materials in the dataset is calculated. The result generated is also given below.

```
SELECT ( COUNT (?matnumber) as ?MaterialNumber )
WHERE { ?mat a ecom:ICEMaterial .
?mat rdfs:label ?label
BIND (  str(?label) as ?matnumber )
}
⍰
```

MaterialNumber
"184"^^<http://www.w3.org/2001/XMLSchema#integer>

Figure 25: Query for retrieving the amount of materials present in the dataset

The above examples give an indication of the potential there is, when publishing a dataset in Linked Data. Extending the particular dataset, creating material categorization, or adding extra properties, could increase significantly the possibilities of data search and manipulation, to serve different purposes and uses in terms of the environmental impacts of building products.

4.6.4. Conclusion of tool

The tool built, within the framework of the present research, is a functioning and accessible tool, aiming to provide awareness during the design stages, in regards to the environmental impacts of the building materials selected in a design. It does so, by linking an environmental impact database with the BIM model, via the use of semantic web formats and specifically the RDF structure, which is a machine-readable format.

Compared to existing carbon calculator tools, this development considers the design project as a total, rather than focusing on a special group of materials. The added value results also from the fact that it is integrated with the BIM model. Through the use of IFC, the material quantities and labels are extracted and used to calculate the EE and EC of the materials. Furthermore, it constitutes a more sustainable tool due to Semantic Web implementation, which nowadays is gaining more utility and value. Interoperability issues can also be overcome, since no external software is needed, in order to open and reason upon the datasets. Additional benefits of using such technology is that the IFC model can be semantically enriched with environmental impact information, without being subject to direct property attachment, which could possibly pollute the IFC model and increase its size.

4.7. Tool validation

Following the development of the tool, a validation process is needed, in order to check whether it is a functioning application. The validation is divided into two different aspects, Practical validation and Theoretical validation. In what concerns the former, the tool is validated in terms of the technical parts, i.e. generated RDF graphs, applicability of script in different IFC building models and testing of the results generated by the SPARQL queries. Regarding the latter, the results produced by the tool are compared to the ones of an actual study of the environmental impact of building project, so that to examine whether these results belong to a realistic and logical framework.

4.7.1. Practical validation

4.7.1.1. RDF syntax validation

The RDF graphs generated by the two tabs of the tool are initially checked syntactically-wise using the online W3C RDF Validation Service. Both graphs, the RDF dataset with the material mapping and the RDF dataset with the IFC material volumes are parsed successfully in the online validation server with no error results.

4.7.1.2. Applicability in different IFC models

Validation of the tool, in respect to its applicability using different IFC models, will be conducted for the part of the tool that is connected to the script written for retrieving the necessary information from the design model. This, due to the fact that the part of the environmental impact data is restricted to material tags, which as mentioned, usually differ from a software to another or even between different versions of the same software. Discussion over the possibilities of extension of this tool's aspect is realized in section 5.3.

The Python script for the RDF graph creation of the building elements, their constituent materials and their respective volumes is validated in the following models, all of which were downloaded from the Open IFC Model Repository (University of Auckland):

1. Duplex
2. 20160124OTC-Conference Center
3. 20160125Trapelo - Existing-Trapelo_Design_Intent
4. Clinic_A_20110906_optimized

The RDF file is generated successfully in all of the examined models. The partial RDF datasets generated by the four models are given in Appendix V. Thorough review of the data did not show any problematic output. It should be mentioned that all of the above models contained element volumes of the building elements. In cases where volumes are not present in the IFC schema, the script would not work. In those rare cases, Open CASCADE Technology can be used, which supports most commonly used geometric objects in 3D modeling applications (e.g. points, lines, curves, surfaces etc.) (OpenCascade), and therefore quantities can be generated from the geometry of the elements. OpenCascade is used in IfcOpenshell software library, in order to transform implicit geometry into explicit that can be interpreted by any CAD program or modelling package (IfcOpenshell).

Regarding the models examined, the key attributes of the tool, which enable functionality in different models are the following:

- Allocation of volume values in the IFC schema
- Consideration of units of measurement
- Material representation types

4.7.1.3. Correctness of results from SPARQL queries

The SPARQL queries used to calculate the different embodied energy and carbon values need to be tested to validate the correctness of the calculations. In order to do that, the calculations performed by an example query are done also manually and the results can be compared in Figure 26 and Table 4 . The query in question is given below:

```
SELECT (SUM(?totalec) AS ?materialec)
WHERE {
ifcmat:1hOSvn6df7F8_7GcBWIRqU a ifcmat:IfcBuildingElement .
ifcmat:1hOSvn6df7F8_7GcBWIRqU ifcmat:elementVolume ?volume .
ifcmat:1hOSvn6df7F8_7GcBWIRqU ifcmat:isAssociatedTo ?mat .
?mat a ifcmat:IfcMaterial .
?mat rdfs:label ?label .
BIND  ( str(?label) AS ?label2 ) .
?mat ifcmat:fractionOfVolume ?fraction .
       ?material a ecom:ICEMaterial .
       ?material rdfs:label ?label1 .
BIND  ( str(?label1) AS ?label3 ) .
?material ecom:density ?density .
?material ecom:hasECVirgin ?ec .
FILTER (?label2 = ?label3) .
BIND ((?fraction *?volume) AS ?matVolume) .
BIND  ((?density * ?matVolume) AS ?weight) .
BIND  ((?weight *?ec ) AS ?totalec) .
}
```

Listing 7: Query used for validation

This query involved the calculation of the embodied carbon of an element instance (*ifcmat:1hOSvn6df7F8_7GcBWlRqU*), when virgin materials are used (*ecom:hasECVirgin*). The specific element consists of two materials, as shown in Table 4, together with the manual calculations, i.e. the embodied carbon conversion.

```
SPARQL query:

SELECT      (SUM(?totalec) AS ?materialec)
WHERE       {
ifcmat:1hOSvn6df7F8_7GcBWIRqU a ifcmat:IfcBuildingElement .
ifcmat:1hOSvn6df7F8_7GcBWIRqU ifcmat:elementVolume ?volume .
ifcmat:1hOSvn6df7F8_7GcBWIRqU ifcmat:isAssociatedTo ?mat .
?mat a ifcmat:IfcMaterial .
?mat rdfs:label ?label .
BIND        ( str(?label) AS ?label2 ) .
?mat ifcmat:fractionOfVolume ?fraction .
            ?material a ecom:ICEMaterial .
            ?material rdfs:label ?label1 .
BIND        ( str(?label1) AS ?label3 ) .
?material ecom:density ?density .
?material ecom:hasECVirgin ?ec .
FILTER      (?label2 = ?label3) .
BIND ((?fraction *?volume) AS ?matVolume) .
BIND        ((?density * ?matVolume) AS ?weight) .
BIND        ((?weight *?ec ) AS ?totalec) .
}

materialec
"5660.9316"^^<http://www.w3.org/2001/XMLSchema#float>
```

Figure 26: SPARQL query and results after running on Protégé program

Table 4: Manual calculation of embodied carbon of an instance element from Duplex model

ifcmat:1hOSvn6df7F8_7GcBWIRqU				
Mat01	Volume (m^3)	1.12535	Weight	607.689
	Density (kg/m^3)	540		
	EC Virgin ($kgCO_2/kg$)	1.07	EC Virgin ($kgCO_2$)	**650.227**
Mat02	Volume (m^3)	16.9395	Weight	8639.145
	Density (kg/m^3)	510		
	EC Virgin ($kgCO_2/kg$)	0.58	EC Virgin ($kgCO_2$)	**5010.7041**
Total	**EC Virgin ($kgCO_2$)**	**5660.93**		

The result generated by running the query is the same as the one from the manual calculation. Hence, validation of the query results is considered successful.

4.7.2. Theoretical validation

The tool is further tested in terms of the actual results it generates. Therefore, it is tested whether the results of environmental impact values (i.e. embodied energy and carbon) are realistic.

The validation is based on De Wolf's et al. (2016) paper, which conducts an analysis for the embodied environmental impact of building structures, using data from 200 buildings (De Wolf et al., 2016). The system boundary followed by this paper is cradle-to-gate, therefore matching exactly the system boundary implemented by the ICE database, which is used for the tool development. The analysis realized in this paper takes into account only the structural materials of the construction, i.e. structural steel, rebar, concrete. Thus, in order to be able to compare the results of this paper with the results from the tool, only the structural materials are taken into account. Furthermore, the paper accounts specifically for the embodied carbon equivalent, also known as Global Warming Potential (GWP), hence the particular coefficients are chosen from the database, in order to generate the results and enable the comparison.

Table 5 is the summary of the calculation of GWP of the Duplex model. The materials included in the validation are *Concrete – Cast In Situ*; *Metal – Stud Layer*; *Concrete*. This results in 187012,194 kgCO_2e per kg of construction or ***381,66*** kgCO_2e per m^2 of construction. According to De Wolf et al. (2016) the examined buildings belonged to a range of **150-600 kgCO_2e/m^2**. Consequently, the result for Duplex model (i.e. 381,66 kgCO_2e/m^2) stands within the range. The detailed results of the CO_2e of the materials existent in Duplex model are given in Appendix VI.

Table 5 : Calculation of GWP of Duplex model

Materials	GWP: kgCO_2e/kg
Wood - Dimensional Lumber	21642,473
Masonry - Grout	46,077427
Insulation / Thermal Barriers - Rigid insulation	25316,684
Wood - Flooring	1338,43
Concrete - Cast In Situ	**10250,755**
Wood - Flooring	948,0546
Metal - Stud Layer	**172531,9**
Concrete	**4229,539**
Ceramic Tile	700,5924
Plasterboard	4421,8086
Wood - Sheathing - plywood	2838,3027
Masonry - Concrete Block	12977,342
Masonry - Brick	11325,969
Insulation / Thermal Barriers - Semi-rigid insulation	637,503
Whole construction	269205,4307
Main structure	187012,194
GWP: kgCO2e/m2 of main structure	**381,66**

Additionally, to the general range, Wolf's et al. (2016) study gives an overview of the results generated by the different building types that were analysed. As shown in Figure 27, residential buildings have a median of approximately 300 kgCO_2e/m^2, placing the result of Duplex residency examined for this validation very close to the median.

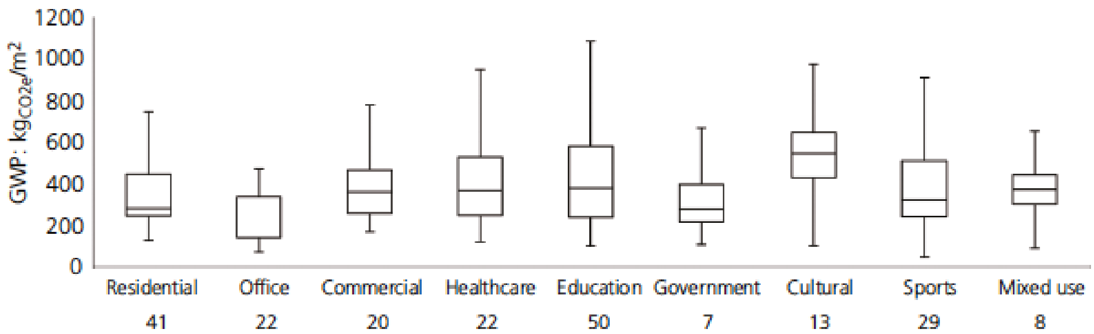

Figure 27: GWP for 200 real projects (De Wolf et al., 2016)

4.8. Tool limitations

The tool developed for this graduation project, aims to function as a decision-support tool, in the hands of the end user, in order to inform him/her over the embodied impacts of the selected building materials, targeting the design phase of a construction project. The development of the tool was built upon Semantic web formats, which included RDF graphs from embodied impact data and from IFC material quantities. These graphs were then queried in order to calculate the environmental impact of the materials existing in the design.

The functions of the tool were incorporated in a user interface. With the aid of such interface, the end user is able to convert environmental impact data from CSV to RDF, as well as view in a 3D virtual environment the embodied impacts of his/her choice of building materials. The user-friendly interface offers a detailed insight into all the different embodied impact aspects, providing the user with a variety of possibilities for assessment (e.g. embodied impact of recycled materials, GWP, critical building components etc.). Despite these features and benefits, limitations regarding the nature and the function of the tool need to be considered.

First of all, limitations of the environmental impact information used for the tool development are considered. The ICE database contains value coefficients for EE and EC limited to the boundary *cradle-to-gate*. Therefore, the tool cannot be used outside this boundary, as for example for a whole LCA. This is an important point to take into account, since there exist materials with high levels of embodied impact but which have for instance very long life-time or low operational impacts. An additional aspect, not considered in the ICE database is the local context, specifically the landscape; there are for instance, particular landscapes, able to store significant amounts of carbon, which are released when the landscape is subject to disturbance (Build Carbon Neutral, 2007).

Second, limitations regarding the IFC aspect of the tool are discussed. In what concerns the material selection, the software chosen as the basis was Revit and its basic material library. This implies that the use of a different design software will require certain manual input to the material mapping CSV file, in order for the tool to function. This due to the fact that, the matching of the materials from the IFC model and the material mapping are based on material labels, which vary significantly in the different software programs. Regarding the IFC version used for the Python script, even though 2X3 was used, it is expected to run without problems in the more recent version of IFCX4, taking into account that the fields used remain the same. Additionally, heavy IFC models can reduce the performance of the tool.

Finally, with respect to the Semantic web, it could be argued that for making use of the created dataset, somebody should be aware of a query language, its syntax, as well as the ontology in question. Nevertheless, this limitation does not apply, when considering strictly the use of the tool through the user interface.

5. Conclusion

In this research study, an ontology-based approach is explored, seeking to provide a tool with which designers´ awareness can be enhanced during the design phase, regarding the embodied impacts of the materials selected for a construction project. The objective of the thesis is driven by the motive of first taking into account the aspect of sustainability within future construction, and ultimately working towards increase in sustainability.

The implementation of the proposed research is conducted with the use of Semantic Web principles, namely ontology development, RDF applications and use of SPARQL queries, within the AEC industry. In this context, a tool has been developed supporting BIM integration, which links building elements and materials existing in a design with an embodied impact dataset, aiming at influencing the user's decision-making into selecting more environmentally-friendly materials.

The domains investigated in this research include architectural design and sustainability. Applying this domain knowledge, two ontologies are created, based on which RDF graphs are generated with information from these two areas of expertise. These graphs, due to being machine-readable, enable computer as well as human processing and consequent deduction of relevant information or results.

5.1. Scientific relevance

The following section portrays the scientific relevance, by reflecting on the research questions. The main research question is answered, after discussion of the sub-questions.

What is the added value of publishing an environmental impact dataset as Linked Data?

Environmental impact information is traditionally maintained in formats (i.e. databases, spreadsheets, lists, tables) that do not facilitate data exchange or in data exchange formats (i.e. XML) that can impede interoperability between the different sources. Such interoperability issues can be handled through the implementation of Semantic Web technologies. The ICE database used for the tool development, even though available on the Web, is in Excel format. This by itself, requires the possession of a vendor-dependent software, in order to be able to open and use the content of the database. For the development implemented in this research, partial content of the database is transformed into RDF triples, a structure that complies with Linked Data. Publication of the database as a Linked dataset, eliminates the need for special software and enables direct data accessibility and manipulation, while supporting open standards and non-proprietary tools.

Additionally, to data interoperability, translation and publication of environmental impact data into RDF format suggests that relationships between entities or features of entities do not occur in a one-to-one base, as in the case of tabular data, but instead one-to-many links are possible. For instance, in the RDF graph with the material mapping, material instances have a set of properties attached to them, with their corresponding values, however each instance appears only once, identified by its own URI. Due to the dataset being available on the web and open for editing, data extension becomes well feasible. This for example facilitates the addition of more material instances; the update of certain property values when more recent studies and experiments suggest so; or the incorporation of extra parameters which would be of interest for an EIA study (e.g. expected lifetime of material).

Furthermore, entities within a graph can be linked to ones of cross-domain datasets, to enable a more spherical representation. As an illustration, apart from the environmental impact of the materials, monetary impacts could be considered. The environmental impact dataset can be connected to a product manufacturer dataset. In that case a material instance is characterized by the environmental impact coefficients, while by being linked to another dataset, it is further characterized by its manufacturing cost. For such connection to work, it is implied that the manufacturer makes use of RDF datasets for his/her product bases. This possibility increases the dataset's reusability potential across different disciplines. Another application would be that the material instances together with their environmental impact coefficients, to have a property which would link to sustainability certificate credits (e.g. BREEAM, LEED); in this case when an EE or EC coefficient changes significantly, the certificate points would automatically correspond to different values.

Moreover, linked data offers the possibility to attach language tags to entity labels. In the case of the environmental impact dataset, this multilingual feature is useful, since it enables the capture of material entities in different contexts. Especially, when considering the fact that the IFC materials are represented mainly by a string attribute (i.e. Name), expressing these labels in multiple languages can have two beneficial implications. First, it enables the use of the dataset across a country's borders; and second it allows for the recognition of an entity being represented by different labels, instead of misconceiving that the different strings symbolize different entities. The linked dataset developed for this thesis' implementation expresses the material entities in two languages, English and Dutch, due to these two being more commonly used in the Netherlands, however more language tags would further support reusability of the dataset. Finally, the particular aspect would resolve to a certain extent the lack of material standardization around the globe. The increased material customization does not facilitate classification processes in order to place materials under pre-determined categories, therefore, multilingual tags of materials could reduce this problem's impacts.

Finally, the computer-readability attribute of the RDF structure accommodates the optimization of data searches. Using SPARQL queries, it is possible to retrieve specific information from a graph, without having to go through the whole dataset. In the environmental impact dataset for example, a user is able to compute a query for extracting the embodied impacts of a particular material or a group of materials; for getting the highest or lowest values of EC; for getting material densities and more. These information retrievals can be achieved just by constructing single queries, improving research efficiency.

How can BIM contribute to the environmental impact assessment of a building project during the design phase?

For the development of this research, the focus lies on the choice of materials, within the building components, based on their embodied impacts (i.e. EE,EC). Based on the objectives and framework of the developed tool, the use of BIM assists in the quantification of the materials in the design, and thus, use of these quantities to execute the calculation of the impacts.

More specifically, in order to assess the embodied impacts of the building materials selected in a design, the information required is the element geometry, meaning the materials that constitute these elements. The reason why geometry is needed, is mainly for retrieving the quantities in which the materials appear in the design, and thus in the future construction project. The BIM standard, the IFC data model offers this possibility, through element geometric representation and often through element quantity attributes, which give values of quantities such as the volume. In cases of layered building elements or elements using plain material lists, where material quantities are not directly available in the IFC model, an estimation of the constituent material volumes is done. This estimation is based on the fractions of materials based on layer thicknesses for the first case, and assuming equally distributed quantities of materials in the second case.

Apart from the geometric information that allows material quantification, BIM, based on object-oriented design, is able to provide different kinds of information of the design objects, about their whole lifecycle (e.g. environmental surroundings, materials, ventilation systems etc.). It functions as a database of a multi-disciplinary content, associated to the semantics of the building, which can be retrieved to conduct analysis of the energy and building performance, already in the design phase. Realization of such analysis during the design phase enables more flexible decision-making for optimization, as it takes place early in the process.

Finally, BIM allows for more efficient use of resources. Since the whole digital structure is available and the detailed construction process can be planned prior to the start, surplus of cut materials can be predicted and either avoided or handled accordingly at the construction site, in order to be recycled or reused.

How can BIM models be linked to external datasets adopting Semantic Web principles?

The present thesis explores the possibilities to integrate BIM and environmental impact data. Adoption of Semantic web technologies for accomplishing this link is chosen, after critical examination of this principle's potential.

The representation of Semantic web in the tool development occurs through the generation of RDF graphs and use of SPARQL queries to estimate the environmental impact of building materials. Specifically, two RDF graphs are generated, based on the development of the corresponding ontologies for each one. The first of these graphs contains materials and their embodied impact coefficients, and is generated from the environmental impact database. The second one, includes the relevant model information (i.e. building elements, their constituent materials and their quantities), and is retrieved from the BIM model. SPARQL queries are then computed against these two graphs, in order to match materials existing in both and calculate their environmental impact.

Even though validation of the tool proved to be successful and the tool can be considered working and functional, linking of entities in this case is achieved through matching of string labels. This connection does not constitute a sustainable solution for linking concepts, bearing in mind the absolute lack of standardization that outlines a string. In a different scenario, for instance, where materials are designer-specific, mapping of the RDF entities would not be possible, since the string names of materials would not match. The key to achieve Linked Open Data would be linking of different datasets based on entity URIs. An establishment of URIs for material identification would create a more solid mapping of common concepts. Discussion on this aspect is done in section 5.3.

Having answered the sub-questions, the answer to the main research question is discussed:

How can 3D Building Information Models and Semantic Web technologies be used to assess the selected building materials during the design phase, seeking to reduce environmental impact?

Evaluation of the selection of building materials is done throughout this thesis, in terms of the impact of the materials on the environment. The ultimate purpose of this assessment is to encourage sustainability in construction and reduce the environmental impact of construction projects, with the framework in the particular study being the construction materials. The hypothesis is that this reduction will be accomplished through influencing the decision-making of the responsible stakeholder during the design phase of a building project, where the choice of materials takes place. The methodology adopted to exercise this influence is the creation of a functional and easy to use tool. With the aid of this tool, which functions as a carbon calculator, the potential user can anticipate the embodied impacts of the materials he/she has chosen in the design. By enabling the visualization of the environmental impacts of the materials and having the possibility to identify which the most critical components are, it is more likely that he/she will attempt to modify materials through design alternatives for decreasing these impacts.

For the development of this tool, the adopted approach includes integration of BIM and environmental impact data through Semantic Web application. The environmental impact data from a freely available database is converted from tabular to RDF and then linked to IFC materials, which are also formatted to comply with the RDF structure. Publication of the environmental impact dataset as Linked Data implies solution to interoperability issues, enables dataset extensibility, as well as reusability from cross-domain disciplines and improved search results, due to query implementation. Integration with BIM is suggested, based on the fact that, the necessary information to realize the impact assessment are present in the IFC model, so connection between the two can make the process more automated, compared to traditional methods of manual calculations. Additionally, the fact that EE and EC coefficients are not directly attached to the IFC objects as built-in properties, prevents the IFC file from becoming overloaded.

5.2. Societal relevance

The societal relevance of this research emanates from the environmental consequences of the built environment, which demand imminent action on behalf of the responsible stakeholders of the AEC industry. Achieving to deliver more efficient and environmentally-friendly buildings, through management of the building materials' embodied carbon is what this research brings to the table, as a way to approach the issue and initiate action. Such initiation can benefit from the early communication of the environmental effects of the building materials, as proposed in this tool development. Consequently, this thesis assists in encountering a solution that can be applied in practice, for integrating design and environmental impact data for sustainability enforcement in future projects. Implementation of sustainability practices in the built environment can in the long term ensure healthy living spaces that boost the occupants' well-being and consequently have a positive influence in society.

Furthermore, the technologies used for the research implementation introduce new dimensions in data management and usage, but require a significant deviation from conventional ways of doing things within the construction sector. Therefore, from the perspective of adoption of such technologies in the social context, it is concluded that innovation motives and people's relevant education are essential to overcome the established procedures and embrace more efficient methods.

5.3. Recommendations for further research

This section offers insight into the possibilities for further research, based on the adopted approach and end result. Recommendations are given in regards to the environmental impact aspect, as well as the technical aspect of BIM, Semantic Web and Linked Data applications.

In regards to the data collection of this research, due to the focus on architectural models, only partial use of the range of materials offered in the ICE database took place. Nevertheless, the ICE database is rich in material types, which implies that possible applications could be extended beyond the architectural discipline. Such applications could be structural or mechanical, electrical, plumbing (MEP). Therefore, the same way the architectural Revit template was used for the material mapping, different templates or software programs can be used to map the materials existing in their basic libraries.

One direction for further research would be to investigate the possibility of the tool to propose alternative materials for specific building elements with less embodied impacts. This implies an elaborated examination into the structural aspect of the design, in order to identify alternatives, which would serve the same purpose. By same purpose, it should be considered that factors such as strength and material quality should be equivalent, while the suitability of the alternative material should not be omitted. An example would be use of bamboo instead of steel for concrete reinforcement (Imbulana et al., 2013). This would facilitate the decision-making on behalf of the user, who would get the chance to view automatically different material alternatives, without having to remodel the building design.

Moreover, as acknowledged, the system boundaries of the study are *cradle-to-gate*. Further research would be beneficial, in order to extend these boundaries, to a whole lifecycle assessment, including the operational and demolition/refurbishment phases of a material's life, i.e. *cradle-to-grave*. Other possibilities would be to take into account the potential reuse of the selected materials. By examining the possible reuse applications of the materials and predetermining these applications, the material environmental impact could be reduced. Additionally, the consideration of factors, such as distance between factory and construction site could be included, taking into account their significant role in the carbon emissions.

The most important field for further research in association to the scope of this study, is towards standardization of building materials. As identified in the development process, the linking of materials based on their string labels does not offer a sustainable solution, due to string data types being susceptible to modifications, amongst design software, different versions or customized material libraries. Therefore, from a BIM perspective, this could be explored by creating stricter classifications of materials within the IFC data model. From the Linked Data perspective, the establishment of a standardized ontology for building materials, would offer a much more efficient and accurate connection. This way, broader development of the tool could be accomplished via connections with diverse data sources and vocabularies that have been published as Linked Data, such as the BauDataWeb, which can be used to search for products, manufacturers and warehouses for all kinds of construction-related activities (Radinger et al., 2013).

6. References

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7. Appendices

Appendix I: Ontologies (.ttl)

1. ECOM Ontology

```
@base <http://www.semanticweb.org/marianiki/ecom>

@prefix ecom: <http://www.semanticweb.org/marianiki/ecom#> .
@prefix owl: <http://www.w3.org/2002/07/owl#> .
@prefix rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#> .
@prefix xml: <http://www.w3.org/XML/1998/namespace> .
@prefix xsd: <http://www.w3.org/2001/XMLSchema#> .
@prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#> .

<http://www.semanticweb.org/marianiki/ecom> rdf:type owl:Ontology ;
                                             owl:versionIRI
<http://www.semanticweb.org/marianiki/ecom> .

#################################################################
#    Data properties
#################################################################

###  http://www.semanticweb.org/marianiki/ecom#density
ecom:Density rdf:type owl:DatatypeProperty ;
             rdfs:subPropertyOf owl:topDataProperty ;
             rdfs:domain ecom:ICEMaterial ;
             rdfs:range xsd:float .


###  http://www.semanticweb.org/marianiki/ecom#hasECEquivalent
ecom:hasECEquivalent rdf:type owl:DatatypeProperty ;
                     rdfs:subPropertyOf owl:topDataProperty ;
                     rdfs:range xsd:float .


###  http://www.semanticweb.org/marianiki/ecom#hasECGeneral
ecom:hasECGeneral rdf:type owl:DatatypeProperty ;
                  rdfs:subPropertyOf owl:topDataProperty ;
                  rdfs:range xsd:float .


###  http://www.semanticweb.org/marianiki/ecom#hasECRecycled
ecom:hasECRecycled rdf:type owl:DatatypeProperty ;
                   rdfs:subPropertyOf owl:topDataProperty ;
                   rdfs:range xsd:float .


###  http://www.semanticweb.org/marianiki/ecom#hasECVirgin
ecom:hasECVirgin rdf:type owl:DatatypeProperty ;
                 rdfs:subPropertyOf owl:topDataProperty ;
                 rdfs:range xsd:float .
```

```
### http://www.semanticweb.org/marianiki/ecom#hasEEGeneral
ecom:hasEEGeneral rdf:type owl:DatatypeProperty ;
                  rdfs:subPropertyOf owl:topDataProperty ;
                  rdfs:range xsd:float .


#################################################################
#    Classes
#################################################################

### http://www.semanticweb.org/marianiki/ecom#Material
ecom:Material rdf:type owl:Class .

### http://www.semanticweb.org/marianiki/ecom#ICEMaterial
ecom:ICEMaterial rdf:type owl:Class ;
     rdfs:subClassOf ifcmat:IfcMaterial .


#################################################################
#    Annotations
#################################################################

rdfs:label rdfs:comment ""@nl ,
                        ""@en .


### Generated by the OWL API (version 4.2.8.20170104-2310) https://github.com/owlcs/owlapi
```

2. IFCMAT Ontology

```
@base: <http://www.semanticweb.org/marianiki/ifcmat>

@prefix ifcmat: <http://www.semanticweb.org/marianiki/ifcmat#> .
@prefix owl: <http://www.w3.org/2002/07/owl#> .
@prefix rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#> .
@prefix xml: <http://www.w3.org/XML/1998/namespace> .
@prefix xsd: <http://www.w3.org/2001/XMLSchema#> .
@prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#>
.

<http://www.semanticweb.org/marianiki/ifcmat> rdf:type owl:Ontology .

#################################################################
#    Annotation properties
#################################################################

### http://www.w3.org/2000/01/rdf-schema#label
rdfs:label rdfs:range xsd:string ;
           rdfs:domain ifcmat:IfcMaterial .
```

```
#################################################################
#    Object Properties
#################################################################

###  http://www.semanticweb.org/marianiki/ifcmat#hasMaterial
ifcmat:hasMaterial rdf:type owl:ObjectProperty ;
                   rdfs:domain ifcmat:IfcMaterialLayer ,
                               ifcmat:IfcMaterialList ;
                   rdfs:range ifcmat:IfcMaterial .


###  http://www.semanticweb.org/marianiki/ifcmat#isAssociatedTo
ifcmat:isAssociatedTo rdf:type owl:ObjectProperty ;
                      rdfs:subPropertyOf owl:topObjectProperty ;
                      rdfs:domain ifcmat:IfcBuildingElement ;
                      rdfs:range ifcmat:IfcMaterialSelection .


#################################################################
#    Data properties
#################################################################

###  http://www.semanticweb.org/marianiki/ifcmat#elementVolume
ifcmat:elementVolume rdf:type owl:DatatypeProperty ;
                     rdfs:subPropertyOf owl:topDataProperty ;
                     rdfs:domain ifcmat:IfcBuildingElement ;
                     rdfs:range xsd:float .


###  http://www.semanticweb.org/marianiki/ifcmat#fractionOfVolume
ifcmat:fractionOfVolume rdf:type owl:DatatypeProperty ;
                        rdfs:subPropertyOf owl:topDataProperty ;
                        rdfs:domain ifcmat:IfcMaterial ;
                        rdfs:range [ rdf:type rdfs:Datatype ;
                                     owl:onDatatype xsd:float ;
                                     owl:withRestrictions     (     [     xsd:minInclusive
"0.0"^^xsd:float
                                                                ]
                                                                [           xsd:maxInclusive
"1.0"^^xsd:float
                                                                ]
                                                              )
                                   ] .


###  http://www.semanticweb.org/marianiki/ifcmat#layerThickness
ifcmat:layerThickness rdf:type owl:DatatypeProperty ;
                      rdfs:subPropertyOf owl:topDataProperty ;
                      rdfs:domain ifcmat:IfcMaterialLayer ;
                      rdfs:range xsd:float .
```

```
#################################################################
#    Classes
#################################################################

###  http://www.semanticweb.org/marianiki/ifcmat#IfcBuildingElement
ifcmat:IfcBuildingElement rdf:type owl:Class ;
                       owl:disjointWith ifcmat:IfcMaterial .


###  http://www.semanticweb.org/marianiki/ifcmat#IfcMaterial
ifcmat:IfcMaterial rdf:type owl:Class ;
                rdfs:subClassOf ifcmat:IfcMaterialSelection .


###  http://www.semanticweb.org/marianiki/ifcmat#IfcMaterialLayer
ifcmat:IfcMaterialLayer rdf:type owl:Class ;
                     rdfs:subClassOf ifcmat:IfcMaterialSelection .


###  http://www.semanticweb.org/marianiki/ifcmat#IfcMaterialList
ifcmat:IfcMaterialList rdf:type owl:Class ;
                    rdfs:subClassOf ifcmat:IfcMaterialSelection .


###  http://www.semanticweb.org/marianiki/ifcmat#IfcMaterialSelection
ifcmat:IfcMaterialSelection rdf:type owl:Class .


###  Generated by the OWL API (version 4.2.8.20170104-2310) https://github.com/owlcs/owlapi
```

Appendix II: ICE-Revit Material Mapping (CSV)

ICEDatabase	RevitMaterialBrowser@EN	RevitMaterialBrowser@NL	EE_General	EC_General	EC_Virgin	EC_Recycled	EC_Equivalent	Density
Aluminium	Aluminium	Aluminium	155.00	8.24	11.46	1.69	9.16	270
Asphalt	Asphalt Shingle	Asfalt Kiezelsteen	3.93	0.0678	0.0678	NotApplicable	0.075	170
GeneralCommonBrick	Masonry Brick	Metselwerk Baksteen	3.00	0.23	0.23	NotApplicable	0.24	192
GeneralCommonBrick	Brick Soldier Course	Bakstenen rollaag	3.00	0.23	0.23	NotApplicable	0.24	192
GeneralCarpet	Carpet	Tapijt	74.00	3.9	3.9	NotApplicable	NotApplicable	40
TimberGeneral	Cherry	Kers	10.00	0.71	0.71	NotApplicable	0.72	63
20/25Mpa	Concrete	Beton	0.74	0.100	0.1	NotApplicable	0.107	240
20/25Mpa	Masonry Concrete Block	Metselwerk Betonblok	0.70	0.079	0.079	NotApplicable	0.084	195
20/25Mpa	Concrete Cast In Situ	Beton Cast In Situ	0.74	0.1	0.1	NotApplicable	0.107	240
25/30Mpa	Concrete Lightweight	Beton Lichtgewicht	0.78	0.106	0.106	NotApplicable	0.113	175
PrecastConcrete	Concrete Precast	Beton Precast	1.19	0.127	0.127	NotApplicable	0.136	240
Copper	Copper	Koper	42.00	2.60	3.65	0.80	2.71	860
Asphalt	Damp Proofing	Dampremmende laag	3.93	0.0678	3.93	NotApplicable	0.075	170
GeneralRammedSoil	Earth	Aarde	0.45	0.023	0.023	NotApplicable	0.024	146
ExpandedPolystyrene	EIFS Exterior Insulation	EIFS Exterieur Isolatie	88.60	2.55	2.55	NotApplicable	3.29	32
PrimaryGlass	Glass	Glas	15.00	0.86	0.86	NotApplicable	0.91	260
Plasterboard	Plasterboard	Gipsplaat	6.75	0.38	0.38	NotApplicable	0.39	80
Plasterboard	Gypsum Wall Board	Gips Wall Board	6.75	0.38	0.38	NotApplicable	0.39	80
IronGeneral	Iron Ductile	Ijzeren pijp	25.00	1.91	1.91	NotApplicable	2.03	787
SteelGeneral	Metal Deck	Metalen Dek	20.10	1.37	0.44	0.44	0.47	780
SteelGeneral	Metal Stud Layer	Metaal Stud Laag	20.10	1.37	0.44	0.44	0.47	780
SteelGeneral	Metal Steel 345MPa	Metaal Staal 345MPa	20.10	1.37	0.44	0.44	0.47	780
SawnHardwood	Wood Flooring	Houten vloer	10.40	0.86	0.86	NotApplicable	0.59	72
Paint	Parking Stripe	Parkeerstrip	70.00	2.42	2.42	NotApplicable	2.91	100
Plywood	Wood Sheathing plywood	Hout Schede Multiplex	15.00	1.07	1.07	NotApplicable	1.10	54
PlasticsHighDensityPolyethylene	Polyvinyl Chloride Rigid	Polyvinyl Chloride Stijf	76.70	1.57	1.57	NotApplicable	1.93	95
ExpandedPolystyrene	Insulation / Thermal Barriers Semi-rigid Insulation	Isolatie / Thermische barrieres semi-drukvaste isola	88.60	2.55	2.55	NotApplicable	3.29	32
ExpandedPolystyrene	Insulation / Thermal Barriers Rigid Insulation	Isolatie / Thermische barrieres drukvaste isolatie	88.60	2.55	2.55	NotApplicable	3.29	32
Bitumen	Roofing Barrier	Dak Barriere	51.00	0.40	0.40	NotApplicable	0.49	100
Rubber	Roofing EPDM Membrane	Dakbedekking EPDM Membraan	91.00	2.66	2.66	NotApplicable	2.85	150
SawnSoftwood	Wood Dimensional Lumber	Naaldhout	7.40	0.58	0.58	NotApplicable	0.59	51
SawnSoftwood	Wood Flooring	Houten vloer	7.40	0.58	0.59	NotApplicable	0.59	51
StainlessSteel	Stainless Steel	Roestvrij staal	56.70	6.15	6.15	NotApplicable	NotApplicable	785
StainlessSteel	stainless steel	Roestvrij staal	56.70	6.15	6.15	NotApplicable	NotApplicable	785
SteelGeneral	Steel ASTMA992	Staal ASTMA992	20.10	1.37	2.71	0.44	1.46	780
SteelGeneral	Steel Carbon	Staalkoolstof	20.10	1.37	2.71	0.44	1.46	780
Plate	Steel Chrome Plated	Staal verchroomd	25.10	1.55	3.05	NotApplicable	1.66	780
Plate	Metal Chrome	Staal verchroomd	25.10	1.55	3.05	NotApplicable	1.66	780
InsulationFibreglass	Structure Wood Joist Rafter Layer Batt Insulation	Dakelement met glaswol	28.00	1.35	1.35	NotApplicable	NotApplicable	25
TilesAndCladdingPanels	Tile Mosaic Gray	Tegel Moza_ek Grijs	12.00	0.74	0.74	NotApplicable	0.78	200
TilesAndCladdingPanels	Ceramic Tile	Keramische Tegel	12.00	0.74	0.74	NotApplicable	0.78	200
PlasticsLDPEFilm	Vapor Retarder	Dampremmende folie	89.30	2.13	2.13	NotApplicable	2.60	925
Mortar	Masonry Grout	Metselwerk Specie	1.07	0.174	0.174	NotApplicable	0.18	190

Appendix III: Partial RDF dataset from ECOM Ontology

```
@prefix ecom: <http://www.semanticweb.org/marianiki/ecom#> .
@prefix rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#> .
@prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#> .
@prefix xml: <http://www.w3.org/XML/1998/namespace> .
@prefix xsd: <http://www.w3.org/2001/XMLSchema#> .

ecom:Mat01 a ecom:ICEMaterial ;
   rdfs:label "Aluminium"@en,
      "Aluminium"@nl ;
   ecom:density "2700.0"^^xsd:float ;
   ecom:hasECEquivalent "9.16"^^xsd:float ;
   ecom:hasECGeneral "8.24"^^xsd:float ;
   ecom:hasECRecycled "1.69"^^xsd:float ;
   ecom:hasECVirgin "11.46"^^xsd:float ;
   ecom:hasEEGeneral "155.0"^^xsd:float .

ecom:Mat02 a ecom:ICEMaterial ;
   rdfs:label "Metal - Aluminum Polished"@en,
      "Aluminium"@nl ;
   ecom:density "2700.0"^^xsd:float ;
   ecom:hasECEquivalent "9.16"^^xsd:float ;
   ecom:hasECGeneral "8.24"^^xsd:float ;
   ecom:hasECRecycled "1.69"^^xsd:float ;
   ecom:hasECVirgin "11.46"^^xsd:float ;
   ecom:hasEEGeneral "155.0"^^xsd:float .

ecom:Mat03 a ecom:ICEMaterial ;
   rdfs:label "Metal - Aluminium Smooth"@en,
      "Aluminium"@nl ;
   ecom:density "2700.0"^^xsd:float ;
   ecom:hasECEquivalent "9.16"^^xsd:float ;
   ecom:hasECGeneral "8.24"^^xsd:float ;
   ecom:hasECRecycled "1.69"^^xsd:float ;
   ecom:hasECVirgin "11.46"^^xsd:float ;
   ecom:hasEEGeneral "155.0"^^xsd:float .

ecom:Mat04 a ecom:ICEMaterial ;
   rdfs:label "Metal - Aluminium Large Screen"@en,
      "Aluminium"@nl ;
   ecom:density "2700.0"^^xsd:float ;
   ecom:hasECEquivalent "9.16"^^xsd:float ;
   ecom:hasECGeneral "8.24"^^xsd:float ;
   ecom:hasECRecycled "1.69"^^xsd:float ;
   ecom:hasECVirgin "11.46"^^xsd:float ;
   ecom:hasEEGeneral "155.0"^^xsd:float .
```

```
ecom:Mat05 a ecom:ICEMaterial ;
   rdfs:label "Asphalt Shingle"@en,
      "Asfalt Shingle"@nl ;
   ecom:density "1700.0"^^xsd:float ;
   ecom:hasECEquivalent "0.075"^^xsd:float ;
   ecom:hasECGeneral "0.0678"^^xsd:float ;
   ecom:hasECVirgin "0.0678"^^xsd:float ;
   ecom:hasEEGeneral "3.93"^^xsd:float .

ecom:Mat06 a ecom:ICEMaterial ;
   rdfs:label "Masonry - Brick"@en,
      "Metselwerk - Baksteen"@nl ;
   ecom:density "1920.0"^^xsd:float ;
   ecom:hasECEquivalent "0.24"^^xsd:float ;
   ecom:hasECGeneral "0.23"^^xsd:float ;
   ecom:hasECVirgin "0.23"^^xsd:float ;
   ecom:hasEEGeneral "3.0"^^xsd:float .

ecom:Mat07 a ecom:ICEMaterial ;
   rdfs:label "Brick Soldier Course"@en,
      "Brick Soldier Course"@nl ;
   ecom:density "1920.0"^^xsd:float ;
   ecom:hasECEquivalent "0.24"^^xsd:float ;
   ecom:hasECGeneral "0.23"^^xsd:float ;
   ecom:hasECVirgin "0.23"^^xsd:float ;
   ecom:hasEEGeneral "3.0"^^xsd:float .

ecom:Mat08 a ecom:ICEMaterial ;
   rdfs:label "Carpet"@en,
      "Tapijt"@nl ;
   ecom:density "400.0"^^xsd:float ;
   ecom:hasECGeneral "3.9"^^xsd:float ;
   ecom:hasECVirgin "3.9"^^xsd:float ;
   ecom:hasEEGeneral "74.0"^^xsd:float .

ecom:Mat09 a ecom:ICEMaterial ;
   rdfs:label "Cherry"@en,
      "Kers"@nl ;
   ecom:density "630.0"^^xsd:float ;
   ecom:hasECEquivalent "0.72"^^xsd:float ;
   ecom:hasECGeneral "0.71"^^xsd:float ;
   ecom:hasECVirgin "0.71"^^xsd:float ;
   ecom:hasEEGeneral "10.0"^^xsd:float .

ecom:Mat10 a ecom:ICEMaterial ;
   rdfs:label "Concrete"@en,
```

```
    "Beton"@nl ;
  ecom:density "2400.0"^^xsd:float ;
  ecom:hasECEquivalent "0.107"^^xsd:float ;
  ecom:hasECGeneral "0.1"^^xsd:float ;
  ecom:hasECVirgin "0.1"^^xsd:float ;
  ecom:hasEEGeneral "0.74"^^xsd:float .

ecom:Mat11 a ecom:ICEMaterial ;
  rdfs:label "Masonry - Concrete Block"@en,
    "Metselwerk - Betonblok"@nl ;
  ecom:density "1950.0"^^xsd:float ;
  ecom:hasECEquivalent "0.084"^^xsd:float ;
  ecom:hasECGeneral "0.079"^^xsd:float ;
  ecom:hasECVirgin "0.079"^^xsd:float ;
  ecom:hasEEGeneral "0.7"^^xsd:float .

ecom:Mat12 a ecom:ICEMaterial ;
  rdfs:label "Concrete - Cast In Situ"@en,
    "Beton - Cast In Situ"@nl ;
  ecom:density "2400.0"^^xsd:float ;
  ecom:hasECEquivalent "0.107"^^xsd:float ;
  ecom:hasECGeneral "0.1"^^xsd:float ;
  ecom:hasECVirgin "0.1"^^xsd:float ;
  ecom:hasEEGeneral "0.74"^^xsd:float .

ecom:Mat13 a ecom:ICEMaterial ;
  rdfs:label "Concrete Lightweight"@en,
    "Beton Lichtgewicht"@nl ;
  ecom:density "1750.0"^^xsd:float ;
  ecom:hasECEquivalent "0.113"^^xsd:float ;
  ecom:hasECGeneral "0.106"^^xsd:float ;
  ecom:hasECVirgin "0.106"^^xsd:float ;
  ecom:hasEEGeneral "0.78"^^xsd:float .

ecom:Mat14 a ecom:ICEMaterial ;
  rdfs:label "Concrete Precast"@en,
    "Beton Precast"@nl ;
  ecom:density "2400.0"^^xsd:float ;
  ecom:hasECEquivalent "0.136"^^xsd:float ;
  ecom:hasECGeneral "0.127"^^xsd:float ;
  ecom:hasECVirgin "0.127"^^xsd:float ;
  ecom:hasEEGeneral "1.19"^^xsd:float .

ecom:Mat15 a ecom:ICEMaterial ;
  rdfs:label "Copper"@en,
    "Koper"@nl ;
  ecom:density "8600.0"^^xsd:float ;
```

```
ecom:hasECEquivalent "2.71"^^xsd:float ;
ecom:hasECGeneral "2.6"^^xsd:float ;
ecom:hasECRecycled "0.8"^^xsd:float ;
ecom:hasECVirgin "3.65"^^xsd:float ;
ecom:hasEEGeneral "42.0"^^xsd:float .
```

Appendix IV: Python Script

```
#IMPORTS
import sys
import os
import ifcopenshell, ifcopenshell.geom
settings = ifcopenshell.geom.settings()
settings.set(settings.USE_PYTHON_OPENCASCADE, True)
import datetime

from PyQt4 import QtCore, QtGui
from OCC.Display.backend import get_backend
get_backend("qt-pyqt4")
import OCC.Display.qtDisplay
from OCC.Display.qtDisplay import qtViewer3d

from OCC.gp import *
import OCC.Bnd, OCC.BRepBndLib
from OCC.Aspect import Aspect_GT_Rectangular, Aspect_GDM_Lines
from OCC.BRepPrimAPI import BRepPrimAPI_MakeBox

import rdflib
import rdfextras
from rdflib import Graph, Literal, URIRef, Namespace, XSD
from rdflib.namespace import NamespaceManager, RDF, RDFS
import csv

#NAMESPACES OF THE ONTOLOGIES
ecom = Namespace("http://www.semanticweb.org/marianiki/ecom#")
ifcmat = Namespace("http://www.semanticweb.org/marianiki/ifcmat#")

#INITIATE SELECTION
guid_selection = None

class ProductViewer(qtViewer3d):
    def __init__(self, *args):
        qtViewer3d.__init__(self)
        self.objects = {}

    @staticmethod
    def Hash(shape):
        return shape.HashCode(1 << 30)

    displayed_shapes = {}

    def Show(self, key, shape, color=None):
        self.objects[ProductViewer.Hash(shape)] = key
        qclr = OCC.Quantity.Quantity_Color(.35, .25, .1, OCC.Quantity.Quantity_TOC_RGB)
        ais = self._display.DisplayColoredShape(shape, qclr)
        self.displayed_shapes[key] = ais
        self._display.FitAll()

    def Color(self, key):
        ais = self.displayed_shapes[key]
        qclr = OCC.Quantity.Quantity_Color(1, 0, 0, OCC.Quantity.Quantity_TOC_RGB)
        ais.GetObject().SetColor(qclr)

    def ColorBack(self, key):
        ais = self.displayed_shapes[key]
        qclr = OCC.Quantity.Quantity_Color(.35, .25, .1, OCC.Quantity.Quantity_TOC_RGB)
        ais.GetObject().SetColor(qclr)

    def ColorWhenElementAcceptable(self, key):
        try:
            ais = self.displayed_shapes[key]
            qclr = OCC.Quantity.Quantity_Color(0, 0.7, 0, OCC.Quantity.Quantity_TOC_RGB)
            ais.GetObject().SetColor(qclr)
        except KeyError as e:
            print( e )
```

```
    def ColorWhenElementNotAcceptable(self, key):
        ais = self.displayed_shapes[key]
        qclr = OCC.Quantity.Quantity_Color(1, 0, 0, OCC.Quantity.Quantity_TOC_RGB)
        ais.GetObject().SetColor(qclr)

    def mouseReleaseEvent(self, *args):
        qtViewer3d.mouseReleaseEvent(self, *args)
        if self._display.selected_shape:
            global guid_selection
            global selected_shape
            selected_shape = self._display.selected_shape
            guid_selection =
(self.objects[ProductViewer.Hash(self._display.selected_shape)])
            print  guid_selection

# Main class of the application
class initUI(object):
    def __init__(self, *args):
        # Constructing an application
        app = QtGui.QApplication(sys.argv)

        # Viewer initialization
        self.main = Main(self)
        self.main.show()
        self.main.canvas.InitDriver()
        self.main.statusBar()
        self.display = self.main.canvas._display

        #  Methods to feed the viewer with content
        self.geometry_box()
        self.geometry_grid()

        # Raise a system exit
        sys.exit(app.exec_())

    def geometry_box(self):
        box = BRepPrimAPI_MakeBox(10., 10., 10.).Shape()
        self.display.DisplayShape(box)
        self.display.FitAll()

    def geometry_grid(self):
        ax3 = gp_Ax3(gp_Pnt(0, 0, 0), gp_Dir(0, 0, 1))
        self.display.GetViewer().GetObject().SetPrivilegedPlane(ax3)
        self.display.GetViewer().GetObject().SetRectangularGridValues(0, 0, 10, 10, 0)
        self.display.GetViewer().GetObject().SetRectangularGridGraphicValues(10, 10, 0)
        self.display.GetViewer().GetObject().ActivateGrid(Aspect_GT_Rectangular,
Aspect_GDM_Lines)
        self.display.FitAll()

# Main class of the Graphical User Interface
class Main(QtGui.QMainWindow):

    def __init__(self, parent=None):
        self.parent = parent
        QtGui.QMainWindow.__init__(self)

        # Instantiating the tabs
        global filename
        self.filename = None

        self.tabs = QtGui.QTabWidget()
        self.setCentralWidget(self.tabs)

        # RDF TAB
        self.rdf_tab = QtGui.QWidget()
        self.tabs.addTab(self.rdf_tab, "Export EC data to RDF")

        #VIEWER TAB
        self.viewer_tab = QtGui.QWidget()
        self.tabs.addTab(self.viewer_tab, "3D IFC-EC Viewer")

        # Implementing the OCC viewer
```

```
        self.canvas = ProductViewer(self)
        self.setGeometry(100, 100, 850, 550)
        self.setWindowTitle("Carbon Calculator - IFC Viewer")

        # Calling both tabs
        self.tab_rdf()
        self.tab_3dview()

# Tab 1

    def tab_rdf(self):

        vbox = QtGui.QVBoxLayout()
        hbox = QtGui.QHBoxLayout()
        hbox2 = QtGui.QHBoxLayout()
        hbox3 = QtGui.QHBoxLayout()
        vbox2 = QtGui.QVBoxLayout()
        vbox3 = QtGui.QVBoxLayout()

        vbox.addLayout(hbox)

        vbox.addLayout(hbox2)
        hbox2.addLayout(vbox2)
        hbox2.addLayout(vbox3)
        vbox3.addLayout(hbox3)
        self.rdf_tab.setLayout(vbox)

        vbox2.setSpacing(50)
        vbox3.setSpacing(50)
        hbox3.setSpacing(10)

        csv_to_rdf_introduction = QtGui.QLabel(
"""
In this tab of the application, it is possible to upload a file in CSV format and
convert it
into RDF triples in a turtle format. The RDF file generated will be used in order to
link
embodied carbon (EC) data of materials to materials existing in the IFC file

In the 3D IFC-EC viewer tab, it is possible to visualise IFC files, calculate the
embodied carbon
per material or building element, calculate the embodied energy and carbon of the total
construction,
visualize critical components and save the results in a csv document.
"""
                )
        csv_to_rdf_introduction.setMaximumHeight(150)
        csv_to_rdf_introduction.setWordWrap(True)

        #BUTTONS
        openCSV_btn_title = QtGui.QLabel("1. Open a CSV file that contains EC data:")
        openCSV_btn = QtGui.QPushButton("Open CSV file", self)
        self.openCSV_btn_path = QtGui.QLineEdit(self)
        self.openCSV_btn_path.setPlaceholderText("Open the required EC data here")
        openCSV_btn.clicked.connect(self.open_csv)

        writetoRDF_btn_title = QtGui.QLabel("2. Write the EC data to an RDF file:")
        writetoRDF_btn = QtGui.QPushButton("Write to RDF", self)
        writetoRDF_btn.clicked.connect(self.writecsv_to_rdf)
        hbox.addWidget(csv_to_rdf_introduction)
        vbox2.addWidget(openCSV_btn_title)
        vbox2.addWidget(writetoRDF_btn_title)
        hbox3.addWidget(self.openCSV_btn_path)
        hbox3.addWidget(openCSV_btn)
        vbox3.addWidget(writetoRDF_btn)

    #LOAD CSV
    def open_csv(self):
        self.csvFilePath = QtGui.QFileDialog.getOpenFileName(self, 'Open file', ".",
"Commaseparated values(*.csv)")
        self.csvFileName = str(os.path.basename('%s' % self.csvFilePath))
        return self.csvFilePath
```

```
        self.openCSV_btn_path.setText(self.csvFilePath)

    #CONVERT CSV TO RDF
    def writecsv_to_rdf(self):

        #INITIATE GRAPH
        g = Graph()

        #BIND NAMESPACE PREFIXES
        g.namespace_manager.bind('ecom',ecom)

        with open(self.csvFileName, "rb") as csvfile:
            reader = csv.reader(csvfile, delimiter=';')
            header = reader.next()
            number = 1
            for row in reader:
                if number < 10:
                    material = URIRef(ecom + "Mat0" + str(number))
                else:
                    material = URIRef(ecom + "Mat" + str(number))
                g.add((material, RDF.type, ecom.ICEMaterial))
                g.add((ecom.ICEMaterial, RDFS.subClassOf, ecom.Material))
                g.add((material, RDFS.label, Literal(row[1], lang='en')))
                g.add((material, RDFS.label, Literal(row[2], lang='nl')))
                g.add((material, ecom.hasEEGeneral, Literal(row[3],
datatype=XSD.float)))
                g.add((material, ecom.hasECGeneral, Literal(row[4],
datatype=XSD.float)))
                g.add((material, ecom.hasECVirgin, Literal(row[5], datatype=XSD.float)))

                if row[6] != 'NotApplicable':
                    g.add((material, ecom.hasECRecycled, Literal(row[6],
datatype=XSD.float)))
                if row[7] != 'NotApplicable':
                    g.add((material, ecom.hasECEquivalent, Literal(row[7],
datatype=XSD.float)))
                g.add((material, ecom.density, Literal(row[8], datatype=XSD.float)))
                number += 1

            g.serialize('%s.ttl' % self.csvFileName, format='turtle')
            print "RDF file successfully generated! Data written to %s.ttl." %
self.csvFileName

# Tab 2

    def tab_3dview(self):

         # Initializing a split-view layout
         font = QtGui.QFont("Calibri", 10, QtGui.QFont.Bold, True)
         sizePolicy = QtGui.QSizePolicy(QtGui.QSizePolicy.Fixed,
QtGui.QSizePolicy.MinimumExpanding)

         self.propertybox = QtGui.QTextBrowser()
         self.propertybox.setFont(font)
         self.propertybox.setSizePolicy(sizePolicy)

         self.propertybox2 = QtGui.QTextBrowser()
         self.propertybox2.setFont(font)
         self.propertybox2.setSizePolicy(sizePolicy)

         self.propertybox3 = QtGui.QTextBrowser()
         self.propertybox3.setFont(font)
         self.propertybox3.setSizePolicy(sizePolicy)

         # Define a widget for the 3D viewer
         center = QtGui.QWidget()

         # Define and set layout
         mainLayout = QtGui.QHBoxLayout(center)
         viewer_hbox = QtGui.QHBoxLayout()
         viewer_vbox = QtGui.QVBoxLayout()
```

```
        #BUTTONS
        viewer_open_ifc_btn = QtGui.QPushButton("Load IFC", self)
        viewer_open_ifc_btn.clicked.connect(self.open_ifc_file)

        viewer_open_rdf_btn = QtGui.QPushButton("Load EC RDF", self)
        viewer_open_rdf_btn.clicked.connect(self.open_rdf_data)

        viewer_open_quantities_btn = QtGui.QPushButton("Convert IFC to RDF", self)
        viewer_open_quantities_btn.clicked.connect(self.extract_quantities)

        viewer_open_total_eec_btn = QtGui.QPushButton("Total EC,EE", self)
        viewer_open_total_eec_btn.clicked.connect(self.calculate_total_ec)

        viewer_open_ec_material_btn = QtGui.QPushButton("EC per building material", self)
        viewer_open_ec_material_btn.clicked.connect(self.calculate_ec_material)

        viewer_open_ec_element_btn = QtGui.QPushButton("EC per building component", self)
        viewer_open_ec_element_btn.clicked.connect(self.calculate_ec_element)

        viewer_open_ec_recycled_btn  =  QtGui.QPushButton("EC  for  recycled  materials",
self)
        viewer_open_ec_recycled_btn.clicked.connect(self.calculate_ec_recycled)

        viewer_csv_results_btn = QtGui.QPushButton("Save results to CSV", self)
        viewer_csv_results_btn.clicked.connect(self.save_to_csv)

        viewer_open_color_components_btn     =     QtGui.QPushButton("Color     critical
components", self)
        viewer_open_color_components_btn.clicked.connect(self.color_components)

        splitter = QtGui.QSplitter(QtCore.Qt.Horizontal)
        splitterH = QtGui.QSplitter(QtCore.Qt.Vertical)

        splitter.addWidget(self.canvas)
        splitter.addWidget(splitterH)
        splitterH.addWidget(viewer_csv_results_btn)
        splitterH.addWidget(self.propertybox)
        splitterH.addWidget(self.propertybox2)
        splitterH.addWidget(self.propertybox3)

        viewer_vbox.addWidget(splitter)
        viewer_vbox.addLayout(viewer_hbox)
        self.viewer_tab.setLayout(viewer_vbox)
        viewer_hbox.addWidget(viewer_open_ifc_btn)
        viewer_hbox.addWidget(viewer_open_rdf_btn)
        viewer_hbox.addWidget(viewer_open_quantities_btn)
        viewer_hbox.addWidget(viewer_open_total_eec_btn)
        viewer_hbox.addWidget(viewer_open_ec_material_btn)
        viewer_hbox.addWidget(viewer_open_ec_element_btn)
        viewer_hbox.addWidget(viewer_open_ec_recycled_btn)
        viewer_hbox.addWidget(viewer_open_color_components_btn)

        self.count = 0
        self.rdf_graph = None

    #LOAD IFC
    def open_ifc_file(self, filename=None):
        self.filename = QtGui.QFileDialog.getOpenFileName(self, 'Open file', ".",
"Industry Foundation Classes(*.ifc)")
        if self.filename:
            self.parent.display.EraseAll()
            self.propertybox.clear()
        self.parse_ifc(self.filename)

    #PARSE IFC
    def parse_ifc(self, filename):
        self.created_shapes = {}
        self.ifc_file = ifcopenshell.open(filename)
        rooms = self.ifc_file.by_type("IfcBuildingElement")
        for room in rooms:
            if room.Representation:
                ifcgeom = ifcopenshell.geom.create_shape(settings, room).geometry
```

```
                shp = self.canvas.Show(room.GlobalId, ifcgeom, None)
            print "IFC file successfully loaded!"

    #LOAD EC RDF DATA
    def open_rdf_data(self, filename=None):
        self.RDFfilename = QtGui.QFileDialog.getOpenFileName(self, 'Open file', ".",
"Resource Description Framework(*.ttl)")
        g = rdflib.Graph()
        g.parse(str(self.RDFfilename), format="turtle")
        print "RDF data successfully loaded!"

    #EXTRACT QUANTITIES AND CONVERT FROM IFC TO RDF
    def extract_quantities(self):

        if not self.filename:
            QtGui.QMessageBox.warning(self,
                                      "No IFC loaded",
                                      "Please load a model first!")
            return

        #Inititate rdf file
        rdffile = open("MaterialVolume.ttl", "w")

        g = Graph()
        g.namespace_manager.bind('ifcmat',ifcmat)

        #Check units of measurement
        unit = self.ifc_file.by_type("IfcUnitAssignment")
        conversion_factor = 1
        for u in unit:
            for namedUnit in u.Units:
                if namedUnit.is_a("IfcConversionBasedUnit"):
                    if namedUnit.UnitType == "VOLUMEUNIT":
                        for cfactor in namedUnit.ConversionFactor.ValueComponent:
                            conversion_factor = cfactor
        print conversion_factor

        #Material usage
        def get_materials(element):
            material_layers = None
            for alk in element.HasAssociations:
                if alk.is_a("IfcRelAssociatesMaterial"):

                    if alk.RelatingMaterial.is_a("IfcMaterialLayerSetUsage"):
                        material_layers = []
                        thickness = []
                        for mls in alk.RelatingMaterial.ForLayerSet.MaterialLayers:
                            layer_thickness = mls.LayerThickness
                            thickness.append(layer_thickness)
                            total_thickness = sum(thickness)
                        for mls in alk.RelatingMaterial.ForLayerSet.MaterialLayers:
                            if mls.Material.is_a("IfcMaterial"):
                                for ml in mls.Material:
                                    layer_thickness = mls.LayerThickness
                                    material = {}
                                    fraction = (layer_thickness/total_thickness)
                                    material['Material Name'] = ml
                                    material['Fraction of Volume'] = fraction
                                    material['Element GUID'] = e.GlobalId
                                    material['Element Volume'] = volume
                                    material['Element Name'] = e.Name
                                    material['Layer Thickness'] = layer_thickness
                                    material_layers.append(material)

                    elif alk.RelatingMaterial.is_a("IfcMaterial"):
                        material_layers = []
                        for ml in alk.RelatingMaterial:
                            material = {}
                            fraction = 1
                            material['Material Name'] = ml
                            material['Fraction of Volume'] = fraction
                            material['Element GUID'] = e.GlobalId
```

```
                            material['Element Volume'] = volume
                            material['Element Name'] = e.Name
                            material['Layer Thickness'] = 0
                            material_layers.append(material)

                    elif alk.RelatingMaterial.is_a("IfcMaterialList"):
                        material_layers = []
                        for ml in alk.RelatingMaterial.Materials:
                            material = {}
                            fraction = len(alk.RelatingMaterial.Materials)
                            material['Material Name'] = ml.Name
                            material['Fraction of Volume'] = fraction
                            material['Element GUID'] = e.GlobalId
                            material['Element Volume'] = volume
                            material['Element Name'] = e.Name
                            material['Layer Thickness'] = 0
                            material_layers.append(material)

            number = 1

            #After getting the IFC information, create an RDF dataset
            if material_layers is not None:
                for m in material_layers:
                    elem = URIRef(ifcmat + m['Element GUID'])
                    if number < 10:
                        mat = URIRef(ifcmat + "Mat0" + str(number) +"_" + m['Element 
GUID'])
                        matlayer = URIRef(ifcmat + "MatLayer0" + str(number)+"_" + 
m['Element GUID'])
                    else:
                        mat = URIRef(ifcmat + "Mat" + str(number) +"_" + m['Element 
GUID'])
                        matlayer = URIRef(ifcmat + "MatLayer" + str(number) + "_" + 
m['Element GUID'])


                    #Add RDF triples
                    g.add((elem, RDF.type, ifcmat.IfcBuildingElement))
                    g.add((elem, ifcmat.hasGUID, Literal(m['Element GUID'], 
datatype=XSD.string)))
                    g.add((elem, ifcmat.elementName, Literal(m['Element Name'], 
datatype=XSD.string)))
                    g.add((elem, ifcmat.isAssociatedTo, mat))
                    g.add((elem, ifcmat.elementVolume, Literal(m['Element Volume'], 
datatype=XSD.float)))
                    g.add((mat, RDF.type, ifcmat.IfcMaterial))
                    g.add((matlayer, RDF.type, ifcmat.IfcMaterialLayer))
                    g.add((matlayer, ifcmat.hasMaterial, mat))
                    if m['Layer Thickness'] != 0:
                        g.add((matlayer, ifcmat.layerThickness, Literal(m['Layer 
Thickness'], datatype=XSD.float)))
                    g.add((mat, RDFS.label, Literal(m['Material Name'], 
datatype=XSD.string)))
                    g.add((mat, ifcmat.fractionOfVolume, Literal(m['Fraction of 
Volume'], datatype=XSD.float)))

                    number+=1

            return material_layers

        #Get volumes of IFC building elements
        element = self.ifc_file.by_type("IfcBuildingElement")
        for e in element:

            for relDefinesByProperties in e.IsDefinedBy:
                if relDefinesByProperties.is_a("IfcRelDefinesByProperties"):

                    if 
relDefinesByProperties.RelatingPropertyDefinition.is_a("IfcElementQuantity"):
                        for vol in 
relDefinesByProperties.RelatingPropertyDefinition.Quantities:
                            if vol.is_a("IfcQuantityVolume"):
```

```
                                volume = vol.VolumeValue * conversion_factor

                        elif
relDefinesByProperties.RelatingPropertyDefinition.is_a("IfcPropertySet"):
                            for vol in
relDefinesByProperties.RelatingPropertyDefinition.HasProperties:
                                if vol.Name == "Volume":
                                    for totalvolume in vol.NominalValue:
                                        volume = totalvolume * conversion_factor

            if e.is_a("IfcWall"):
                get_materials(e)
            elif e.is_a("IfcCurtainWall"):
                get_materials(e)
            elif e.is_a("IfcSlab"):
                get_materials(e)
            elif e.is_a("IfcCovering"):
                get_materials(e)
            elif e.is_a("IfcFooting"):
                get_materials(e)
            elif e.is_a("IfcRoof"):
                get_materials(e)
            elif e.is_a("IfcStair"):
                get_materials(e)
            elif e.is_a("IfcBeam"):
                get_materials(e)
            elif e.is_a("IfcRailing"):
                get_materials(e)
            elif e.is_a("IfcRampFlight"):
                get_materials(e)
            elif e.is_a("IfcRamp"):
                get_materials(e)
            elif e.is_a("IfcStairFlight"):
                get_materials(e)
            elif e.is_a("IfcPile"):
                get_materials(e)
            elif e.is_a("IfcPlate"):
                get_materials(e)
            elif e.is_a("IfcColumn"):
                get_materials(e)

        for el in element:
            if el.is_a("IfcDoor"):
                door_thickness = 0.05
                volume = el.OverallHeight * el.OverallWidth * door_thickness
                get_materials(el)
            elif el.is_a("IfcWindow"):
                window_thickness = 0.03
                volume = el.OverallHeight * el.OverallWidth * window_thickness
                get_materials(el)

        a = g.serialize(format='turtle')
        rdffile.write(a)
        rdffile.close()
        print "RDF successfully generated!"

    #SPARQL query for calculation of total EC
    def calculate_total_ec(self, filename):

        if not self.filename:
            QtGui.QMessageBox.warning(self,
                                      "No IFC loaded",
                                      "Please load a model first!")
            return

        rdfextras.registerplugins()
        materialVolume = "MaterialVolume.ttl"
        g = rdflib.Graph()

        #Parse both RDF graphs
        g.parse(str(self.RDFfilename), format="turtle")
        g.parse(materialVolume, format="turtle")
```

```
        query_total = g.query("""PREFIX ifcmat:
<http://www.semanticweb.org/marianiki/ifcmat#>
                PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
                PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
                PREFIX xml: <http://www.w3.org/XML/1998/namespace>
                PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
                PREFIX ecom: <http://www.semanticweb.org/marianiki/ecom#>
                SELECT (SUM(?ee) AS ?totalee) (SUM(?ec) AS ?totalec) (SUM(?equiv) AS
?totalequiv) WHERE{?material a ecom:ICEMaterial .
                ?material rdfs:label ?label .
                ?material ecom:density ?density .
                ?material ecom:hasEEGeneral ?eegeneral .
                ?material ecom:hasECGeneral ?ecgeneral .
                ?material ecom:hasECEquivalent ?ecequivalent .
                ?element a ifcmat:IfcBuildingElement .
                ?element ifcmat:isAssociatedTo ?mat .
                ?element ifcmat:elementVolume ?volume .
                ?mat a ifcmat:IfcMaterial .
                ?mat ifcmat:fractionOfVolume ?fraction .
                ?mat rdfs:label ?label1 .
                BIND ( str(?label) AS ?label2 ) .
                BIND ( str(?label1) AS ?label3 ) .
                FILTER (?label2 = ?label3 ) .
                BIND ((?fraction * ?volume ) AS ?materialvol ) .
                BIND ((?materialvol * ?density ) AS ?weight ) .
                BIND ((?weight * ?eegeneral ) AS ?ee ) .
                BIND ((?weight * ?ecgeneral ) AS ?ec ) .
                BIND ((?weight * ?ecequivalent ) AS ?equiv ) .
                }
        """)

        for row in query_total:
            eegen = str(row[0])
            ecgen = str(row[1])
            ecequiv = str(row[2])

            #Append results of query to the propertybox
            self.propertybox.clear()
            self.propertybox.append("Embodied Energy (MJ/kg) of total construction:" + "
" + eegen)
            self.propertybox.append("Embodied Carbon (kgCO2/kg) of total construction:"
+ " " + ecgen)
            self.propertybox.append("Embodied Carbon Equivalent (kgCO2e/kg) of total
construction:" + " " + ecequiv)


    #SPARQL query to calculate EC per material
    def calculate_ec_material(self, filename):

        if not self.filename:
            QtGui.QMessageBox.warning(self,
                                      "No IFC loaded",
                                      "Please load a model first!")
            return

        rdfextras.registerplugins()
        materialVolume = "MaterialVolume.ttl"
        g = rdflib.Graph()

        # Parse both RDF graphs
        g.parse(str(self.RDFfilename), format="turtle")
        g.parse(materialVolume, format="turtle")

        query1 = g.query("""PREFIX ifcmat:
<http://www.semanticweb.org/marianiki/ifcmat#>
                        PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
                        PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
                        PREFIX xml: <http://www.w3.org/XML/1998/namespace>
                        PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
                        PREFIX ecom: <http://www.semanticweb.org/marianiki/ecom#>
```

```
                        SELECT ?label3 (SUM(?equiv) AS ?equivmaterial) WHERE{?material a 
ecom:ICEMaterial .
                        ?material rdfs:label ?label .
                        ?material ecom:density ?density .
                        ?material ecom:hasECEquivalent ?ecequivalent .
                        ?element a ifcmat:IfcBuildingElement .
                        ?element ifcmat:elementVolume ?volume .
                        ?element ifcmat:isAssociatedTo ?mat .
                        ?mat a ifcmat:IfcMaterial .
                        ?mat ifcmat:fractionOfVolume ?fraction .
                        ?mat rdfs:label ?label1 .
                        BIND ( str(?label) AS ?label2 ) .
                        BIND ( str(?label1) AS ?label3 ) .
                        FILTER (?label2 = ?label3 ) .
                        BIND ((?fraction * ?volume ) AS ?matvol ) .
                        BIND ((?density * ?matvol ) AS ?weight ) .
                        BIND ((?weight * ?ecequivalent ) AS ?equiv ) .
                        }
                        GROUP BY ?label3
                """)

        self.propertybox2.append("CO2e per material")

        for row in query1:
            name = row[0]
            equiv = row[1]

            self.propertybox2.append(name + ":" + " " + equiv + " " + "kgCO2e")


    #SPARQL query to calculate EC per element
    def calculate_ec_element(self, filename):

        if not self.filename:
            QtGui.QMessageBox.warning(self,
                                    "No IFC loaded",
                                    "Please load a model first!")
            return

        rdfextras.registerplugins()
        materialVolume = "MaterialVolume.ttl"
        g = rdflib.Graph()

        # Parse both RDF graphs
        g.parse(str(self.RDFfilename), format="turtle")
        g.parse(materialVolume, format="turtle")

        query_el = g.query("""PREFIX ifcmat: 
<http://www.semanticweb.org/marianiki/ifcmat#>
                                PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-
ns#>

                                PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
                                PREFIX xml: <http://www.w3.org/XML/1998/namespace>
                                PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
                                PREFIX ecom: 
<http://www.semanticweb.org/marianiki/ecom#>
                                SELECT ?guid (SUM(?equiv) AS ?equivalentelem) 
WHERE{?material a ecom:ICEMaterial .
                                ?material rdfs:label ?label .
                                ?material ecom:density ?density .
                                ?material ecom:hasECEquivalent ?ecequivalent .
                                ?element a ifcmat:IfcBuildingElement .
                                ?element ifcmat:hasGUID ?guid .
                                ?element ifcmat:isAssociatedTo ?mat .
                                ?element ifcmat:elementVolume ?volume .
                                ?mat a ifcmat:IfcMaterial .
                                ?mat ifcmat:fractionOfVolume ?fraction .
                                ?mat rdfs:label ?label1 .
                                BIND ( str(?label) AS ?label2 ) .
                                BIND ( str(?label1) AS ?label3 ) .
                                FILTER (?label2 = ?label3 ) .
                                BIND ((?fraction * ?volume ) AS ?matvol ) .
```

```
                                BIND ((?density * ?matvol ) AS ?weight ) .
                                BIND ((?weight * ?ecequivalent ) AS ?equiv ) .
                                }
                                GROUP BY ?guid
                        """)

        self.propertybox3.append("CO2e per element")

        for row in query_el:
            GUID = row[0]
            equiv = row[1]

            self.propertybox3.append(str(GUID) + ":" + " " + str(equiv) + " " +
"kgCO2e")


    #Calculate EC for recycled materials
    def calculate_ec_recycled(self, filename):

        if not self.filename:
            QtGui.QMessageBox.warning(self,
                                    "No IFC loaded",
                                    "Please load a model first!")
            return

        rdfextras.registerplugins()
        materialVolume = "MaterialVolume.ttl"
        g = rdflib.Graph()

        # Parse both RDF graphs
        g.parse(str(self.RDFfilename), format="turtle")
        g.parse(materialVolume, format="turtle")

        query_recycled = g.query("""PREFIX ifcmat:
<http://www.semanticweb.org/marianiki/ifcmat#>
                                PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-
ns#>

                                PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
                                PREFIX xml: <http://www.w3.org/XML/1998/namespace>
                                PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
                                PREFIX ecom:
<http://www.semanticweb.org/marianiki/ecom#>
                                SELECT ?label3 (SUM(?matvol) AS ?totalvol)
(SUM(?recycled) AS ?recmat) WHERE{?material a ecom:ICEMaterial .
                                ?material rdfs:label ?label .
                                ?material ecom:density ?density .
                                ?material ecom:hasECRecycled ?ecrecycled .
                                ?element a ifcmat:IfcBuildingElement .
                                ?element ifcmat:hasGUID ?guid .
                                ?element ifcmat:isAssociatedTo ?mat .
                                ?element ifcmat:elementVolume ?volume .
                                ?mat a ifcmat:IfcMaterial .
                                ?mat ifcmat:fractionOfVolume ?fraction .
                                ?mat rdfs:label ?label1 .
                                BIND ( str(?label) AS ?label2 ) .
                                BIND ( str(?label1) AS ?label3 ) .
                                FILTER (?label2 = ?label3 ) .
                                BIND ((?fraction * ?volume ) AS ?matvol ) .
                                BIND ((?density * ?matvol ) AS ?weight ) .
                                BIND ((?weight * ?ecrecycled ) AS ?recycled ) .
                                }
                                GROUP BY ?label3
                        """)

        self.propertybox3.append("Available recycled materials")

        for row in query_recycled:
            labelmat = row[0]
            volumemat = row[1]
            recycledec = row[2]

            self.propertybox3.append(labelmat)
```

```
            self.propertybox3.append("Material Volume:" + " " + volumemat)
            self.propertybox3.append("CO2:" + " " + recycledec)

    #Save results to CSV files
    def save_to_csv(self, filename):

        if not self.filename:
            QtGui.QMessageBox.warning(self,
                                      "No IFC loaded",
                                      "Please load a model first!")
            return

        #Definition of datetime for file naming
        def _getToday():
            return datetime.datetime.now().strftime("%Y%m%d-%H%M")

        #Define names of CSV files
        file1_csv = "%s_%s.%s" % ("CO2perMaterial", _getToday(), "csv")
        file2_csv = "%s_%s.%s" % ("CO2perElement", _getToday(), "csv")

        rdfextras.registerplugins()
        materialVolume = "MaterialVolume.ttl"
        g = rdflib.Graph()
        g.parse(str(self.RDFfilename), format="turtle")
        g.parse(materialVolume, format="turtle")

        #Query to export in CSV, the EC of materials
        query_mat = g.query("""PREFIX ifcmat:
<http://www.semanticweb.org/marianiki/ifcmat#>
                        PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
                        PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
                        PREFIX xml: <http://www.w3.org/XML/1998/namespace>
                        PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
                        PREFIX ecom: <http://www.semanticweb.org/marianiki/ecom#>
                        SELECT ?label3 (SUM(?matvol) AS ?totvol) (SUM(?equiv) AS
?equivmaterial) WHERE{?material a ecom:ICEMaterial .
                        ?material rdfs:label ?label .
                        ?material ecom:density ?density .
                        ?material ecom:hasECEquivalent ?ecequivalent .
                        ?element a ifcmat:IfcBuildingElement .
                        ?element ifcmat:elementVolume ?volume .
                        ?element ifcmat:isAssociatedTo ?mat .
                        ?mat a ifcmat:IfcMaterial .
                        ?mat ifcmat:fractionOfVolume ?fraction .
                        ?mat rdfs:label ?label1 .
                        BIND ( str(?label) AS ?label2 ) .
                        BIND ( str(?label1) AS ?label3 ) .
                        FILTER (?label2 = ?label3 ) .
                        BIND ((?fraction * ?volume ) AS ?matvol ) .
                        BIND ((?density * ?matvol ) AS ?weight ) .
                        BIND ((?weight * ?ecequivalent ) AS ?equiv ) .
                        }
                        GROUP BY ?label3
                """)

        with open(file1_csv, 'wb') as testfile1:
            for r in query_mat:
                csv_writer = csv.writer(testfile1, delimiter=';')
                csv_writer.writerow(r)

        #Query to export in CSV, the EC of elements
        query_element = g.query("""PREFIX ifcmat:
<http://www.semanticweb.org/marianiki/ifcmat#>
                                PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-
ns#>
                                PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
                                PREFIX xml: <http://www.w3.org/XML/1998/namespace>
                                PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
                                PREFIX ecom:
<http://www.semanticweb.org/marianiki/ecom#>
                                SELECT ?guid ?volume (SUM(?equiv) AS ?equivalentelem)
WHERE{?material a ecom:ICEMaterial .
```

```
                                ?material rdfs:label ?label .
                                ?material ecom:density ?density .
                                ?material ecom:hasECEquivalent ?ecequivalent .
                                ?element a ifcmat:IfcBuildingElement .
                                ?element ifcmat:hasGUID ?guid .
                                ?element ifcmat:isAssociatedTo ?mat .
                                ?element ifcmat:elementVolume ?volume .
                                ?mat a ifcmat:IfcMaterial .
                                ?mat ifcmat:fractionOfVolume ?fraction .
                                ?mat rdfs:label ?label1 .
                                BIND ( str(?label) AS ?label2 ) .
                                BIND ( str(?label1) AS ?label3 ) .
                                FILTER (?label2 = ?label3 ) .
                                BIND ((?fraction * ?volume ) AS ?matvol ) .
                                BIND ((?density * ?matvol ) AS ?weight ) .
                                BIND ((?weight * ?ecequivalent ) AS ?equiv ) .
                                }
                                GROUP BY ?guid
                        """)

        with open(file2_csv, 'wb') as testfile2:
            for r in query_element:
                csv_writer = csv.writer(testfile2, delimiter=';')
               # csv_writer.writerow("Material", "EC Equivalent (CO2e)")
                csv_writer.writerow(r)

        testfile1.close()
        testfile2.close()

    #Color critical and non critical components
    def color_components(self):
        rdfextras.registerplugins()
        materialVolume = "MaterialVolume.ttl"
        g = rdflib.Graph()
        g.parse(str(self.RDFfilename), format="turtle")
        g.parse(materialVolume, format="turtle")

        query_color = g.query("""PREFIX ifcmat:
<http://www.semanticweb.org/marianiki/ifcmat#>
                                PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-
ns#>
                                PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
                                PREFIX xml: <http://www.w3.org/XML/1998/namespace>
                                PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
                                PREFIX ecom:
<http://www.semanticweb.org/marianiki/ecom#>
                                SELECT ?guid (SUM(?equiv) AS ?equivalentelem)
WHERE{?material a ecom:ICEMaterial .
                                ?material rdfs:label ?label .
                                ?material ecom:density ?density .
                                ?material ecom:hasECEquivalent ?ecequivalent .
                                ?element a ifcmat:IfcBuildingElement .
                                ?element ifcmat:hasGUID ?guid .
                                ?element ifcmat:isAssociatedTo ?mat .
                                ?element ifcmat:elementVolume ?volume .
                                ?mat a ifcmat:IfcMaterial .
                                ?mat ifcmat:fractionOfVolume ?fraction .
                                ?mat rdfs:label ?label1 .
                                BIND ( str(?label) AS ?label2 ) .
                                BIND ( str(?label1) AS ?label3 ) .
                                FILTER (?label2 = ?label3 ) .
                                BIND ((?fraction * ?volume ) AS ?matvol ) .
                                BIND ((?density * ?matvol ) AS ?weight ) .
                                BIND ((?weight * ?ecequivalent ) AS ?equiv ) .
                                }
                                GROUP BY ?guid
                        """)

        critical_components_tmp = []
        critical_components = []
        for row in query_color:
            critical_components_tmp.append( [ row[0], row[1] ] )
```

```
        for data in critical_components_tmp:
            if float( data[1] ) > 500.0:
                thing = str( data[0] ).replace("[u'", "").replace("']", "")
                critical_components.append( thing )

        for element in self.ifc_file.by_type("IfcBuildingElement"):
            globalId = str(element.GlobalId).replace("[u'", "").replace("']", "")

            if globalId in critical_components:
                #print element.GlobalId
                print("Red")
                if element.Representation:

                    self.canvas.ColorWhenElementNotAcceptable(globalId)
            else:
                print("Green")

                self.canvas.ColorWhenElementAcceptable(globalId)



    def closeEvent(self, event):
        result = QtGui.QMessageBox.question(self,
                                                    "Confirm Exit",
                                                    "Are you sure you want to exit ?",
                                                    QtGui.QMessageBox.Yes |
QtGui.QMessageBox.No)
        event.ignore()

        if result == QtGui.QMessageBox.Yes:
            event.accept()

init = initUI()
```

Appendix V: Partial RDF datasets of the IFC associated information

Following, partial RDF triples of the generated datasets are given for the 4 IFC models, for which the particular aspect of the script (i.e. IFC information retrieval) was validated.

1. Duplex model

```
@prefix ifcmat: <http://www.semanticweb.org/marianiki/ifcmat#> .
@prefix rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#> .
@prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#> .
@prefix xml: <http://www.w3.org/XML/1998/namespace> .
@prefix xsd: <http://www.w3.org/2001/XMLSchema#> .

<http://www.semanticweb.org/marianiki/ifcmat#0dxE1Sy6nDqfpDb5vIMN_Z> a ifcmat:IfcBuildingElement ;
   ifcmat:elementName "Basic Wall:Interior - Furring (152 mm Stud):194166"^^xsd:string ;
   ifcmat:elementVolume "1.6408704"^^xsd:float ;
   ifcmat:hasGUID "0dxE1Sy6nDqfpDb5vIMN_Z"^^xsd:string ;
   ifcmat:isAssociatedTo ifcmat:Mat01_0dxE1Sy6nDqfpDb5vIMN_Z,
      ifcmat:Mat02_0dxE1Sy6nDqfpDb5vIMN_Z .

<http://www.semanticweb.org/marianiki/ifcmat#0dxE1Sy6nDqfpDb5vIMNiA> a ifcmat:IfcBuildingElement ;
   ifcmat:elementName "Basic Wall:Interior - Furring (152 mm Stud):193247"^^xsd:string ;
   ifcmat:elementVolume "1.6408704"^^xsd:float ;
   ifcmat:hasGUID "0dxE1Sy6nDqfpDb5vIMNiA"^^xsd:string ;
   ifcmat:isAssociatedTo ifcmat:Mat01_0dxE1Sy6nDqfpDb5vIMNiA,
      ifcmat:Mat02_0dxE1Sy6nDqfpDb5vIMNiA .

<http://www.semanticweb.org/marianiki/ifcmat#0iEHWY1$XA8eQeeULq4jDb> a ifcmat:IfcBuildingElement ;
   ifcmat:elementName "Basic Wall:Interior - Furring (152 mm Stud):190774"^^xsd:string ;
   ifcmat:elementVolume "0.9750078"^^xsd:float ;
   ifcmat:hasGUID "0iEHWY1$XA8eQeeULq4jDb"^^xsd:string ;
   ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0iEHWY1$XA8eQeeULq4jDb>,
      <http://www.semanticweb.org/marianiki/ifcmat#Mat02_0iEHWY1$XA8eQeeULq4jDb> .

<http://www.semanticweb.org/marianiki/ifcmat#0iEHWY1$XA8eQeeULq4jE6> a ifcmat:IfcBuildingElement ;
   ifcmat:elementName "Basic Wall:Interior - Furring (152 mm Stud):190933"^^xsd:string ;
   ifcmat:elementVolume "1.78475284"^^xsd:float ;
   ifcmat:hasGUID "0iEHWY1$XA8eQeeULq4jE6"^^xsd:string ;
   ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0iEHWY1$XA8eQeeULq4jE6>,
      <http://www.semanticweb.org/marianiki/ifcmat#Mat02_0iEHWY1$XA8eQeeULq4jE6> .

<http://www.semanticweb.org/marianiki/ifcmat#0iEHWY1$XA8eQeeULq4jZ1> a ifcmat:IfcBuildingElement ;
   ifcmat:elementName "Basic Wall:Interior - Furring (152 mm Stud):189074"^^xsd:string ;
   ifcmat:elementVolume "1.84932852"^^xsd:float ;
   ifcmat:hasGUID "0iEHWY1$XA8eQeeULq4jZ1"^^xsd:string ;
   ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0iEHWY1$XA8eQeeULq4jZ1>,
      <http://www.semanticweb.org/marianiki/ifcmat#Mat02_0iEHWY1$XA8eQeeULq4jZ1> .

<http://www.semanticweb.org/marianiki/ifcmat#0iEHWY1$XA8eQeeULq4j_U> a ifcmat:IfcBuildingElement ;
   ifcmat:elementName "Basic Wall:Interior - Furring (152 mm Stud):189901"^^xsd:string ;
   ifcmat:elementVolume "1.0097816"^^xsd:float ;
   ifcmat:hasGUID "0iEHWY1$XA8eQeeULq4j_U"^^xsd:string ;
   ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0iEHWY1$XA8eQeeULq4j_U>,
      <http://www.semanticweb.org/marianiki/ifcmat#Mat02_0iEHWY1$XA8eQeeULq4j_U> .

<http://www.semanticweb.org/marianiki/ifcmat#0iEHWY1$XA8eQeeULq4jpl> a ifcmat:IfcBuildingElement ;
   ifcmat:elementName "Basic Wall:Interior - Partition (92mm Stud):190140"^^xsd:string ;
   ifcmat:elementVolume "0.50462048"^^xsd:float ;
   ifcmat:hasGUID "0iEHWY1$XA8eQeeULq4jpl"^^xsd:string ;
   ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0iEHWY1$XA8eQeeULq4jpl>,
      <http://www.semanticweb.org/marianiki/ifcmat#Mat02_0iEHWY1$XA8eQeeULq4jpl>,
      <http://www.semanticweb.org/marianiki/ifcmat#Mat03_0iEHWY1$XA8eQeeULq4jpl> .

<http://www.semanticweb.org/marianiki/ifcmat#0jf0rYHfX3RAB3bSIRjmmy> a ifcmat:IfcBuildingElement ;
   ifcmat:elementName "Basic Wall:Exterior - Brick on Block:184944"^^xsd:string ;
   ifcmat:elementVolume "2.2347864"^^xsd:float ;
   ifcmat:hasGUID "0jf0rYHfX3RAB3bSIRjmmy"^^xsd:string ;
```

```
    ifcmat:isAssociatedTo ifcmat:Mat01_0jf0rYHfX3RAB3bSIRjmmy,
        ifcmat:Mat02_0jf0rYHfX3RAB3bSIRjmmy,
        ifcmat:Mat03_0jf0rYHfX3RAB3bSIRjmmy,
        ifcmat:Mat04_0jf0rYHfX3RAB3bSIRjmmy,
        ifcmat:Mat05_0jf0rYHfX3RAB3bSIRjmmy,
        ifcmat:Mat06_0jf0rYHfX3RAB3bSIRjmmy .

<http://www.semanticweb.org/marianiki/ifcmat#0jf0rYHfX3RAB3bSIRjmoa> a ifcmat:IfcBuildingElement ;
    ifcmat:elementName "Basic Wall:Exterior - Brick on Block:185064"^^xsd:string ;
    ifcmat:elementVolume "2.128887999"^^xsd:float ;
    ifcmat:hasGUID "0jf0rYHfX3RAB3bSIRjmoa"^^xsd:string ;

ifcmat:MatLayer01_0dxE1Sy6nDqfpDb5vIMN_Z a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat01_0dxE1Sy6nDqfpDb5vIMN_Z ;
    ifcmat:layerThickness "0.136"^^xsd:float .

ifcmat:MatLayer01_0dxE1Sy6nDqfpDb5vIMNiA a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat01_0dxE1Sy6nDqfpDb5vIMNiA ;
    ifcmat:layerThickness "0.136"^^xsd:float .

<http://www.semanticweb.org/marianiki/ifcmat#MatLayer01_0iEHWY1$XA8eQeeULq4jDb> a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0iEHWY1$XA8eQeeULq4jDb> ;
    ifcmat:layerThickness "0.136"^^xsd:float .

<http://www.semanticweb.org/marianiki/ifcmat#MatLayer01_0iEHWY1$XA8eQeeULq4jE6> a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0iEHWY1$XA8eQeeULq4jE6> ;
    ifcmat:layerThickness "0.136"^^xsd:float .

<http://www.semanticweb.org/marianiki/ifcmat#MatLayer01_0iEHWY1$XA8eQeeULq4jZ1> a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0iEHWY1$XA8eQeeULq4jZ1> ;
    ifcmat:layerThickness "0.136"^^xsd:float .

<http://www.semanticweb.org/marianiki/ifcmat#MatLayer01_0iEHWY1$XA8eQeeULq4j_U> a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0iEHWY1$XA8eQeeULq4j_U> ;
    ifcmat:layerThickness "0.136"^^xsd:float .

<http://www.semanticweb.org/marianiki/ifcmat#MatLayer01_0iEHWY1$XA8eQeeULq4jpl> a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0iEHWY1$XA8eQeeULq4jpl> ;
    ifcmat:layerThickness "0.016"^^xsd:float .

ifcmat:MatLayer01_0jf0rYHfX3RAB3bSIRjmmy a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat01_0jf0rYHfX3RAB3bSIRjmmy ;
    ifcmat:layerThickness "0.092"^^xsd:float .

ifcmat:MatLayer01_0jf0rYHfX3RAB3bSIRjmoa a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat01_0jf0rYHfX3RAB3bSIRjmoa ;
    ifcmat:layerThickness "0.092"^^xsd:float .

ifcmat:MatLayer01_0jf0rYHfX3RAB3bSIRjmpw a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat01_0jf0rYHfX3RAB3bSIRjmpw ;
    ifcmat:layerThickness "0.092"^^xsd:float .

ifcmat:MatLayer01_0jf0rYHfX3RAB3bSIRjmr1 a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat01_0jf0rYHfX3RAB3bSIRjmr1 ;
    ifcmat:layerThickness "0.092"^^xsd:float .

ifcmat:MatLayer01_0jf0rYHfX3RAB3bSIRjmxl a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat01_0jf0rYHfX3RAB3bSIRjmxl ;
    ifcmat:layerThickness "0.064"^^xsd:float .

ifcmat:MatLayer01_1CZILmCaHETO8tf3SgGEWh a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat01_1CZILmCaHETO8tf3SgGEWh ;
    ifcmat:layerThickness "0.15"^^xsd:float .

ifcmat:MatLayer01_1CZILmCaHETO8tf3SgGEXu a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat01_1CZILmCaHETO8tf3SgGEXu ;
    ifcmat:layerThickness "0.15"^^xsd:float .

<http://www.semanticweb.org/marianiki/ifcmat#MatLayer01_1aj$VJZFn2TxepZUBcKpZw> a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial <http://www.semanticweb.org/marianiki/ifcmat#Mat01_1aj$VJZFn2TxepZUBcKpZw> ;
    ifcmat:layerThickness "0.016"^^xsd:float .
```

```
<http://www.semanticweb.org/marianiki/ifcmat#MatLayer01_1aj$VJZFn2TxepZUBcKpee> a ifcmat:IfcMaterialLayer ;
   ifcmat:hasMaterial <http://www.semanticweb.org/marianiki/ifcmat#Mat01_1aj$VJZFn2TxepZUBcKpee> ;
   ifcmat:layerThickness "0.016"^^xsd:float .

ifcmat:Mat01_0dxE1Sy6nDqfpDb5vIMN_Z a ifcmat:IfcMaterial ;
   rdfs:label "Metal - Stud Layer"^^xsd:string ;
   ifcmat:fractionOfVolume "0.894736842105"^^xsd:float .

ifcmat:Mat01_0dxE1Sy6nDqfpDb5vIMNiA a ifcmat:IfcMaterial ;
   rdfs:label "Metal - Stud Layer"^^xsd:string ;
   ifcmat:fractionOfVolume "0.894736842105"^^xsd:float .

<http://www.semanticweb.org/marianiki/ifcmat#Mat01_0iEHWY1$XA8eQeeULq4jDb> a ifcmat:IfcMaterial ;
   rdfs:label "Metal - Stud Layer"^^xsd:string ;
   ifcmat:fractionOfVolume "0.894736842105"^^xsd:float .

<http://www.semanticweb.org/marianiki/ifcmat#Mat01_0iEHWY1$XA8eQeeULq4jE6> a ifcmat:IfcMaterial ;
   rdfs:label "Metal - Stud Layer"^^xsd:string ;
   ifcmat:fractionOfVolume "0.894736842105"^^xsd:float .

<http://www.semanticweb.org/marianiki/ifcmat#Mat01_0iEHWY1$XA8eQeeULq4jZ1> a ifcmat:IfcMaterial ;
   rdfs:label "Metal - Stud Layer"^^xsd:string ;
   ifcmat:fractionOfVolume "0.894736842105"^^xsd:float .

<http://www.semanticweb.org/marianiki/ifcmat#Mat01_0iEHWY1$XA8eQeeULq4j_U> a ifcmat:IfcMaterial ;
   rdfs:label "Metal - Stud Layer"^^xsd:string ;
   ifcmat:fractionOfVolume "0.894736842105"^^xsd:float .

<http://www.semanticweb.org/marianiki/ifcmat#Mat01_0iEHWY1$XA8eQeeULq4jpl> a ifcmat:IfcMaterial ;
   rdfs:label "Plasterboard"^^xsd:string ;
   ifcmat:fractionOfVolume "0.129032258065"^^xsd:float .

ifcmat:Mat01_0jf0rYHfX3RAB3bSIRjmmy a ifcmat:IfcMaterial ;
   rdfs:label "Masonry - Brick"^^xsd:string ;
   ifcmat:fractionOfVolume "0.220623501199"^^xsd:float .

ifcmat:Mat01_0jf0rYHfX3RAB3bSIRjmoa a ifcmat:IfcMaterial ;
   rdfs:label "Masonry - Brick"^^xsd:string ;
   ifcmat:fractionOfVolume "0.220623501199"^^xsd:float .

ifcmat:Mat01_0jf0rYHfX3RAB3bSIRjmpw a ifcmat:IfcMaterial ;
   rdfs:label "Masonry - Brick"^^xsd:string ;
   ifcmat:fractionOfVolume "0.220623501199"^^xsd:float .

ifcmat:Mat01_0jf0rYHfX3RAB3bSIRjmr1 a ifcmat:IfcMaterial ;
   rdfs:label "Masonry - Brick"^^xsd:string ;
   ifcmat:fractionOfVolume "0.220623501199"^^xsd:float .

ifcmat:Mat01_0jf0rYHfX3RAB3bSIRjmxl a ifcmat:IfcMaterial ;
   rdfs:label "Site - Grass"^^xsd:string ;
   ifcmat:fractionOfVolume "0.140043763676"^^xsd:float .

ifcmat:Mat01_1CZILmCaHETO8tf3SgGEWh a ifcmat:IfcMaterial ;
   rdfs:label "Concrete - Cast In Situ"^^xsd:string ;
   ifcmat:fractionOfVolume "1.0"^^xsd:float .

ifcmat:Mat01_1CZILmCaHETO8tf3SgGEXu a ifcmat:IfcMaterial ;
   rdfs:label "Concrete - Cast In Situ"^^xsd:string ;
   ifcmat:fractionOfVolume "1.0"^^xsd:float .

<http://www.semanticweb.org/marianiki/ifcmat#Mat01_1aj$VJZFn2TxepZUBcKpZw> a ifcmat:IfcMaterial ;
   rdfs:label "Plasterboard"^^xsd:string ;
   ifcmat:fractionOfVolume "0.129032258065"^^xsd:float .

<http://www.semanticweb.org/marianiki/ifcmat#Mat01_1aj$VJZFn2TxepZUBcKpee> a ifcmat:IfcMaterial ;
   rdfs:label "Plasterboard"^^xsd:string ;
   ifcmat:fractionOfVolume "0.129032258065"^^xsd:float .

<http://www.semanticweb.org/marianiki/ifcmat#Mat01_1aj$VJZFn2TxepZUBcKphf> a ifcmat:IfcMaterial ;
   rdfs:label "Plasterboard"^^xsd:string ;
```

```
   ifcmat:fractionOfVolume "0.129032258065"^^xsd:float .

<http://www.semanticweb.org/marianiki/ifcmat#Mat01_1aj$VJZFn2TxepZUBcKpvt> a ifcmat:IfcMaterial ;
   rdfs:label "Plasterboard"^^xsd:string ;
   ifcmat:fractionOfVolume "0.129032258065"^^xsd:float .

ifcmat:Mat01_1hOSvn6df7F8_7GcBWlRqU a ifcmat:IfcMaterial ;
   rdfs:label "Wood - Sheathing - plywood"^^xsd:string ;
   ifcmat:fractionOfVolume "0.0622950819672"^^xsd:float .

ifcmat:Mat01_1hOSvn6df7F8_7GcBWlRrM a ifcmat:IfcMaterial ;
   rdfs:label "Wood - Sheathing - plywood"^^xsd:string ;
   ifcmat:fractionOfVolume "0.0622950819672"^^xsd:float .

<http://www.semanticweb.org/marianiki/ifcmat#Mat01_2O2Fr$t4X7Zf8NOew3FK04> a ifcmat:IfcMaterial ;
   rdfs:label "Concrete - Cast In Situ"^^xsd:string ;
   ifcmat:fractionOfVolume "1.0"^^xsd:float .

<http://www.semanticweb.org/marianiki/ifcmat#Mat01_2O2Fr$t4X7Zf8NOew3FK1b> a ifcmat:IfcMaterial ;
   rdfs:label "Concrete - Cast In Situ"^^xsd:string ;
   ifcmat:fractionOfVolume "1.0"^^xsd:float .

<http://www.semanticweb.org/marianiki/ifcmat#Mat01_2O2Fr$t4X7Zf8NOew3FK3E> a ifcmat:IfcMaterial ;
   rdfs:label "Concrete - Cast In Situ"^^xsd:string ;
   ifcmat:fractionOfVolume "1.0"^^xsd:float .

<http://www.semanticweb.org/marianiki/ifcmat#Mat01_2O2Fr$t4X7Zf8NOew3FK4F> a ifcmat:IfcMaterial ;
   rdfs:label "Concrete"^^xsd:string ;
   ifcmat:fractionOfVolume "1.0"^^xsd:float .
```


2. 20160124OTC-Conference Center Model


```
@prefix ifcmat: <http://www.semanticweb.org/marianiki/ifcmat#> .
@prefix rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#> .
@prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#> .
@prefix xml: <http://www.w3.org/XML/1998/namespace> .
@prefix xsd: <http://www.w3.org/2001/XMLSchema#> .

<http://www.semanticweb.org/marianiki/ifcmat#0$0wWgDL56NO_bMed9R3xO> a ifcmat:IfcBuildingElement ;
   ifcmat:elementName "Floor:Commercial 1' 6\":311863"^^xsd:string ;
   ifcmat:elementVolume "39.4650866613"^^xsd:float ;
   ifcmat:hasGUID "0$0wWgDL56NO_bMed9R3xO"^^xsd:string ;
   ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$0wWgDL56NO_bMed9R3xO>,
      <http://www.semanticweb.org/marianiki/ifcmat#Mat02_0$0wWgDL56NO_bMed9R3xO>,
      <http://www.semanticweb.org/marianiki/ifcmat#Mat03_0$0wWgDL56NO_bMed9R3xO>,
      <http://www.semanticweb.org/marianiki/ifcmat#Mat04_0$0wWgDL56NO_bMed9R3xO>,
      <http://www.semanticweb.org/marianiki/ifcmat#Mat05_0$0wWgDL56NO_bMed9R3xO> .

<http://www.semanticweb.org/marianiki/ifcmat#0$CxV2tzr2EO_RSzEkoxKF> a ifcmat:IfcBuildingElement ;
   ifcmat:elementName "System Panel:Interior Center Glazed:318056"^^xsd:string ;
   ifcmat:elementVolume "1.06236495508"^^xsd:float ;
   ifcmat:hasGUID "0$CxV2tzr2EO_RSzEkoxKF"^^xsd:string ;
   ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$CxV2tzr2EO_RSzEkoxKF> .

<http://www.semanticweb.org/marianiki/ifcmat#0$CxV2tzr2EO_RSzEkoxKI> a ifcmat:IfcBuildingElement ;
   ifcmat:elementName "System Panel:Interior Center Glazed:318069"^^xsd:string ;
   ifcmat:elementVolume "1.06236495508"^^xsd:float ;
   ifcmat:hasGUID "0$CxV2tzr2EO_RSzEkoxKI"^^xsd:string ;
   ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$CxV2tzr2EO_RSzEkoxKI> .

<http://www.semanticweb.org/marianiki/ifcmat#0$CxV2tzr2EO_RSzEkoxKJ> a ifcmat:IfcBuildingElement ;
   ifcmat:elementName "System Panel:Interior Center Glazed:318068"^^xsd:string ;
   ifcmat:elementVolume "1.06236495508"^^xsd:float ;
   ifcmat:hasGUID "0$CxV2tzr2EO_RSzEkoxKJ"^^xsd:string ;
   ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$CxV2tzr2EO_RSzEkoxKJ> .

<http://www.semanticweb.org/marianiki/ifcmat#0$CxV2tzr2EO_RSzEkoxKK> a ifcmat:IfcBuildingElement ;
   ifcmat:elementName "System Panel:Interior Center Glazed:318067"^^xsd:string ;
   ifcmat:elementVolume "1.06236495508"^^xsd:float ;
```

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  ifcmat:hasGUID "0$CxV2tzr2EO_RSzEkoxKK"^^xsd:string ;
  ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$CxV2tzr2EO_RSzEkoxKK> .

<http://www.semanticweb.org/marianiki/ifcmat#0$CxV2tzr2EO_RSzEkoxKN> a ifcmat:IfcBuildingElement ;
  ifcmat:elementName "System Panel:Interior Center Glazed:318064"^^xsd:string ;
  ifcmat:elementVolume "1.06236495508"^^xsd:float ;
  ifcmat:hasGUID "0$CxV2tzr2EO_RSzEkoxKN"^^xsd:string ;
  ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$CxV2tzr2EO_RSzEkoxKN> .

<http://www.semanticweb.org/marianiki/ifcmat#0$CxV2tzr2EO_RSzEkoxQy> a ifcmat:IfcBuildingElement ;
  ifcmat:elementName "Railing:Guardrail - Glass Panel v4:317915"^^xsd:string ;
  ifcmat:elementVolume "1.33446135325"^^xsd:float ;
  ifcmat:hasGUID "0$CxV2tzr2EO_RSzEkoxQy"^^xsd:string ;
  ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$CxV2tzr2EO_RSzEkoxQy> .

<http://www.semanticweb.org/marianiki/ifcmat#0$CxV2tzr2EO_RSzEkoxRj> a ifcmat:IfcBuildingElement ;
  ifcmat:elementName "Railing:Guardrail - Glass Panel v4:317834"^^xsd:string ;
  ifcmat:elementVolume "1.33446135325"^^xsd:float ;
  ifcmat:hasGUID "0$CxV2tzr2EO_RSzEkoxRj"^^xsd:string ;
  ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$CxV2tzr2EO_RSzEkoxRj> .

<http://www.semanticweb.org/marianiki/ifcmat#00HbM2VVj6cPVbDKcVXmh0> a ifcmat:IfcBuildingElement ;
  ifcmat:elementName "Basic Wall:Interior - 6 1/8\" Partition (2-hr):969769"^^xsd:string ;
  ifcmat:elementVolume "2.77776097673"^^xsd:float ;
  ifcmat:hasGUID "00HbM2VVj6cPVbDKcVXmh0"^^xsd:string ;
  ifcmat:isAssociatedTo ifcmat:Mat01_00HbM2VVj6cPVbDKcVXmh0,
    ifcmat:Mat02_00HbM2VVj6cPVbDKcVXmh0,
    ifcmat:Mat03_00HbM2VVj6cPVbDKcVXmh0,
    ifcmat:Mat04_00HbM2VVj6cPVbDKcVXmh0,
    ifcmat:Mat05_00HbM2VVj6cPVbDKcVXmh0 .

<http://www.semanticweb.org/marianiki/ifcmat#00HbM2VVj6cPVbDKcVXmh9> a ifcmat:IfcBuildingElement ;
  ifcmat:elementName "Basic Wall:Interior - 6 1/8\" Partition (2-hr):969760"^^xsd:string ;
  ifcmat:elementVolume "2.77776097673"^^xsd:float ;
  ifcmat:hasGUID "00HbM2VVj6cPVbDKcVXmh9"^^xsd:string ;
  ifcmat:isAssociatedTo ifcmat:Mat01_00HbM2VVj6cPVbDKcVXmh9,
    ifcmat:Mat02_00HbM2VVj6cPVbDKcVXmh9,
    ifcmat:Mat03_00HbM2VVj6cPVbDKcVXmh9,
    ifcmat:Mat04_00HbM2VVj6cPVbDKcVXmh9,
    ifcmat:Mat05_00HbM2VVj6cPVbDKcVXmh9 .

<http://www.semanticweb.org/marianiki/ifcmat#00HbM2VVj6cPVbDKcVXmh_> a ifcmat:IfcBuildingElement ;
  ifcmat:elementName "Basic Wall:Interior - 6 1/8\" Partition (2-hr):969751"^^xsd:string ;
  ifcmat:elementVolume "2.77776097673"^^xsd:float ;
  ifcmat:hasGUID "00HbM2VVj6cPVbDKcVXmh_"^^xsd:string ;
  ifcmat:isAssociatedTo ifcmat:Mat01_00HbM2VVj6cPVbDKcVXmh_,
    ifcmat:Mat02_00HbM2VVj6cPVbDKcVXmh_,
    ifcmat:Mat03_00HbM2VVj6cPVbDKcVXmh_,
    ifcmat:Mat04_00HbM2VVj6cPVbDKcVXmh_,
    ifcmat:Mat05_00HbM2VVj6cPVbDKcVXmh_ .

<http://www.semanticweb.org/marianiki/ifcmat#00HbM2VVj6cPVbDKcVXmhd> a ifcmat:IfcBuildingElement ;
  ifcmat:elementName "Basic Wall:Interior - 6 1/8\" Partition (2-hr):969742"^^xsd:string ;
  ifcmat:elementVolume "2.77776097673"^^xsd:float ;
  ifcmat:hasGUID "00HbM2VVj6cPVbDKcVXmhd"^^xsd:string ;
  ifcmat:isAssociatedTo ifcmat:Mat01_00HbM2VVj6cPVbDKcVXmhd,
    ifcmat:Mat02_00HbM2VVj6cPVbDKcVXmhd,
    ifcmat:Mat03_00HbM2VVj6cPVbDKcVXmhd,
    ifcmat:Mat04_00HbM2VVj6cPVbDKcVXmhd,
    ifcmat:Mat05_00HbM2VVj6cPVbDKcVXmhd .

<http://www.semanticweb.org/marianiki/ifcmat#00HbM2VVj6cPVbDKcVXmhi> a ifcmat:IfcBuildingElement ;
  ifcmat:elementName "Basic Wall:Interior - 6 1/8\" Partition (2-hr):969733"^^xsd:string ;
  ifcmat:elementVolume "2.77776097673"^^xsd:float ;
  ifcmat:hasGUID "00HbM2VVj6cPVbDKcVXmhi"^^xsd:string ;
  ifcmat:isAssociatedTo ifcmat:Mat01_00HbM2VVj6cPVbDKcVXmhi,
    ifcmat:Mat02_00HbM2VVj6cPVbDKcVXmhi,
    ifcmat:Mat03_00HbM2VVj6cPVbDKcVXmhi,
    ifcmat:Mat04_00HbM2VVj6cPVbDKcVXmhi,
    ifcmat:Mat05_00HbM2VVj6cPVbDKcVXmhi .
```

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<http://www.semanticweb.org/marianiki/ifcmat#00HbM2VVj6cPVbDKcVXmrR> a ifcmat:IfcBuildingElement ;
    ifcmat:elementName "Basic Wall:Interior - 6 1/8\" Partition (2-hr):969650"^^xsd:string ;
    ifcmat:elementVolume "2.77776097673"^^xsd:float ;
    ifcmat:hasGUID "00HbM2VVj6cPVbDKcVXmrR"^^xsd:string ;
    ifcmat:isAssociatedTo ifcmat:Mat01_00HbM2VVj6cPVbDKcVXmrR,
        ifcmat:Mat02_00HbM2VVj6cPVbDKcVXmrR,
        ifcmat:Mat03_00HbM2VVj6cPVbDKcVXmrR,
        ifcmat:Mat04_00HbM2VVj6cPVbDKcVXmrR,
        ifcmat:Mat05_00HbM2VVj6cPVbDKcVXmrR .

<http://www.semanticweb.org/marianiki/ifcmat#00HbM2VVj6cPVbDKcVXmtz> a ifcmat:IfcBuildingElement ;
    ifcmat:elementName "Basic Wall:Interior - 6 1/8\" Partition (2-hr):969492"^^xsd:string ;
    ifcmat:elementVolume "19.2979862589"^^xsd:float ;
    ifcmat:hasGUID "00HbM2VVj6cPVbDKcVXmtz"^^xsd:string ;
    ifcmat:isAssociatedTo ifcmat:Mat01_00HbM2VVj6cPVbDKcVXmtz,
        ifcmat:Mat02_00HbM2VVj6cPVbDKcVXmtz,
        ifcmat:Mat03_00HbM2VVj6cPVbDKcVXmtz,
        ifcmat:Mat04_00HbM2VVj6cPVbDKcVXmtz,
        ifcmat:Mat05_00HbM2VVj6cPVbDKcVXmtz .

<http://www.semanticweb.org/marianiki/ifcmat#00I$S1B218hPnFO57M13R$> a ifcmat:IfcBuildingElement ;
    ifcmat:elementName "Stair:Metal Pan Stair:439494:2"^^xsd:string ;
    ifcmat:elementVolume "0.904541352201"^^xsd:float ;
    ifcmat:hasGUID "00I$S1B218hPnFO57M13R$"^^xsd:string ;
    ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_00I$S1B218hPnFO57M13R$>,
        <http://www.semanticweb.org/marianiki/ifcmat#Mat02_00I$S1B218hPnFO57M13R$> .

<http://www.semanticweb.org/marianiki/ifcmat#02K6rBbIv8nOWIjDKFN3qX> a ifcmat:IfcBuildingElement ;
    ifcmat:elementName "Stair:Metal Pan Stair:439494:2"^^xsd:string ;
    ifcmat:elementVolume "0.904541352201"^^xsd:float ;
    ifcmat:hasGUID "02K6rBbIv8nOWIjDKFN3qX"^^xsd:string ;
    ifcmat:isAssociatedTo ifcmat:Mat01_02K6rBbIv8nOWIjDKFN3qX .

<http://www.semanticweb.org/marianiki/ifcmat#03B4OLWev3cxv9li9U$CbU> a ifcmat:IfcBuildingElement ;
    ifcmat:elementName "Railing:Handrail - Glass Panel 3:439926"^^xsd:string ;
    ifcmat:elementVolume "1.33446135325"^^xsd:float ;
    ifcmat:hasGUID "03B4OLWev3cxv9li9U$CbU"^^xsd:string ;
    ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_03B4OLWev3cxv9li9U$CbU> .

<http://www.semanticweb.org/marianiki/ifcmat#043A3oSoH10vw4_RJrAoeC> a ifcmat:IfcBuildingElement ;
    ifcmat:elementName "Basic Wall:Interior - 4 1/2\" Partition NonRated:163430"^^xsd:string ;
    ifcmat:elementVolume "0.15596388162"^^xsd:float ;
    ifcmat:hasGUID "043A3oSoH10vw4_RJrAoeC"^^xsd:string ;
    ifcmat:isAssociatedTo ifcmat:Mat01_043A3oSoH10vw4_RJrAoeC,
        ifcmat:Mat02_043A3oSoH10vw4_RJrAoeC,
        ifcmat:Mat03_043A3oSoH10vw4_RJrAoeC .

<http://www.semanticweb.org/marianiki/ifcmat#043A3oSoH10vw4_RJrAoeT> a ifcmat:IfcBuildingElement ;
    ifcmat:elementName "Basic Wall:Interior - 4 1/2\" Partition NonRated:163447"^^xsd:string ;
    ifcmat:elementVolume "0.350918733645"^^xsd:float ;
    ifcmat:hasGUID "043A3oSoH10vw4_RJrAoeT"^^xsd:string ;
    ifcmat:isAssociatedTo ifcmat:Mat01_043A3oSoH10vw4_RJrAoeT,
        ifcmat:Mat02_043A3oSoH10vw4_RJrAoeT,
        ifcmat:Mat03_043A3oSoH10vw4_RJrAoeT .

<http://www.semanticweb.org/marianiki/ifcmat#043A3oSoH10vw4_RJrAoed> a ifcmat:IfcBuildingElement ;
    ifcmat:elementName "Basic Wall:Interior - 4 1/2\" Partition NonRated:163405"^^xsd:string ;
    ifcmat:elementVolume "0.136468396417"^^xsd:float ;
    ifcmat:hasGUID "043A3oSoH10vw4_RJrAoed"^^xsd:string ;
    ifcmat:isAssociatedTo ifcmat:Mat01_043A3oSoH10vw4_RJrAoed,
        ifcmat:Mat02_043A3oSoH10vw4_RJrAoed,
        ifcmat:Mat03_043A3oSoH10vw4_RJrAoed .


ifcmat:MatLayer01_08oS0cmBf6I8rmvq1fCWG8 a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat01_08oS0cmBf6I8rmvq1fCWG8 ;
    ifcmat:layerThickness "0.0520833333333"^^xsd:float .

ifcmat:MatLayer01_08oS0cmBf6I8rmvq1fCWG9 a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat01_08oS0cmBf6I8rmvq1fCWG9 ;
    ifcmat:layerThickness "0.0520833333333"^^xsd:float .
```

```
ifcmat:MatLayer01_08oS0cmBf6I8rmvq1fCWGB a ifcmat:IfcMaterialLayer ;
   ifcmat:hasMaterial ifcmat:Mat01_08oS0cmBf6I8rmvq1fCWGB ;
   ifcmat:layerThickness "0.0520833333333"^^xsd:float .

ifcmat:MatLayer01_08oS0cmBf6I8rmvq1fCWGE a ifcmat:IfcMaterialLayer ;
   ifcmat:hasMaterial ifcmat:Mat01_08oS0cmBf6I8rmvq1fCWGE ;
   ifcmat:layerThickness "0.0520833333333"^^xsd:float .

ifcmat:MatLayer01_08oS0cmBf6I8rmvq5fCWG8 a ifcmat:IfcMaterialLayer ;
   ifcmat:hasMaterial ifcmat:Mat01_08oS0cmBf6I8rmvq5fCWG8 ;
   ifcmat:layerThickness "0.0520833333333"^^xsd:float .

ifcmat:MatLayer01_08oS0cmBf6I8rmvq5fCWG9 a ifcmat:IfcMaterialLayer ;
   ifcmat:hasMaterial ifcmat:Mat01_08oS0cmBf6I8rmvq5fCWG9 ;
   ifcmat:layerThickness "0.0520833333333"^^xsd:float .

ifcmat:MatLayer01_08oS0cmBf6I8rmvq5fCWGB a ifcmat:IfcMaterialLayer ;
   ifcmat:hasMaterial ifcmat:Mat01_08oS0cmBf6I8rmvq5fCWGB ;
   ifcmat:layerThickness "0.0520833333333"^^xsd:float .

ifcmat:MatLayer01_08oS0cmBf6I8rmvq5fCWGE a ifcmat:IfcMaterialLayer ;
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ifcmat:MatLayer01_08oS0cmBf6I8rmvq9fCWG8 a ifcmat:IfcMaterialLayer ;
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   ifcmat:layerThickness "0.0520833333333"^^xsd:float .

ifcmat:MatLayer01_08oS0cmBf6I8rmvq9fCWG9 a ifcmat:IfcMaterialLayer ;
   ifcmat:hasMaterial ifcmat:Mat01_08oS0cmBf6I8rmvq9fCWG9 ;
   ifcmat:layerThickness "0.0520833333333"^^xsd:float .

ifcmat:MatLayer01_08oS0cmBf6I8rmvq9fCWGB a ifcmat:IfcMaterialLayer ;
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ifcmat:MatLayer01_08oS0cmBf6I8rmvqDfCWG8 a ifcmat:IfcMaterialLayer ;
   ifcmat:hasMaterial ifcmat:Mat01_08oS0cmBf6I8rmvqDfCWG8 ;
   ifcmat:layerThickness "0.0520833333333"^^xsd:float .

ifcmat:MatLayer01_08oS0cmBf6I8rmvqDfCWG9 a ifcmat:IfcMaterialLayer ;
   ifcmat:hasMaterial ifcmat:Mat01_08oS0cmBf6I8rmvqDfCWG9 ;
   ifcmat:layerThickness "0.0520833333333"^^xsd:float .

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   ifcmat:layerThickness "0.0520833333333"^^xsd:float .

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ifcmat:MatLayer01_08oS0cmBf6I8rmvqLfCWG9 a ifcmat:IfcMaterialLayer ;
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   ifcmat:layerThickness "0.0520833333333"^^xsd:float .

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    ifcmat:layerThickness "0.0520833333333"^^xsd:float .

ifcmat:MatLayer01_08oS0cmBf6I8rmvqPfCWG9 a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat01_08oS0cmBf6I8rmvqPfCWG9 ;
    ifcmat:layerThickness "0.0520833333333"^^xsd:float .

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    ifcmat:hasMaterial ifcmat:Mat01_08oS0cmBf6I8rmvqPfCWGB ;
    ifcmat:layerThickness "0.0520833333333"^^xsd:float .

ifcmat:MatLayer01_08oS0cmBf6I8rmvqPfCWGE a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat01_08oS0cmBf6I8rmvqPfCWGE ;
    ifcmat:layerThickness "0.0520833333333"^^xsd:float .

ifcmat:MatLayer01_08oS0cmBf6I8rmvqTfCWG8 a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat01_08oS0cmBf6I8rmvqTfCWG8 ;
    ifcmat:layerThickness "0.0520833333333"^^xsd:float .

ifcmat:MatLayer01_08oS0cmBf6I8rmvqTfCWG9 a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat01_08oS0cmBf6I8rmvqTfCWG9 ;
    ifcmat:layerThickness "0.0520833333333"^^xsd:float .

ifcmat:MatLayer01_08oS0cmBf6I8rmvqTfCWGB a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat01_08oS0cmBf6I8rmvqTfCWGB ;
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    ifcmat:layerThickness "0.0520833333333"^^xsd:float .

ifcmat:MatLayer01_08oS0cmBf6I8rmvqnfCWG8 a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat01_08oS0cmBf6I8rmvqnfCWG8 ;
    ifcmat:layerThickness "0.0520833333333"^^xsd:float .

ifcmat:MatLayer01_08oS0cmBf6I8rmvqnfCWG9 a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat01_08oS0cmBf6I8rmvqnfCWG9 ;
    ifcmat:layerThickness "0.0520833333333"^^xsd:float .

ifcmat:MatLayer01_08oS0cmBf6I8rmvqnfCWGB a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat01_08oS0cmBf6I8rmvqnfCWGB ;
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    ifcmat:layerThickness "0.0520833333333"^^xsd:float .

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    ifcmat:layerThickness "0.0520833333333"^^xsd:float .

ifcmat:MatLayer01_08oS0cmBf6I8rmvqrfCWG9 a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat01_08oS0cmBf6I8rmvqrfCWG9 ;
    ifcmat:layerThickness "0.0520833333333"^^xsd:float .

ifcmat:MatLayer01_08oS0cmBf6I8rmvqrfCWGB a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat01_08oS0cmBf6I8rmvqrfCWGB ;
    ifcmat:layerThickness "0.0520833333333"^^xsd:float .

ifcmat:MatLayer01_08oS0cmBf6I8rmvqrfCWGE a ifcmat:IfcMaterialLayer ;
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    ifcmat:layerThickness "0.0520833333333"^^xsd:float .

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ifcmat:MatLayer01_08oS0cmBf6I8rmvqvfCWG9 a ifcmat:IfcMaterialLayer ;
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    ifcmat:layerThickness "0.0520833333333"^^xsd:float .

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    ifcmat:layerThickness "0.0520833333333"^^xsd:float .

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    ifcmat:layerThickness "0.0520833333333"^^xsd:float .

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    ifcmat:layerThickness "0.302083333333"^^xsd:float .

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ifcmat:Mat01_08oS0cmBf6I8rmvqzfCWGE a ifcmat:IfcMaterial ;
   rdfs:label "Finishes - Interior - GWB TypeX Layer1 of 2"^^xsd:string ;
   ifcmat:fractionOfVolume "0.1"^^xsd:float .

ifcmat:Mat01_0A_uwLmzDFwxF1KgW45KWS a ifcmat:IfcMaterial ;
   rdfs:label "Plaza Tile"^^xsd:string ;
   ifcmat:fractionOfVolume "0.0186335403727"^^xsd:float .

ifcmat:Mat01_0A_uwLmzDFwxF1KgW45KZ9 a ifcmat:IfcMaterial ;
   rdfs:label "Wood - Flooring Entry"^^xsd:string ;
   ifcmat:fractionOfVolume "0.0472440944882"^^xsd:float .

ifcmat:Mat01_0A_uwLmzDFwxF1KgW45Kgt a ifcmat:IfcMaterial ;
   rdfs:label "Wood - Flooring Entry"^^xsd:string ;
   ifcmat:fractionOfVolume "0.0472440944882"^^xsd:float .

ifcmat:Mat01_0A_uwLmzDFwxF1KgW45LLO a ifcmat:IfcMaterial ;
   rdfs:label "Glass"^^xsd:string ;
   ifcmat:fractionOfVolume "1"^^xsd:float .
```


3. 20160125Trapelo - Existing-Trapelo_Design_Intent Model


```
@prefix ifcmat: <http://www.semanticweb.org/marianiki/ifcmat#> .
@prefix rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#> .
@prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#> .
@prefix xml: <http://www.w3.org/XML/1998/namespace> .
@prefix xsd: <http://www.w3.org/2001/XMLSchema#> .

<http://www.semanticweb.org/marianiki/ifcmat#0$9XvkH910sOnMNxhKM4f0> a ifcmat:IfcBuildingElement ;
   ifcmat:elementName "HSS-Hollow Structural Section-Column:HSS6X6X5/16:789515"^^xsd:string ;
   ifcmat:elementVolume "0.0279718280816"^^xsd:float ;
   ifcmat:hasGUID "0$9XvkH910sOnMNxhKM4f0"^^xsd:string ;
   ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$9XvkH910sOnMNxhKM4f0> .

<http://www.semanticweb.org/marianiki/ifcmat#0$9XvkH910sOnMNxhKM4f1> a ifcmat:IfcBuildingElement ;
   ifcmat:elementName "HSS-Hollow Structural Section-Column:HSS6X6X5/16:789514"^^xsd:string ;
   ifcmat:elementVolume "0.0279718280816"^^xsd:float ;
   ifcmat:hasGUID "0$9XvkH910sOnMNxhKM4f1"^^xsd:string ;
   ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$9XvkH910sOnMNxhKM4f1> .
```

<http://www.semanticweb.org/marianiki/ifcmat#0$9XvkH910sOnMNxhKM4f2> a ifcmat:IfcBuildingElement ;
ifcmat:elementName "HSS-Hollow Structural Section-Column:HSS6X6X5/16:789513"^^xsd:string ;
ifcmat:elementVolume "0.0279718280816"^^xsd:float ;
ifcmat:hasGUID "0$9XvkH910sOnMNxhKM4f2"^^xsd:string ;
ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$9XvkH910sOnMNxhKM4f2> .

<http://www.semanticweb.org/marianiki/ifcmat#0$9XvkH910sOnMNxhKM4f3> a ifcmat:IfcBuildingElement ;
ifcmat:elementName "HSS-Hollow Structural Section-Column:HSS6X6X5/16:789512"^^xsd:string ;
ifcmat:elementVolume "0.0279718280816"^^xsd:float ;
ifcmat:hasGUID "0$9XvkH910sOnMNxhKM4f3"^^xsd:string ;
ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$9XvkH910sOnMNxhKM4f3> .

<http://www.semanticweb.org/marianiki/ifcmat#0$9XvkH910sOnMNxhKM4f7> a ifcmat:IfcBuildingElement ;
ifcmat:elementName "HSS-Hollow Structural Section-Column:HSS6X6X5/16:789516"^^xsd:string ;
ifcmat:elementVolume "0.0279718280816"^^xsd:float ;
ifcmat:hasGUID "0$9XvkH910sOnMNxhKM4f7"^^xsd:string ;
ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$9XvkH910sOnMNxhKM4f7> .

<http://www.semanticweb.org/marianiki/ifcmat#0$9XvkH910sOnMNxhKM4f8> a ifcmat:IfcBuildingElement ;
ifcmat:elementName "HSS-Hollow Structural Section-Column:HSS6X6X5/16:789507"^^xsd:string ;
ifcmat:elementVolume "0.0279718280816"^^xsd:float ;
ifcmat:hasGUID "0$9XvkH910sOnMNxhKM4f8"^^xsd:string ;
ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$9XvkH910sOnMNxhKM4f8> .

<http://www.semanticweb.org/marianiki/ifcmat#0$9XvkH910sOnMNxhKM4f9> a ifcmat:IfcBuildingElement ;
ifcmat:elementName "HSS-Hollow Structural Section-Column:HSS6X6X5/16:789506"^^xsd:string ;
ifcmat:elementVolume "0.0279718280816"^^xsd:float ;
ifcmat:hasGUID "0$9XvkH910sOnMNxhKM4f9"^^xsd:string ;
ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$9XvkH910sOnMNxhKM4f9> .

<http://www.semanticweb.org/marianiki/ifcmat#0$9XvkH910sOnMNxhKM4fA> a ifcmat:IfcBuildingElement ;
ifcmat:elementName "HSS-Hollow Structural Section-Column:HSS6X6X5/16:789505"^^xsd:string ;
ifcmat:elementVolume "0.0279718280816"^^xsd:float ;
ifcmat:hasGUID "0$9XvkH910sOnMNxhKM4fA"^^xsd:string ;
ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$9XvkH910sOnMNxhKM4fA> .

<http://www.semanticweb.org/marianiki/ifcmat#0$9XvkH910sOnMNxhKM4fB> a ifcmat:IfcBuildingElement ;
ifcmat:elementName "HSS-Hollow Structural Section-Column:HSS6X6X5/16:789504"^^xsd:string ;
ifcmat:elementVolume "0.0279718280816"^^xsd:float ;
ifcmat:hasGUID "0$9XvkH910sOnMNxhKM4fB"^^xsd:string ;
ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$9XvkH910sOnMNxhKM4fB> .

<http://www.semanticweb.org/marianiki/ifcmat#0$9XvkH910sOnMNxhKM4fC> a ifcmat:IfcBuildingElement ;
ifcmat:elementName "HSS-Hollow Structural Section-Column:HSS6X6X5/16:789511"^^xsd:string ;
ifcmat:elementVolume "0.0279718280816"^^xsd:float ;
ifcmat:hasGUID "0$9XvkH910sOnMNxhKM4fC"^^xsd:string ;
ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$9XvkH910sOnMNxhKM4fC> .

<http://www.semanticweb.org/marianiki/ifcmat#0$9XvkH910sOnMNxhKM4fD> a ifcmat:IfcBuildingElement ;
ifcmat:elementName "HSS-Hollow Structural Section-Column:HSS6X6X5/16:789510"^^xsd:string ;
ifcmat:elementVolume "0.0279718280816"^^xsd:float ;
ifcmat:hasGUID "0$9XvkH910sOnMNxhKM4fD"^^xsd:string ;
ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$9XvkH910sOnMNxhKM4fD> .

<http://www.semanticweb.org/marianiki/ifcmat#0$9XvkH910sOnMNxhKM4fE> a ifcmat:IfcBuildingElement ;
ifcmat:elementName "HSS-Hollow Structural Section-Column:HSS6X6X5/16:789509"^^xsd:string ;
ifcmat:elementVolume "0.0279718280816"^^xsd:float ;
ifcmat:hasGUID "0$9XvkH910sOnMNxhKM4fE"^^xsd:string ;
ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$9XvkH910sOnMNxhKM4fE> .

<http://www.semanticweb.org/marianiki/ifcmat#0$9XvkH910sOnMNxhKM4fF> a ifcmat:IfcBuildingElement ;
ifcmat:elementName "HSS-Hollow Structural Section-Column:HSS6X6X5/16:789508"^^xsd:string ;
ifcmat:elementVolume "0.0279718280816"^^xsd:float ;
ifcmat:hasGUID "0$9XvkH910sOnMNxhKM4fF"^^xsd:string ;
ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$9XvkH910sOnMNxhKM4fF> .

<http://www.semanticweb.org/marianiki/ifcmat#0$9XvkH910sOnMNxhKM4s$> a ifcmat:IfcBuildingElement ;
ifcmat:elementName "HSS-Hollow Structural Section-Column:HSS6X6X5/16:789492"^^xsd:string ;
ifcmat:elementVolume "0.0279718280816"^^xsd:float ;
ifcmat:hasGUID "0$9XvkH910sOnMNxhKM4s$"^^xsd:string ;

```
    ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$9XvkH910sOnMNxhKM4s$> .

<http://www.semanticweb.org/marianiki/ifcmat#0$9XvkH910sOnMNxhKM4sW> a ifcmat:IfcBuildingElement ;
    ifcmat:elementName "HSS-Hollow Structural Section-Column:HSS6X6X5/16:789483"^^xsd:string ;
    ifcmat:elementVolume "0.0279718280816"^^xsd:float ;
    ifcmat:hasGUID "0$9XvkH910sOnMNxhKM4sW"^^xsd:string ;
    ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$9XvkH910sOnMNxhKM4sW> .

<http://www.semanticweb.org/marianiki/ifcmat#0$9XvkH910sOnMNxhKM4sX> a ifcmat:IfcBuildingElement ;
    ifcmat:elementName "HSS-Hollow Structural Section-Column:HSS6X6X5/16:789482"^^xsd:string ;
    ifcmat:elementVolume "0.0279718280816"^^xsd:float ;
    ifcmat:hasGUID "0$9XvkH910sOnMNxhKM4sX"^^xsd:string ;
    ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$9XvkH910sOnMNxhKM4sX> .

<http://www.semanticweb.org/marianiki/ifcmat#0$9XvkH910sOnMNxhKM4sY> a ifcmat:IfcBuildingElement ;
    ifcmat:elementName "HSS-Hollow Structural Section-Column:HSS6X6X5/16:789481"^^xsd:string ;
    ifcmat:elementVolume "0.0279718280816"^^xsd:float ;
    ifcmat:hasGUID "0$9XvkH910sOnMNxhKM4sY"^^xsd:string ;
    ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$9XvkH910sOnMNxhKM4sY> .

<http://www.semanticweb.org/marianiki/ifcmat#0$9XvkH910sOnMNxhKM4sZ> a ifcmat:IfcBuildingElement ;
    ifcmat:elementName "HSS-Hollow Structural Section-Column:HSS6X6X5/16:789480"^^xsd:string ;
    ifcmat:elementVolume "0.0279718280816"^^xsd:float ;
    ifcmat:hasGUID "0$9XvkH910sOnMNxhKM4sZ"^^xsd:string ;
    ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$9XvkH910sOnMNxhKM4sZ> .

<http://www.semanticweb.org/marianiki/ifcmat#0$9XvkH910sOnMNxhKM4s_> a ifcmat:IfcBuildingElement ;
    ifcmat:elementName "HSS-Hollow Structural Section-Column:HSS6X6X5/16:789493"^^xsd:string ;
    ifcmat:elementVolume "0.0279718280816"^^xsd:float ;
    ifcmat:hasGUID "0$9XvkH910sOnMNxhKM4s_"^^xsd:string ;
    ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$9XvkH910sOnMNxhKM4s_> .

<http://www.semanticweb.org/marianiki/ifcmat#0$9XvkH910sOnMNxhKM4sa> a ifcmat:IfcBuildingElement ;
    ifcmat:elementName "HSS-Hollow Structural Section-Column:HSS6X6X5/16:789487"^^xsd:string ;
    ifcmat:elementVolume "0.0279718280816"^^xsd:float ;
    ifcmat:hasGUID "0$9XvkH910sOnMNxhKM4sa"^^xsd:string ;
    ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$9XvkH910sOnMNxhKM4sa> .

<http://www.semanticweb.org/marianiki/ifcmat#0$9XvkH910sOnMNxhKM4sb> a ifcmat:IfcBuildingElement ;
    ifcmat:elementName "HSS-Hollow Structural Section-Column:HSS6X6X5/16:789486"^^xsd:string ;
    ifcmat:elementVolume "0.0279718280816"^^xsd:float ;
    ifcmat:hasGUID "0$9XvkH910sOnMNxhKM4sb"^^xsd:string ;
    ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$9XvkH910sOnMNxhKM4sb> .

<http://www.semanticweb.org/marianiki/ifcmat#0$9XvkH910sOnMNxhKM4sc> a ifcmat:IfcBuildingElement ;
    ifcmat:elementName "HSS-Hollow Structural Section-Column:HSS6X6X5/16:789485"^^xsd:string ;
    ifcmat:elementVolume "0.0279718280816"^^xsd:float ;
    ifcmat:hasGUID "0$9XvkH910sOnMNxhKM4sc"^^xsd:string ;
    ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$9XvkH910sOnMNxhKM4sc> .

<http://www.semanticweb.org/marianiki/ifcmat#0$9XvkH910sOnMNxhKM4sd> a ifcmat:IfcBuildingElement ;
    ifcmat:elementName "HSS-Hollow Structural Section-Column:HSS6X6X5/16:789484"^^xsd:string ;
    ifcmat:elementVolume "0.0279718280816"^^xsd:float ;
    ifcmat:hasGUID "0$9XvkH910sOnMNxhKM4sd"^^xsd:string ;
    ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$9XvkH910sOnMNxhKM4sd> .

<http://www.semanticweb.org/marianiki/ifcmat#0$9XvkH910sOnMNxhKM4si> a ifcmat:IfcBuildingElement ;
    ifcmat:elementName "HSS-Hollow Structural Section-Column:HSS6X6X5/16:789479"^^xsd:string ;
    ifcmat:elementVolume "0.0279718280816"^^xsd:float ;
    ifcmat:hasGUID "0$9XvkH910sOnMNxhKM4si"^^xsd:string ;
    ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$9XvkH910sOnMNxhKM4si> .

<http://www.semanticweb.org/marianiki/ifcmat#0$9XvkH910sOnMNxhKM4sm> a ifcmat:IfcBuildingElement ;
    ifcmat:elementName "HSS-Hollow Structural Section-Column:HSS6X6X5/16:789499"^^xsd:string ;
    ifcmat:elementVolume "0.0279718280816"^^xsd:float ;
    ifcmat:hasGUID "0$9XvkH910sOnMNxhKM4sm"^^xsd:string ;
    ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$9XvkH910sOnMNxhKM4sm> .

<http://www.semanticweb.org/marianiki/ifcmat#0$9XvkH910sOnMNxhKM4sn> a ifcmat:IfcBuildingElement ;
    ifcmat:elementName "HSS-Hollow Structural Section-Column:HSS6X6X5/16:789498"^^xsd:string ;
    ifcmat:elementVolume "0.0279718280816"^^xsd:float ;
```

ifcmat:hasGUID "0$9XvkH910sOnMNxhKM4sn"^^xsd:string ;
ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$9XvkH910sOnMNxhKM4sn> .

<http://www.semanticweb.org/marianiki/ifcmat#0$9XvkH910sOnMNxhKM4so> a ifcmat:IfcBuildingElement ;
ifcmat:elementName "HSS-Hollow Structural Section-Column:HSS6X6X5/16:789497"^^xsd:string ;
ifcmat:elementVolume "0.0279718280816"^^xsd:float ;
ifcmat:hasGUID "0$9XvkH910sOnMNxhKM4so"^^xsd:string ;
ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$9XvkH910sOnMNxhKM4so> .

<http://www.semanticweb.org/marianiki/ifcmat#0$9XvkH910sOnMNxhKM4sp> a ifcmat:IfcBuildingElement ;
ifcmat:elementName "HSS-Hollow Structural Section-Column:HSS6X6X5/16:789496"^^xsd:string ;
ifcmat:elementVolume "0.0279718280816"^^xsd:float ;
ifcmat:hasGUID "0$9XvkH910sOnMNxhKM4sp"^^xsd:string ;
ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$9XvkH910sOnMNxhKM4sp> .

<http://www.semanticweb.org/marianiki/ifcmat#0$9XvkH910sOnMNxhKM4sq> a ifcmat:IfcBuildingElement ;
ifcmat:elementName "HSS-Hollow Structural Section-Column:HSS6X6X5/16:789503"^^xsd:string ;
ifcmat:elementVolume "0.0279718280816"^^xsd:float ;
ifcmat:hasGUID "0$9XvkH910sOnMNxhKM4sq"^^xsd:string ;
ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$9XvkH910sOnMNxhKM4sq> .

<http://www.semanticweb.org/marianiki/ifcmat#0$9XvkH910sOnMNxhKM4sr> a ifcmat:IfcBuildingElement ;
ifcmat:elementName "HSS-Hollow Structural Section-Column:HSS6X6X5/16:789502"^^xsd:string ;
ifcmat:elementVolume "0.0279718280816"^^xsd:float ;
ifcmat:hasGUID "0$9XvkH910sOnMNxhKM4sr"^^xsd:string ;
ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$9XvkH910sOnMNxhKM4sr> .

<http://www.semanticweb.org/marianiki/ifcmat#00dynY_TzFnuWjoIvBuiv6> a ifcmat:IfcBuildingElement ;
ifcmat:elementName "Basic Wall:D 3 D_Core:1215706"^^xsd:string ;
ifcmat:elementVolume "0.813052953751"^^xsd:float ;
ifcmat:hasGUID "00dynY_TzFnuWjoIvBuiv6"^^xsd:string ;
ifcmat:isAssociatedTo ifcmat:Mat01_00dynY_TzFnuWjoIvBuiv6 .

<http://www.semanticweb.org/marianiki/ifcmat#00dynY_TzFnuWjoIvBuix2> a ifcmat:IfcBuildingElement ;
ifcmat:elementName "Basic Wall:Interior - 4 7/8\" Partition TYPE 3:1215582"^^xsd:string ;
ifcmat:elementVolume "0.99863289714"^^xsd:float ;
ifcmat:hasGUID "00dynY_TzFnuWjoIvBuix2"^^xsd:string ;
ifcmat:isAssociatedTo ifcmat:Mat01_00dynY_TzFnuWjoIvBuix2,
ifcmat:Mat02_00dynY_TzFnuWjoIvBuix2,
ifcmat:Mat03_00dynY_TzFnuWjoIvBuix2 .

<http://www.semanticweb.org/marianiki/ifcmat#00dynY_TzFnuWjoIvBuixX> a ifcmat:IfcBuildingElement ;
ifcmat:elementName "Basic Wall:Interior - 4 7/8\" Partition TYPE 3:1215613"^^xsd:string ;
ifcmat:elementVolume "0.256204896683"^^xsd:float ;
ifcmat:hasGUID "00dynY_TzFnuWjoIvBuixX"^^xsd:string ;
ifcmat:isAssociatedTo ifcmat:Mat01_00dynY_TzFnuWjoIvBuixX,
ifcmat:Mat02_00dynY_TzFnuWjoIvBuixX,
ifcmat:Mat03_00dynY_TzFnuWjoIvBuixX .

<http://www.semanticweb.org/marianiki/ifcmat#00dynY_TzFnuWjoIvBuiyW> a ifcmat:IfcBuildingElement ;
ifcmat:elementName "Basic Wall:Interior - 6 1/8\" Partition (2-hr) TYPE 8:1215932"^^xsd:string ;
ifcmat:elementVolume "0.497075245835"^^xsd:float ;
ifcmat:hasGUID "00dynY_TzFnuWjoIvBuiyW"^^xsd:string ;
ifcmat:isAssociatedTo ifcmat:Mat01_00dynY_TzFnuWjoIvBuiyW,
ifcmat:Mat02_00dynY_TzFnuWjoIvBuiyW,
ifcmat:Mat03_00dynY_TzFnuWjoIvBuiyW,
ifcmat:Mat04_00dynY_TzFnuWjoIvBuiyW,
ifcmat:Mat05_00dynY_TzFnuWjoIvBuiyW .

<http://www.semanticweb.org/marianiki/ifcmat#00dynY_TzFnuWjoIvBuiz0> a ifcmat:IfcBuildingElement ;
ifcmat:elementName "Basic Wall:Interior - 6 1/8\" Partition (2-hr) TYPE 8:1215964"^^xsd:string ;
ifcmat:elementVolume "0.453681199032"^^xsd:float ;
ifcmat:hasGUID "00dynY_TzFnuWjoIvBuiz0"^^xsd:string ;
ifcmat:isAssociatedTo ifcmat:Mat01_00dynY_TzFnuWjoIvBuiz0,
ifcmat:Mat02_00dynY_TzFnuWjoIvBuiz0,
ifcmat:Mat03_00dynY_TzFnuWjoIvBuiz0,
ifcmat:Mat04_00dynY_TzFnuWjoIvBuiz0,
ifcmat:Mat05_00dynY_TzFnuWjoIvBuiz0 .

<http://www.semanticweb.org/marianiki/ifcmat#00dynY_TzFnuWjoIvBuizg> a ifcmat:IfcBuildingElement ;
ifcmat:elementName "Basic Wall:Interior - 6 1/8\" Partition (2-hr) TYPE 8:1215990"^^xsd:string ;

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    ifcmat:elementVolume "0.497075245835"^^xsd:float ;
    ifcmat:hasGUID "00dynY_TzFnuWjoIvBuizg"^^xsd:string ;
    ifcmat:isAssociatedTo ifcmat:Mat01_00dynY_TzFnuWjoIvBuizg,
        ifcmat:Mat02_00dynY_TzFnuWjoIvBuizg,
        ifcmat:Mat03_00dynY_TzFnuWjoIvBuizg,
        ifcmat:Mat04_00dynY_TzFnuWjoIvBuizg,
        ifcmat:Mat05_00dynY_TzFnuWjoIvBuizg .

<http://www.semanticweb.org/marianiki/ifcmat#01_3E6l5bCLuqBJy_nxyDS> a ifcmat:IfcBuildingElement ;
    ifcmat:elementName "Floor:Floor Finish - CA-1:1273676"^^xsd:string ;
    ifcmat:elementVolume "0.51711428835"^^xsd:float ;
    ifcmat:hasGUID "01_3E6l5bCLuqBJy_nxyDS"^^xsd:string ;
    ifcmat:isAssociatedTo ifcmat:Mat01_01_3E6l5bCLuqBJy_nxyDS .

<http://www.semanticweb.org/marianiki/ifcmat#01_3E6l5bCLuqBJy_nxzo0> a ifcmat:IfcBuildingElement ;
    ifcmat:elementName "Basic Wall:Interior - 4 1/4\" Partition TYPE 10:1274000"^^xsd:string ;
    ifcmat:elementVolume "1.38809672311"^^xsd:float ;
    ifcmat:hasGUID "01_3E6l5bCLuqBJy_nxzo0"^^xsd:string ;
    ifcmat:isAssociatedTo ifcmat:Mat01_01_3E6l5bCLuqBJy_nxzo0,
        ifcmat:Mat02_01_3E6l5bCLuqBJy_nxzo0 .

<http://www.semanticweb.org/marianiki/ifcmat#01_3E6l5bCLuqBJy_nxzoe> a ifcmat:IfcBuildingElement ;
    ifcmat:elementName "Basic Wall:Interior - 4 1/4\" Partition TYPE 10:1274040"^^xsd:string ;
    ifcmat:elementVolume "1.38809672311"^^xsd:float ;
    ifcmat:hasGUID "01_3E6l5bCLuqBJy_nxzoe"^^xsd:string ;
    ifcmat:isAssociatedTo ifcmat:Mat01_01_3E6l5bCLuqBJy_nxzoe,
        ifcmat:Mat02_01_3E6l5bCLuqBJy_nxzoe .

<http://www.semanticweb.org/marianiki/ifcmat#01_3E6l5bCLuqBJy_nxzqK> a ifcmat:IfcBuildingElement ;
    ifcmat:elementName "Basic Wall:Interior - 4 1/4\" Partition TYPE 10:1274116"^^xsd:string ;
    ifcmat:elementVolume "1.61788907055"^^xsd:float ;
    ifcmat:hasGUID "01_3E6l5bCLuqBJy_nxzqK"^^xsd:string ;
    ifcmat:isAssociatedTo ifcmat:Mat01_01_3E6l5bCLuqBJy_nxzqK,
        ifcmat:Mat02_01_3E6l5bCLuqBJy_nxzqK .

<http://www.semanticweb.org/marianiki/ifcmat#01_3E6l5bCLuqBJy_nxzqk> a ifcmat:IfcBuildingElement ;
    ifcmat:elementName "Basic Wall:Interior - 4 1/4\" Partition TYPE 10:1274174"^^xsd:string ;
    ifcmat:elementVolume "1.62478828054"^^xsd:float ;
    ifcmat:hasGUID "01_3E6l5bCLuqBJy_nxzqk"^^xsd:string ;
    ifcmat:isAssociatedTo ifcmat:Mat01_01_3E6l5bCLuqBJy_nxzqk,
        ifcmat:Mat02_01_3E6l5bCLuqBJy_nxzqk .

<http://www.semanticweb.org/marianiki/ifcmat#01_3E6l5bCLuqBJy_nxzre> a ifcmat:IfcBuildingElement ;
    ifcmat:elementName "Basic Wall:Interior - 4 1/4\" Partition TYPE 10:1274232"^^xsd:string ;
    ifcmat:elementVolume "1.61788907055"^^xsd:float ;
    ifcmat:hasGUID "01_3E6l5bCLuqBJy_nxzre"^^xsd:string ;
    ifcmat:isAssociatedTo ifcmat:Mat01_01_3E6l5bCLuqBJy_nxzre,
        ifcmat:Mat02_01_3E6l5bCLuqBJy_nxzre .

<http://www.semanticweb.org/marianiki/ifcmat#01_3E6l5bCLuqBJy_nxztq> a ifcmat:IfcBuildingElement ;
    ifcmat:elementName "Basic Wall:Interior - 4 1/4\" Partition TYPE 10:1274340"^^xsd:string ;
    ifcmat:elementVolume "1.65581039805"^^xsd:float ;
    ifcmat:hasGUID "01_3E6l5bCLuqBJy_nxztq"^^xsd:string ;
    ifcmat:isAssociatedTo ifcmat:Mat01_01_3E6l5bCLuqBJy_nxztq,
        ifcmat:Mat02_01_3E6l5bCLuqBJy_nxztq .

<http://www.semanticweb.org/marianiki/ifcmat#01_3E6l5bCLuqBJy_nxzu_> a ifcmat:IfcBuildingElement ;
    ifcmat:elementName "Basic Wall:Interior - 4 1/4\" Partition TYPE 10:1274414"^^xsd:string ;
    ifcmat:elementVolume "1.38114570125"^^xsd:float ;
    ifcmat:hasGUID "01_3E6l5bCLuqBJy_nxzu_"^^xsd:string ;
    ifcmat:isAssociatedTo ifcmat:Mat01_01_3E6l5bCLuqBJy_nxzu_,
        ifcmat:Mat02_01_3E6l5bCLuqBJy_nxzu_ .

<http://www.semanticweb.org/marianiki/ifcmat#03CjCfZc5CJRsXyD4QHNW6> a ifcmat:IfcBuildingElement ;
    ifcmat:elementName "Basic Wall:Interior - 4 1/4\" Partition TYPE 10:1201045"^^xsd:string ;
    ifcmat:elementVolume "1.32464831844"^^xsd:float ;
    ifcmat:hasGUID "03CjCfZc5CJRsXyD4QHNW6"^^xsd:string ;
    ifcmat:isAssociatedTo ifcmat:Mat01_03CjCfZc5CJRsXyD4QHNW6,
        ifcmat:Mat02_03CjCfZc5CJRsXyD4QHNW6 .

<http://www.semanticweb.org/marianiki/ifcmat#03CjCfZc5CJRsXyD4QHNWl> a ifcmat:IfcBuildingElement ;
```

```
    ifcmat:elementName "Basic Wall:Interior - 4 1/4\" Partition TYPE 10:1201084"^^xsd:string ;
    ifcmat:elementVolume "1.82277127985"^^xsd:float ;
    ifcmat:hasGUID "03CjCfZc5CJRsXyD4QHNWl"^^xsd:string ;
    ifcmat:isAssociatedTo ifcmat:Mat01_03CjCfZc5CJRsXyD4QHNWl,
        ifcmat:Mat02_03CjCfZc5CJRsXyD4QHNWl .

<http://www.semanticweb.org/marianiki/ifcmat#03CjCfZc5CJRsXyD4QHNXu> a ifcmat:IfcBuildingElement ;
    ifcmat:elementName "Basic Wall:Interior - 4 1/4\" Partition TYPE 10:1201131"^^xsd:string ;
    ifcmat:elementVolume "1.82277127985"^^xsd:float ;
    ifcmat:hasGUID "03CjCfZc5CJRsXyD4QHNXu"^^xsd:string ;
    ifcmat:isAssociatedTo ifcmat:Mat01_03CjCfZc5CJRsXyD4QHNXu,
        ifcmat:Mat02_03CjCfZc5CJRsXyD4QHNXu .

<http://www.semanticweb.org/marianiki/ifcmat#03CjCfZc5CJRsXyD4QHNY2> a ifcmat:IfcBuildingElement ;
    ifcmat:elementName "Basic Wall:Interior - 4 1/4\" Partition TYPE 10:1200913"^^xsd:string ;
    ifcmat:elementVolume "0.35067868671"^^xsd:float ;
    ifcmat:hasGUID "03CjCfZc5CJRsXyD4QHNY2"^^xsd:string ;
    ifcmat:isAssociatedTo ifcmat:Mat01_03CjCfZc5CJRsXyD4QHNY2,
        ifcmat:Mat02_03CjCfZc5CJRsXyD4QHNY2 .

ifcmat:MatLayer02_3j7ZcrARP1eeaxjkzRbK4v a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat02_3j7ZcrARP1eeaxjkzRbK4v ;
    ifcmat:layerThickness "0.333333333333"^^xsd:float .

ifcmat:MatLayer02_3j7ZcrARP1eeaxjkzRbK7G a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat02_3j7ZcrARP1eeaxjkzRbK7G ;
    ifcmat:layerThickness "0.333333333333"^^xsd:float .

ifcmat:MatLayer02_3j7ZcrARP1eeaxjkzRbK7h a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat02_3j7ZcrARP1eeaxjkzRbK7h ;
    ifcmat:layerThickness "0.333333333333"^^xsd:float .

ifcmat:MatLayer02_3j7ZcrARP1eeaxjkzRbK8U a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat02_3j7ZcrARP1eeaxjkzRbK8U ;
    ifcmat:layerThickness "0.0520833333333"^^xsd:float .

ifcmat:MatLayer02_3j7ZcrARP1eeaxjkzRbKDD a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat02_3j7ZcrARP1eeaxjkzRbKDD ;
    ifcmat:layerThickness "0.333333333333"^^xsd:float .

ifcmat:MatLayer02_3j7ZcrARP1eeaxjkzRbKDG a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat02_3j7ZcrARP1eeaxjkzRbKDG ;
    ifcmat:layerThickness "0.333333333333"^^xsd:float .

ifcmat:MatLayer02_3j7ZcrARP1eeaxjkzRbKDI a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat02_3j7ZcrARP1eeaxjkzRbKDI ;
    ifcmat:layerThickness "0.333333333333"^^xsd:float .

ifcmat:MatLayer02_3j7ZcrARP1eeaxjkzRbKDJ a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat02_3j7ZcrARP1eeaxjkzRbKDJ ;
    ifcmat:layerThickness "0.333333333333"^^xsd:float .

ifcmat:MatLayer02_3j7ZcrARP1eeaxjkzRbKDl a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat02_3j7ZcrARP1eeaxjkzRbKDl ;
    ifcmat:layerThickness "0.302083333333"^^xsd:float .

ifcmat:MatLayer02_3j7ZcrARP1eeaxjkzRbKGB a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat02_3j7ZcrARP1eeaxjkzRbKGB ;
    ifcmat:layerThickness "0.333333333333"^^xsd:float .

ifcmat:MatLayer02_3j7ZcrARP1eeaxjkzRbKPh a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat02_3j7ZcrARP1eeaxjkzRbKPh ;
    ifcmat:layerThickness "0.302083333333"^^xsd:float .

ifcmat:MatLayer02_3j7ZcrARP1eeaxjkzRbKVF a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat02_3j7ZcrARP1eeaxjkzRbKVF ;
    ifcmat:layerThickness "0.302083333333"^^xsd:float .

ifcmat:MatLayer02_3j7ZcrARP1eeaxjkzRbKcd a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat02_3j7ZcrARP1eeaxjkzRbKcd ;
    ifcmat:layerThickness "0.302083333333"^^xsd:float .
```

```
ifcmat:MatLayer02_3j7ZcrARP1eeaxjkzRbKf1 a ifcmat:IfcMaterialLayer ;
   ifcmat:hasMaterial ifcmat:Mat02_3j7ZcrARP1eeaxjkzRbKf1 ;
   ifcmat:layerThickness "0.333333333333"^^xsd:float .

ifcmat:MatLayer02_3j7ZcrARP1eeaxjkzRbKiz a ifcmat:IfcMaterialLayer ;
   ifcmat:hasMaterial ifcmat:Mat02_3j7ZcrARP1eeaxjkzRbKiz ;
   ifcmat:layerThickness "0.302083333333"^^xsd:float .

ifcmat:MatLayer02_3j7ZcrARP1eeaxjkzRbKj7 a ifcmat:IfcMaterialLayer ;
   ifcmat:hasMaterial ifcmat:Mat02_3j7ZcrARP1eeaxjkzRbKj7 ;
   ifcmat:layerThickness "0.302083333333"^^xsd:float .

ifcmat:MatLayer02_3j7ZcrARP1eeaxjkzRbKja a ifcmat:IfcMaterialLayer ;
   ifcmat:hasMaterial ifcmat:Mat02_3j7ZcrARP1eeaxjkzRbKja ;
   ifcmat:layerThickness "0.302083333333"^^xsd:float .

ifcmat:MatLayer02_3j7ZcrARP1eeaxjkzRbKkS a ifcmat:IfcMaterialLayer ;
   ifcmat:hasMaterial ifcmat:Mat02_3j7ZcrARP1eeaxjkzRbKkS ;
   ifcmat:layerThickness "0.333333333333"^^xsd:float .

ifcmat:MatLayer02_3j7ZcrARP1eeaxjkzRbKlN a ifcmat:IfcMaterialLayer ;
   ifcmat:hasMaterial ifcmat:Mat02_3j7ZcrARP1eeaxjkzRbKlN ;
   ifcmat:layerThickness "0.333333333333"^^xsd:float .

ifcmat:MatLayer02_3j7ZcrARP1eeaxjkzRbLq4 a ifcmat:IfcMaterialLayer ;
   ifcmat:hasMaterial ifcmat:Mat02_3j7ZcrARP1eeaxjkzRbLq4 ;
   ifcmat:layerThickness "0.0520833333333"^^xsd:float .

ifcmat:MatLayer02_3j7ZcrARP1eeaxjkzRbLrv a ifcmat:IfcMaterialLayer ;
   ifcmat:hasMaterial ifcmat:Mat02_3j7ZcrARP1eeaxjkzRbLrv ;
   ifcmat:layerThickness "0.0520833333333"^^xsd:float .

ifcmat:MatLayer02_3j7ZcrARP1eeaxjkzRbLsh a ifcmat:IfcMaterialLayer ;
   ifcmat:hasMaterial ifcmat:Mat02_3j7ZcrARP1eeaxjkzRbLsh ;
   ifcmat:layerThickness "0.0520833333333"^^xsd:float .

ifcmat:MatLayer02_3j7ZcrARP1eeaxjkzRbLtr a ifcmat:IfcMaterialLayer ;
   ifcmat:hasMaterial ifcmat:Mat02_3j7ZcrARP1eeaxjkzRbLtr ;
   ifcmat:layerThickness "0.0520833333333"^^xsd:float .

ifcmat:MatLayer02_3k9FW46j516h_gFhZb6xJQ a ifcmat:IfcMaterialLayer ;
   ifcmat:hasMaterial ifcmat:Mat02_3k9FW46j516h_gFhZb6xJQ ;
   ifcmat:layerThickness "0.0520833333333"^^xsd:float .

ifcmat:MatLayer02_3k9FW46j516h_gFhZb6xbw a ifcmat:IfcMaterialLayer ;
   ifcmat:hasMaterial ifcmat:Mat02_3k9FW46j516h_gFhZb6xbw ;
   ifcmat:layerThickness "0.0520833333333"^^xsd:float .

ifcmat:MatLayer02_3k9SNKX5jFqQYQihHI1iHg a ifcmat:IfcMaterialLayer ;
   ifcmat:hasMaterial ifcmat:Mat02_3k9SNKX5jFqQYQihHI1iHg ;
   ifcmat:layerThickness "0.166666666667"^^xsd:float .

ifcmat:MatLayer02_3k9SNKX5jFqQYQihHI1iLi a ifcmat:IfcMaterialLayer ;
   ifcmat:hasMaterial ifcmat:Mat02_3k9SNKX5jFqQYQihHI1iLi ;
   ifcmat:layerThickness "0.166666666667"^^xsd:float .

ifcmat:MatLayer02_3k9SNKX5jFqQYQihHI1iMn a ifcmat:IfcMaterialLayer ;
   ifcmat:hasMaterial ifcmat:Mat02_3k9SNKX5jFqQYQihHI1iMn ;
   ifcmat:layerThickness "0.166666666667"^^xsd:float .

ifcmat:MatLayer02_3k9SNKX5jFqQYQihHI1iRK a ifcmat:IfcMaterialLayer ;
   ifcmat:hasMaterial ifcmat:Mat02_3k9SNKX5jFqQYQihHI1iRK ;
   ifcmat:layerThickness "0.166666666667"^^xsd:float .

ifcmat:MatLayer02_3k9SNKX5jFqQYQihHI1iRw a ifcmat:IfcMaterialLayer ;
   ifcmat:hasMaterial ifcmat:Mat02_3k9SNKX5jFqQYQihHI1iRw ;
   ifcmat:layerThickness "0.166666666667"^^xsd:float .

ifcmat:MatLayer02_3k9SNKX5jFqQYQihHI1iS6 a ifcmat:IfcMaterialLayer ;
   ifcmat:hasMaterial ifcmat:Mat02_3k9SNKX5jFqQYQihHI1iS6 ;
```

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    ifcmat:layerThickness "0.166666666667"^^xsd:float .

ifcmat:MatLayer02_3k9SNKX5jFqQYQihHI1jjZ a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat02_3k9SNKX5jFqQYQihHI1jjZ ;
    ifcmat:layerThickness "0.166666666667"^^xsd:float .

<http://www.semanticweb.org/marianiki/ifcmat#MatLayer02_3t7dFx7jXCQgrwXR08u4g$> a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial <http://www.semanticweb.org/marianiki/ifcmat#Mat02_3t7dFx7jXCQgrwXR08u4g$> ;
    ifcmat:layerThickness "0.0520833333333"^^xsd:float .

ifcmat:MatLayer03_00dynY_TzFnuWjoIvBuix2 a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat03_00dynY_TzFnuWjoIvBuix2 ;
    ifcmat:layerThickness "0.0520833333333"^^xsd:float .

ifcmat:MatLayer03_00dynY_TzFnuWjoIvBuixX a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat03_00dynY_TzFnuWjoIvBuixX ;
    ifcmat:layerThickness "0.0520833333333"^^xsd:float .

ifcmat:MatLayer03_00dynY_TzFnuWjoIvBuiyW a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat03_00dynY_TzFnuWjoIvBuiyW ;
    ifcmat:layerThickness "0.302083333333"^^xsd:float .

ifcmat:MatLayer03_00dynY_TzFnuWjoIvBuiz0 a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat03_00dynY_TzFnuWjoIvBuiz0 ;
    ifcmat:layerThickness "0.302083333333"^^xsd:float .

ifcmat:MatLayer03_00dynY_TzFnuWjoIvBuizg a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat03_00dynY_TzFnuWjoIvBuizg ;
    ifcmat:layerThickness "0.302083333333"^^xsd:float .

ifcmat:Mat01_132zEo_AX0iP0cfdshgZqo a ifcmat:IfcMaterial ;
    rdfs:label "Metal - Steel - ASTM A992"^^xsd:string ;
    ifcmat:fractionOfVolume "1"^^xsd:float .

ifcmat:Mat01_132zEo_AX0iP0cfdshgZrL a ifcmat:IfcMaterial ;
    rdfs:label "Metal - Steel - ASTM A992"^^xsd:string ;
    ifcmat:fractionOfVolume "1"^^xsd:float .

ifcmat:Mat01_132zEo_AX0iP0cfdshgZrb a ifcmat:IfcMaterial ;
    rdfs:label "Metal - Steel - ASTM A992"^^xsd:string ;
    ifcmat:fractionOfVolume "1"^^xsd:float .

ifcmat:Mat01_141UzFEpPAiBNNDMW3_WIk a ifcmat:IfcMaterial ;
    rdfs:label "Finishes - Interior - Gypsum Wall Board"^^xsd:string ;
    ifcmat:fractionOfVolume "0.102040816327"^^xsd:float .

ifcmat:Mat01_141UzFEpPAiBNNDMW3_WJh a ifcmat:IfcMaterial ;
    rdfs:label "Finishes - Interior - Gypsum Wall Board"^^xsd:string ;
    ifcmat:fractionOfVolume "0.102040816327"^^xsd:float .

ifcmat:Mat01_141UzFEpPAiBNNDMW3_WTJ a ifcmat:IfcMaterial ;
    rdfs:label "Finishes - Interior - Gypsum Wall Board"^^xsd:string ;
    ifcmat:fractionOfVolume "0.102040816327"^^xsd:float .

ifcmat:Mat01_141UzFEpPAiBNNDMW3_WUD a ifcmat:IfcMaterial ;
    rdfs:label "Finishes - Interior - Gypsum Wall Board"^^xsd:string ;
    ifcmat:fractionOfVolume "0.102040816327"^^xsd:float .

<http://www.semanticweb.org/marianiki/ifcmat#Mat01_141UzFEpPAiBNNDMW3_Z$t> a ifcmat:IfcMaterial ;
    rdfs:label "Finishes - Interior - Gypsum Wall Board"^^xsd:string ;
    ifcmat:fractionOfVolume "0.128205128205"^^xsd:float .

ifcmat:Mat01_141UzFEpPAiBNNDMW3_Z0s a ifcmat:IfcMaterial ;
    rdfs:label "Finishes - Interior - Gypsum Wall Board"^^xsd:string ;
    ifcmat:fractionOfVolume "0.128205128205"^^xsd:float .

ifcmat:Mat01_141UzFEpPAiBNNDMW3_Z1a a ifcmat:IfcMaterial ;
    rdfs:label "Finishes - Interior - Gypsum Wall Board"^^xsd:string ;
    ifcmat:fractionOfVolume "0.147058823529"^^xsd:float .

ifcmat:Mat01_141UzFEpPAiBNNDMW3_Z2W a ifcmat:IfcMaterial ;
```

```
    rdfs:label "Finishes - Interior - Gypsum Wall Board"^^xsd:string ;
    ifcmat:fractionOfVolume "0.147058823529"^^xsd:float .

ifcmat:Mat01_141UzFEpPAiBNNDMW3_Z3a a ifcmat:IfcMaterial ;
    rdfs:label "Finishes - Interior - Gypsum Wall Board"^^xsd:string ;
    ifcmat:fractionOfVolume "0.147058823529"^^xsd:float .

ifcmat:Mat01_141UzFEpPAiBNNDMW3_Z4b a ifcmat:IfcMaterial ;
    rdfs:label "Finishes - Interior - Gypsum Wall Board"^^xsd:string ;
    ifcmat:fractionOfVolume "0.147058823529"^^xsd:float .

ifcmat:Mat01_141UzFEpPAiBNNDMW3_Z5i a ifcmat:IfcMaterial ;
    rdfs:label "Finishes - Interior - Gypsum Wall Board"^^xsd:string ;
    ifcmat:fractionOfVolume "0.147058823529"^^xsd:float .

ifcmat:Mat01_141UzFEpPAiBNNDMW3_Z7L a ifcmat:IfcMaterial ;
    rdfs:label "Finishes - Interior - Gypsum Wall Board"^^xsd:string ;
    ifcmat:fractionOfVolume "0.128205128205"^^xsd:float .

ifcmat:Mat01_141UzFEpPAiBNNDMW3_Z7X a ifcmat:IfcMaterial ;
    rdfs:label "Finishes - Interior - Gypsum Wall Board"^^xsd:string ;
    ifcmat:fractionOfVolume "0.128205128205"^^xsd:float .

ifcmat:Mat01_141UzFEpPAiBNNDMW3_Z8k a ifcmat:IfcMaterial ;
    rdfs:label "Finishes - Interior - Gypsum Wall Board"^^xsd:string ;
    ifcmat:fractionOfVolume "0.128205128205"^^xsd:float .

ifcmat:Mat01_1KebJEg2L4IAdY05taZsvf a ifcmat:IfcMaterial ;
    rdfs:label "Metal - Stud Layer"^^xsd:string ;
    ifcmat:fractionOfVolume "0.852941176471"^^xsd:float .

ifcmat:Mat01_1KebJEg2L4IAdY05taZtNb a ifcmat:IfcMaterial ;
    rdfs:label "Metal - Stud Layer"^^xsd:string ;
    ifcmat:fractionOfVolume "0.852941176471"^^xsd:float .

<http://www.semanticweb.org/marianiki/ifcmat#Mat01_1MtyBm1gjEdf$qjWshDh68> a ifcmat:IfcMaterial ;
    rdfs:label "Glass"^^xsd:string ;
    ifcmat:fractionOfVolume "1"^^xsd:float .
```


4. Clinic_A_20110906_optimized Model


```
@prefix ifcmat: <http://www.semanticweb.org/marianiki/ifcmat#> .
@prefix rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#> .
@prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#> .
@prefix xml: <http://www.w3.org/XML/1998/namespace> .
@prefix xsd: <http://www.w3.org/2001/XMLSchema#> .

<http://www.semanticweb.org/marianiki/ifcmat#0$T_kKFfj6eQu9LjJc1Knz> a ifcmat:IfcBuildingElement ;
    ifcmat:elementName "Basic Wall:Exterior - Insul Panel on Mtl. Stud:257918"^^xsd:string ;
    ifcmat:elementVolume "6.16055152129"^^xsd:float ;
    ifcmat:hasGUID "0$T_kKFfj6eQu9LjJc1Knz"^^xsd:string ;
    ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$T_kKFfj6eQu9LjJc1Knz>,
        <http://www.semanticweb.org/marianiki/ifcmat#Mat02_0$T_kKFfj6eQu9LjJc1Knz>,
        <http://www.semanticweb.org/marianiki/ifcmat#Mat03_0$T_kKFfj6eQu9LjJc1Knz>,
        <http://www.semanticweb.org/marianiki/ifcmat#Mat04_0$T_kKFfj6eQu9LjJc1Knz>,
        <http://www.semanticweb.org/marianiki/ifcmat#Mat05_0$T_kKFfj6eQu9LjJc1Knz> .

<http://www.semanticweb.org/marianiki/ifcmat#0$T_kKFfj6eQu9LjJc1L4V> a ifcmat:IfcBuildingElement ;
    ifcmat:elementName "Basic Wall:Exterior - Insul Panel on Mtl. Stud:258588"^^xsd:string ;
    ifcmat:elementVolume "16.5825075549"^^xsd:float ;
    ifcmat:hasGUID "0$T_kKFfj6eQu9LjJc1L4V"^^xsd:string ;
    ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$T_kKFfj6eQu9LjJc1L4V>,
        <http://www.semanticweb.org/marianiki/ifcmat#Mat02_0$T_kKFfj6eQu9LjJc1L4V>,
        <http://www.semanticweb.org/marianiki/ifcmat#Mat03_0$T_kKFfj6eQu9LjJc1L4V>,
        <http://www.semanticweb.org/marianiki/ifcmat#Mat04_0$T_kKFfj6eQu9LjJc1L4V>,
        <http://www.semanticweb.org/marianiki/ifcmat#Mat05_0$T_kKFfj6eQu9LjJc1L4V> .

<http://www.semanticweb.org/marianiki/ifcmat#0$T_kKFfj6eQu9LjJc1L7L> a ifcmat:IfcBuildingElement ;
    ifcmat:elementName "Basic Wall:Exterior - Insul Panel on Mtl. Stud:258774"^^xsd:string ;
    ifcmat:elementVolume "2.656116"^^xsd:float ;
```

```
    ifcmat:hasGUID "0$T_kKFfj6eQu9LjJc1L7L"^^xsd:string ;
    ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$T_kKFfj6eQu9LjJc1L7L>,
        <http://www.semanticweb.org/marianiki/ifcmat#Mat02_0$T_kKFfj6eQu9LjJc1L7L>,
        <http://www.semanticweb.org/marianiki/ifcmat#Mat03_0$T_kKFfj6eQu9LjJc1L7L>,
        <http://www.semanticweb.org/marianiki/ifcmat#Mat04_0$T_kKFfj6eQu9LjJc1L7L>,
        <http://www.semanticweb.org/marianiki/ifcmat#Mat05_0$T_kKFfj6eQu9LjJc1L7L> .

<http://www.semanticweb.org/marianiki/ifcmat#0$T_kKFfj6eQu9LjJc1L7M> a ifcmat:IfcBuildingElement ;
    ifcmat:elementName "Basic Wall:Exterior - Insul Panel on Mtl. Stud:258773"^^xsd:string ;
    ifcmat:elementVolume "0.96654"^^xsd:float ;
    ifcmat:hasGUID "0$T_kKFfj6eQu9LjJc1L7M"^^xsd:string ;
    ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$T_kKFfj6eQu9LjJc1L7M>,
        <http://www.semanticweb.org/marianiki/ifcmat#Mat02_0$T_kKFfj6eQu9LjJc1L7M>,
        <http://www.semanticweb.org/marianiki/ifcmat#Mat03_0$T_kKFfj6eQu9LjJc1L7M>,
        <http://www.semanticweb.org/marianiki/ifcmat#Mat04_0$T_kKFfj6eQu9LjJc1L7M>,
        <http://www.semanticweb.org/marianiki/ifcmat#Mat05_0$T_kKFfj6eQu9LjJc1L7M> .

<http://www.semanticweb.org/marianiki/ifcmat#0$T_kKFfj6eQu9LjJc1L7P> a ifcmat:IfcBuildingElement ;
    ifcmat:elementName "System Panel:Glazed:Glazed:258778"^^xsd:string ;
    ifcmat:elementVolume "0.73229688"^^xsd:float ;
    ifcmat:hasGUID "0$T_kKFfj6eQu9LjJc1L7P"^^xsd:string ;
    ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$T_kKFfj6eQu9LjJc1L7P> .

<http://www.semanticweb.org/marianiki/ifcmat#0$T_kKFfj6eQu9LjJc1L7R> a ifcmat:IfcBuildingElement ;
    ifcmat:elementName "System Panel:Glazed:Glazed:258776"^^xsd:string ;
    ifcmat:elementVolume "0.73229688"^^xsd:float ;
    ifcmat:hasGUID "0$T_kKFfj6eQu9LjJc1L7R"^^xsd:string ;
    ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$T_kKFfj6eQu9LjJc1L7R> .

<http://www.semanticweb.org/marianiki/ifcmat#0$T_kKFfj6eQu9LjJc1L7V> a ifcmat:IfcBuildingElement ;
    ifcmat:elementName "System Panel:Glazed:Glazed:258780"^^xsd:string ;
    ifcmat:elementVolume "0.73229688"^^xsd:float ;
    ifcmat:hasGUID "0$T_kKFfj6eQu9LjJc1L7V"^^xsd:string ;
    ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$T_kKFfj6eQu9LjJc1L7V> .

<http://www.semanticweb.org/marianiki/ifcmat#0$T_kKFfj6eQu9LjJc1LC9> a ifcmat:IfcBuildingElement ;
    ifcmat:elementName "Basic Wall:Exterior - Insul Panel on Mtl. Stud:258058"^^xsd:string ;
    ifcmat:elementVolume "3.32014500001"^^xsd:float ;
    ifcmat:hasGUID "0$T_kKFfj6eQu9LjJc1LC9"^^xsd:string ;
    ifcmat:isAssociatedTo <http://www.semanticweb.org/marianiki/ifcmat#Mat01_0$T_kKFfj6eQu9LjJc1LC9>,
        <http://www.semanticweb.org/marianiki/ifcmat#Mat02_0$T_kKFfj6eQu9LjJc1LC9>,
        <http://www.semanticweb.org/marianiki/ifcmat#Mat03_0$T_kKFfj6eQu9LjJc1LC9>,
        <http://www.semanticweb.org/marianiki/ifcmat#Mat04_0$T_kKFfj6eQu9LjJc1LC9>,
        <http://www.semanticweb.org/marianiki/ifcmat#Mat05_0$T_kKFfj6eQu9LjJc1LC9> .

ifcmat:MatLayer01_0tIhQ6hmz02e5gznEed4TR a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat01_0tIhQ6hmz02e5gznEed4TR ;
    ifcmat:layerThickness "0.038"^^xsd:float .

ifcmat:MatLayer01_0tIhQ6hmz02e5gznEed4_U a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat01_0tIhQ6hmz02e5gznEed4_U ;
    ifcmat:layerThickness "0.038"^^xsd:float .

ifcmat:MatLayer01_0tIhQ6hmz02e5gznEed4_p a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat01_0tIhQ6hmz02e5gznEed4_p ;
    ifcmat:layerThickness "0.038"^^xsd:float .

ifcmat:MatLayer01_0tIhQ6hmz02e5gznEed4aE a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat01_0tIhQ6hmz02e5gznEed4aE ;
    ifcmat:layerThickness "0.038"^^xsd:float .

ifcmat:MatLayer01_0tIhQ6hmz02e5gznEed4ap a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat01_0tIhQ6hmz02e5gznEed4ap ;
    ifcmat:layerThickness "0.038"^^xsd:float .

ifcmat:MatLayer01_0tIhQ6hmz02e5gznEed4bO a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat01_0tIhQ6hmz02e5gznEed4bO ;
    ifcmat:layerThickness "0.038"^^xsd:float .

ifcmat:MatLayer01_0tIhQ6hmz02e5gznEed4bw a ifcmat:IfcMaterialLayer ;
    ifcmat:hasMaterial ifcmat:Mat01_0tIhQ6hmz02e5gznEed4bw ;
```

ifcmat:layerThickness "0.038"^^xsd:float .

ifcmat:MatLayer01_0tIhQ6hmz02e5gznEed5Hk a ifcmat:IfcMaterialLayer ;
ifcmat:hasMaterial ifcmat:Mat01_0tIhQ6hmz02e5gznEed5Hk ;
ifcmat:layerThickness "0.016"^^xsd:float .

ifcmat:MatLayer01_0tIhQ6hmz02e5gznEed5J2 a ifcmat:IfcMaterialLayer ;
ifcmat:hasMaterial ifcmat:Mat01_0tIhQ6hmz02e5gznEed5J2 ;
ifcmat:layerThickness "0.016"^^xsd:float .

ifcmat:MatLayer01_0tIhQ6hmz02e5gznEed5XF a ifcmat:IfcMaterialLayer ;
ifcmat:hasMaterial ifcmat:Mat01_0tIhQ6hmz02e5gznEed5XF .

ifcmat:MatLayer01_0tIhQ6hmz02e5gznEed5Yz a ifcmat:IfcMaterialLayer ;
ifcmat:hasMaterial ifcmat:Mat01_0tIhQ6hmz02e5gznEed5Yz ;
ifcmat:layerThickness "0.016"^^xsd:float .

ifcmat:MatLayer01_2Xm8mTFlXE_vTXaS55sT6f a ifcmat:IfcMaterialLayer ;
ifcmat:hasMaterial ifcmat:Mat01_2Xm8mTFlXE_vTXaS55sT6f ;
ifcmat:layerThickness "0.036"^^xsd:float .

ifcmat:MatLayer01_2Xm8mTFlXE_vTXaS55sT6n a ifcmat:IfcMaterialLayer ;
ifcmat:hasMaterial ifcmat:Mat01_2Xm8mTFlXE_vTXaS55sT6n ;
ifcmat:layerThickness "0.036"^^xsd:float .

ifcmat:MatLayer01_2Xm8mTFlXE_vTXaS55sT6x a ifcmat:IfcMaterialLayer ;
ifcmat:hasMaterial ifcmat:Mat01_2Xm8mTFlXE_vTXaS55sT6x ;
ifcmat:layerThickness "0.036"^^xsd:float .

ifcmat:MatLayer01_2j55VthSj3Lu0J6fyrpHVD a ifcmat:IfcMaterialLayer ;
ifcmat:hasMaterial ifcmat:Mat01_2j55VthSj3Lu0J6fyrpHVD ;
ifcmat:layerThickness "0.045"^^xsd:float .

ifcmat:MatLayer01_2j55VthSj3Lu0J6fyrpHVf a ifcmat:IfcMaterialLayer ;
ifcmat:hasMaterial ifcmat:Mat01_2j55VthSj3Lu0J6fyrpHVf ;
ifcmat:layerThickness "0.045"^^xsd:float .

ifcmat:MatLayer01_2j55VthSj3Lu0J6fyrpHVu a ifcmat:IfcMaterialLayer ;
ifcmat:hasMaterial ifcmat:Mat01_2j55VthSj3Lu0J6fyrpHVu ;
ifcmat:layerThickness "0.045"^^xsd:float .

ifcmat:Mat02_0jJ6Sr2iLA6h0PV14IiNhT a ifcmat:IfcMaterial ;
rdfs:label "Plasterboard"^^xsd:string ;
ifcmat:fractionOfVolume "0.210526315789"^^xsd:float .

ifcmat:Mat02_0lHL5LPIr3RuynIxjjrPON a ifcmat:IfcMaterial ;
rdfs:label "Metal - Stud Layer"^^xsd:string ;
ifcmat:fractionOfVolume "0.741935483871"^^xsd:float .

ifcmat:Mat02_0lHL5LPIr3RuynIxjjrPZ6 a ifcmat:IfcMaterial ;
rdfs:label "Metal - Stud Layer"^^xsd:string ;
ifcmat:fractionOfVolume "0.741935483871"^^xsd:float .

ifcmat:Mat02_0lHL5LPIr3RuynIxjjrPcN a ifcmat:IfcMaterial ;
rdfs:label "Plasterboard"^^xsd:string ;
ifcmat:fractionOfVolume "0.296296296296"^^xsd:float .

<http://www.semanticweb.org/marianiki/ifcmat#Mat02_0mxk1RW8H5mvX1dNnpRq$s> a ifcmat:IfcMaterial ;
rdfs:label "Plasterboard"^^xsd:string ;
ifcmat:fractionOfVolume "0.296296296296"^^xsd:float .

ifcmat:Mat03_0niaWDKEXA48tluuFcC0m6 a ifcmat:IfcMaterial ;
rdfs:label "Wood - Sheathing - plywood"^^xsd:string ;
ifcmat:fractionOfVolume "0.0711610486891"^^xsd:float .

ifcmat:Mat03_0niaWDKEXA48tluuFcC0nG a ifcmat:IfcMaterial ;
rdfs:label "Wood - Sheathing - plywood"^^xsd:string ;
ifcmat:fractionOfVolume "0.0711610486891"^^xsd:float .

Appendix VI: Results of CO_2e for materials in Duplex model

Concrete	4229.539^^<http://www.w3.org/2001/XMLSchema#float>
Wood - Sheathing - plywood	2838.3027^^<http://www.w3.org/2001/XMLSchema#float>
Insulation / Thermal Barriers - Semi-rigid insulation	637.50287^^<http://www.w3.org/2001/XMLSchema#float>
Insulation / Thermal Barriers - Rigid insulation	25316.684^^<http://www.w3.org/2001/XMLSchema#float>
Wood - Flooring	2286.4846^^<http://www.w3.org/2001/XMLSchema#float>
Wood - Dimensional Lumber	21642.473^^<http://www.w3.org/2001/XMLSchema#float>
Metal - Stud Layer	172531.92^^<http://www.w3.org/2001/XMLSchema#float>
Ceramic Tile	700.5924^^<http://www.w3.org/2001/XMLSchema#float>
Roofing - EPDM Membrane	3409.5527^^<http://www.w3.org/2001/XMLSchema#float>
Masonry - Brick	11325.969^^<http://www.w3.org/2001/XMLSchema#float>
Masonry - Grout	46.077427^^<http://www.w3.org/2001/XMLSchema#float>
Plasterboard	4421.8076^^<http://www.w3.org/2001/XMLSchema#float>
Masonry - Concrete Block	12977.343^^<http://www.w3.org/2001/XMLSchema#float>
Roofing - Barrier	390.80255^^<http://www.w3.org/2001/XMLSchema#float>
Concrete - Cast In Situ	10250.754^^<http://www.w3.org/2001/XMLSchema#float>

Appendix VII: SPARQL graph