Tiago António Dias da Silva Santos

BIM in Design for Manufacturing and Assembly: Bridging the gap in AECO Industry 4.0

The European Master in Building Information Modelling is a joint initiative of:
Tiago António Dias da Silva Santos

BIM in Design for Manufacturing and Assembly: Bridging the gap in AECO Industry 4.0

Master Dissertation
European Master in Building Information Modelling

Work conducted under supervision of: Bruno Acácio Ferreira Figueiredo
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Lastly, to all my friends from the masters, I appreciate all the moments we shared even during online classes, you were a family to me.
STATEMENT OF INTEGRITY

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

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

[Signature]

Vasco Santos
RESUMO

A construção civil está a passar por mudanças, a falta de mão de obra é um sinal das alterações que estão afetando o mundo. Desde a crise financeira de 2008, a construção sofre e anseia por encontrar soluções para fazer face à nova procura de habitações e à falta de resposta à atual procura de mercado. A mudança para construção em fábrica tem vindo a ser debatida recentemente com o desenvolvimento na tecnologia, onde Building Information Modeling (BIM) lidera esta nova transição. Projeto para Manufatura e Montagem (DfMA) é a ideia neste contexto, potencializando o projeto e a produção de componentes pré-fabricados (Off-site construction), para serem posteriormente montadas e transportadas para o local, proporcionando uma solução viável para o problema apresentado.

Esta dissertação resulta de uma colaboração com o Grupo Casais, uma empresa de construção portuguesa sediada na cidade de Braga. O objetivo era desenvolver processos de pré-fabricação sustentáveis, para serem aplicados em atuais e futuros projetos. Neste contexto, a integração de ferramentas BIM em projeto e fabricação de sistema de paredes divisórias, com várias aplicações e combinações. O objetivo deste processo desenvolve-se na possibilidade de maximizar a repetição dos elementos pré-fabricados a serem utilizados e sistematizar a sua montagem no local. Portanto, beneficiada implementação de DfMA, maximiza-se recursos e tempo, sem comprometer todas as especialidades envolvidas, aproveitando as vantagens da construção em fábrica.

A solução desenvolvida utiliza a Programação Visual para gerar um processo de divisão e ordenação de espaços pela sua disposição, para posteriormente transformar em dados. Para além disso, através da investigação utilizou-se parâmetros com o objetivo de ajudar a organização e classificação (dentro de limites específicos) das componentes da construção. Este método permite sistematizar os conhecimentos necessários para definir uma ferramenta computacional para a otimização da fabricação dos espaços de um determinado projeto. Com este objetivo em mente, a investigação teve como foco o desenvolvimento de modelos computacionais que maximizem a saída de todas as informações.

Esta investigação visa completar a ligação da pré-fabricação entre arquitetura e engenharia aplicando DfMA por meio de ferramentas BIM. O resultado visado permite a aplicação num projeto que não foi preparado para ser pré-fabricado, tornando-o uma solução que permite a transição. Com a sistematização de um conjunto de modelos computacionais em uma Interface de Programação de Aplicativos (API) BIM, o objetivo foi coordenar e incorporar todas as informações que constam no modelo para otimizar e gerar dados que possam auxiliar na pré-fabricação e planeamento da fabricação das componentes.

Palavras-chave: (BIM, Projeto para Manufatura e Montagem, Pré-fabricação, Programação Visual)
ABSTRACT

The construction industry is changing, the lack of man labour is a sign of the changes that are affecting the world. Since the financial crisis of 2008, the construction suffers and eagers to find solutions to face the new demand for housing and the lack of response to the current market gap. The shift for off-site construction is being talked recently with new development in technology with Building Information Modelling (BIM) leading this new transition. Design for Manufacturing and Assembly (D is the idea in this process, enhancing the design and production of the building parts in-house to be later assemble and transported to the site, providing a viable solution to the challenge presented.

This dissertation result from a collaboration with Grupo Casais, a Portuguese construction company based in the city of Braga. The aim was to develop sustainable prefabrication processes, to be applied in current and future projects. Namely, the integration of BIM tools for the design and manufacturing of partitions walls system with a high degree of combinatorial application. The goal of the process contemplates the possibility of maximizing the repetition of prefabricated elements to be used and systematize their assembly on site. Therefore, by following the principles of DfMA to incorporate the maximization of resources and time, without compromising stakeholders and benefiting from the advantages of offsite construction.

The solution developed uses Visual Programming to generate a process to divide and sort rooms by their typology, to later export as data. Additionally, through the research it used parameters with the aim of helping in grouping and sorting (within specific constrains) the building parts. This method allows to systematize the knowledge needed to define a computational tool for the manufacturing optimization of the rooms of a given project. With this goal in mind, the research was focused on the development of computational models that maximize the output of all the information.

This research aims to bridge the gap of prefabrication between architecture and engineer by applying DfMA through BIM tools. The desirable outcome can be applied to a project that was not prepared to be prefabricated, hence making it a reliable solution to make the transition. With the systematic definition of a set of computational models in a BIM Application Programming Interface (API), the aim was to coordinate and cooperate all the information available inside the model to optimize and generate information that can further help in the prefabrication and planning of building components.

Keywords: (BIM, DfMA, Off-site construction, Prefabrication, Visual Programming)
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1. INTRODUCTION

The construction industry is changing, the lack of man labour is a sign of the changes that are affecting the world. Since the financial crisis of 2008, the construction suffers and eager to find solutions to face the new demand for housing and the lack of response to the current market gap. The shift for off-site construction is being talked recently with new development in technology with Building Information Modelling (BIM) leading this new transition. Design for Manufacturing and Assembly (DfMA) is the idea in this process, enhancing the design and production of the building parts in-house to be later assembled and transported to the site, providing a viable solution to the challenge presented.

This dissertation results from a collaboration with a construction company, that is tackling the transition to DfMA through the development of in-house methods and processes. Despite of what architecture and engineering offices apply to a project, the solution developed employs fabricated principles to a project that was not meant to. Consequently, the solution transports the partition wall system of the building to an assembly factory, and by developing a process of distributing and grouping, it was possible to optimize the elements (for mass production) to be assembled and transported for the site.

The solution developed was a manual process which was time-consuming and could lead to hazards. Acknowledging that, the use of BIM could optimize the process and provide solution to it, by cooperating with Visual Programming to generate information inside the model. Additionally, the definition of parameters with the aim of grouping and sorting (within specific constrains) the building parts and their data, will systematize the knowledge needed to define a computational tool for the manufacturing optimization of the rooms of a given project. With this goal in mind, the research was focused on the development of computational models that maximize the output of all the information and provide a methodology for the integration of DfMA through BIM tools.

The aim of the dissertation was to mind the gap between traditional construction methods and the construction in industry 4.0, where the process is automated and digitalized, creating collaboration through data exploration. Therefore, the principle of digitalization and BIM proofs the need to improve and optimize the process of information and management. Furthermore, a digital process allows all stakeholders to be involved in the integration of DfMA by providing a production tool through the BIM model.

1.1. Scope and motivation

Nowadays, it is urgent to define more sustainable construction processes, the adoption of prefabrication systems in the construction industry. With higher developments in technology and research, and with the current market shifting towards BIM, there is a huge opportunity to make developments in this area. In regards of educating Architects and Engineers towards the use of this systems is resourceful and time consuming. To improve the industry, it is needed to develop knowledge and methods that consider prefabrication processes in all the stages of the project. The construction market urges to shift to prefabrication in order to fight the lack of man labour and optimise the resources and reduce material waste. Since the current pandemic off-site construction has become more pertinent, due to the high restrictions of agglomerates of people.
This dissertation result from a collaboration with Grupo Casais, a Portuguese construction company based in the city of Braga. The aim was to develop sustainable prefabrication processes, to be applied in current and future projects. Namely, the integration of BIM tools for the design and manufacturing of partitions walls system with a high degree of combinatorial application. The goal of the process contemplates the possibility of maximizing the repetition of prefabricated elements to be used and systematize their assembly on site. Therefore, by following the principles of DfMA it is expected to the incorporate the maximization of resources and time, without compromising stakeholders and benefiting from the advantages of offsite construction.

1.2. Objectives and methodology

This research aims to bridge the gap of prefabrication between architecture and engineer by applying DfMA through BIM tools. The desirable outcome can be applied to a project that was not prepared to be prefabricated, hence making it a reliable solution to make the transition. With the systematic definition of a set of computational models in a BIM Application Programming Interface (API), the aim was to coordinate and cooperate all the information available inside the model to optimize and generate information that can further help in the prefabrication and planning of building components. Consequently, the research focusses on following an in-house process developed by the Casais to group multiple similar bathrooms and optimize the typology to be easily replicated and mass produced. The following list stat all the objectives that this dissertation focus:

1. Literature analysis of integration of DfMA in BIM and its applicability in the context of Offsite construction;
2. Creating guidelines to optimize projects to DfMA, by mapping a process of analysis and convert to information and apply in the context of BIM;
3. Create a set of rules to define an algorithm strategy to manage a set-by-step process in an on-going project to be optimized to DfMA;
4. Generate and automate process of developing partition wall to be produced as DfMA in a project;
5. Analyse panelling system customization to be produced and assemble. Working with information to decision making and model analysis;

The study focusses on the analysis of the state of art literature in regards of the topics that belong to off-site construction and DfMA. Consequently, BIM was an analysis as a set of methodologies process and software’s that contribute for the development. Then the case study provided by Casais was analysed so as all the documentation that was developed in-house. Therefore, the analysis of the case study and the methodology, gave boundaries and an idea of how the process contributes to the outcome.

Furthermore, the heavy use of Visual Programming Language systematic definition of a set of computational models in Dynamo (Computational attractor system using the environment data from Autodesk Revit), allow to apply the ideologies develop by the company and combining shared parameter with information to be later exported as resource for design decision. Since, for DfMA there are a lot of stakeholders that need to be consulted before applying changes, the parameters serve as tools in decision making.
For the research a residential project was provided by the construction company as case study. Additionally, the file was a CAD drawing so as all the documentation related to the process for DfMA. Consequently, all the resources used in the model were imported to Revit to be then model with basic walls and slabs that surrounds the room wall to work with IFC, creating a link for a new file to be added to the reference model. Lately, all the optimization process was shown during the dissertation was applied to the Revit file. The use of shared parameter and the collaboration of them were the key criteria to compile all the information in regards of the methodology developed.

The last step was to provide information output in datasheets (Excel) and the use of Power Query and Power Pivot to work with the data form the file Revit schedules into graphics and tables with information in regard of DfMA, that can lead to design optimization and manufacturing automatization.

1.3. Structure of the dissertation

The dissertation is divided in three main chapters, the first is an introduction to off-site construction and DfMA, then a second dedicated on the analyses of the case study and methodology, and lastly a chapter dedicated on developments of the code and explanation of the process and results.

The first chapter is a literature review of the developments on off-site construction and DfMA, dedicated to the analysis of the methodologies and advantages. Further understanding of the liabilities of this process were considered, where the problems that come with the implements in the architecture and engineering companies, and even the lack of solutions and resources, were detected. Additionally, the advantages of BIM and potentially uses for this method of construction were analysed, focusing on the technology developments and the integration with BIM dimensions.

The second chapter is focused on the analysis of the partition wall system which will be the case study of the dissertation. In this chapter it was analysed the process generated from the company Casais, where the walls that to be standardized and mass produced were studied in regards of their properties and application in the room. Additionally, bathroom layouts were surveyed, given the properties of this space, concentrating the investigation on the types of bathrooms and their similarities, to be further applied in the process of DfMA, and ultimately to be sent to the technicians.

The third chapter is the digital systemisation of the process analysed in the chapter 2. The digital process was divided in three milestones, where the process is conducted and generated in phases to achieve the desirable outcome. The first milestone was the reception of information and preparation of the file to be suitable to DfMA. The second milestone focus on defining parameters to identify the typologies of the bathroom with the use of a hierarchical code of parameters. The third code was based on a code that detects sub-typologies of the room, by identifying small variations in the typologies that were created previously. Consequently, after the information being added to the model, a last chapter is dedicated to treat and organise the information, in order to be a useful resource for production stage.
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2. BIM AND OFF-SITE CONSTRUCTION

The roots of the off-site construction stem from the end of World War I that affected the construction industry by major shortages of skilled labour and building materials and this shortage triggered a need for search of new methods of construction (Ezcan, Isikdag and Goulding, 2012).

This chapter focus on the developments in BIM and Off-site construction as a resource which potentialize it’s use in developments in the future of construction. It is structured as a literature review of the current technologies and process, which explores the market uses to empower BIM as a design driven tool to the development of this century old topic. This literature Review creates an analysis of BIM assessments, and his technological advances shows the key factor for taking advantage of current available tools to optimize for future and current challenges in which Off-site construction faces.

2.1. Off-site Construction

Since the financial crisis of 2008 the construction sector suffered from a loss of 20% of man labour. Table 1 shows the current market gap between people who work in the construction sector between 2008 and 2020. This problem outstands with the current pandemic that, during the time this dissertation was written, has suffer in the past months from a reduced number of workers and a slow decrease in productivity, even if there is a lack of information. The construction productivity is directly related with how effective, fast and on budget can a building be constructed.

<table>
<thead>
<tr>
<th>Sectors</th>
<th>Total 2008</th>
<th>Total 2020</th>
<th>Construction 2008</th>
<th>Construction 2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>European Union</td>
<td>193 164 600</td>
<td>197 153 600</td>
<td>15 967 000</td>
<td>12 840 000</td>
</tr>
<tr>
<td>Germany</td>
<td>38 541 500</td>
<td>41 716 000</td>
<td>2 563 500</td>
<td>2 276 600</td>
</tr>
<tr>
<td>Portugal</td>
<td>5 116 600</td>
<td>4 814 100</td>
<td>539 600</td>
<td>297 100</td>
</tr>
<tr>
<td>Italy</td>
<td>23 090 300</td>
<td>22 903 800</td>
<td>1 952 500</td>
<td>1 357 900</td>
</tr>
</tbody>
</table>

Off-site construction involves the fabrication and assembly of construction elements to be later transported to the construction site, being light-steel, wood, and composite material more favoured in the development. With high hopes for on the current technology, the promise of lower project costs, shorter schedules, improved quality, and more efficient use of labour and material, proofs the outgoing interest by the community in making the switch. The expansion of this process is being due to building codes that hinder innovation as well conventional design and construction process and practice.
Following the study released by National Institute of Building Sciences (2014), by comparing 8 cases of use of Off-site construction, there are significant advantages in the use of techniques for modular construction during the building process. The cost average has dropped 16%, compared to typical construction framework, and an average schedule reduction by 45%. According with Construction Users Roundtable (Modular Building Institute, 2010) in 2007 the most important advantages of Off-site construction were:

1. Controlled environment, more quality check and control, easier access to tools and material deliveries;
2. Less environmental impacts due to the reduction in material waste, air and water pollution;
3. Compressed project schedules that result from changing the sequencing of workflow;
4. Less in work conflicts by better scheduling and by creating an in-house assembly of craftsman;
5. Bigger on-site dock by reducing the on-site storage and fewer losses or misplacements of construction material;
6. Increased in safety of the workers through reduced exposures to inclement weather, temperature extremes and ongoing or hazardous operations;

Figure 1 – Graphic that represents the feedback of the engaging the off-site contractor in the process (Smith and Rice, 2017)

The figure 1 shows results that represent how the process of transition to off-site construction technologies is applied to later stages of the operation, and how the workers engaged on the project observed what would be the best time to think about Off-site construction process. When the project team makes decisions of changing the construction strategy to a modular type, it’s more likely that to have an negative impact on the project schedule and cost. The late design changes, lack of collaboration and an adversarial climate for project delivery leads to difficulties in realizing the benefits of off-site construction (National Institute of Building Sciences, 2014). The study that was realized attest that the biggest barrier to Off-site construction is the design and construction culture.
Figure 2 - Cost per square-foot comparison analysed by Cumming Corp. (Smith and Rice, 2017)

Figure 3 - Schedule comparison in months analysed by Cumming Corp (Smith and Rice, 2017)
The literature review helped to frame a set of problems that need to be addressed in order to implement Off-site construction processes in more types of projects:

1. Need for a higher level of technology information application – Need of tools to keep a track of the building attributes;
2. Earlier prefabricated systems which has a bad reputation – Related with post war architecture and related with social housing;
3. Designers and contractors lack of experience – Limited expertise in Off-site construction, making it harder to implement;
4. Hard to make modifications – Requires the project to be stable since the beginning, since it can’t be changed through the process;
5. Transport limitation – Some elements can’t be transported, hence the fact that the system needs to be optimized to be moved;
6. Demanding task – Some tasks take more time that previewed, creating delays when the system is connected to another;
7. Higher Initial Cost – Higher initial cost to be expend in expertise and in a more detailed design to be then applied in the construction site;
8. Aesthetic – Repetitive design and lack of innovation;

![Diagram of On site construction compared with offsite construction, over 5 years](image)

**Figure 4 – On site construction compared with offsite construction, over 5 years (Southern, 2016)**

2.2. BIM relation with Off-site Construction

BIM is shifting the construction industry into breaking new grounds and promoting new technologies and new building techniques through sharing information in a BIM model. The research focused on BIM is mainly concentrated in improving model abilities of acquiring, storing and sharing the construction related data. These improvements not only increase its information management abilities, but also give BIM a role as a facilitator for new technologies and building methods. (Ezcan, Isikdag and Goulding, 2013).
The literature review by Yin et al. (2019) showed the impact of BIM as a mediator which reduces the gap and improves the Off-site construction process. It improves design quality, promotes collaboration, communication and manage, and stores the information in one place, benefitting the technology for Off-site construction implementation. With BIM, an accurate virtual model of a building is constructed with precise geometry and relevant data needed to support the procurement, fabrication, and on-site installation activities. Mullett (Mullet, 2017) defined 8 tools that express the advantages of implementation of BIM systems in Off-site construction:

1. Visualization - Real time visualization of the model and of the components which belongs to the BIM model;
2. Modelling - Ability to generate parametric families which helps to optimize the process of module creation and direct implementation in the main model;
3. Code reviews - Ability to store information in regards the building code and providing access to the information inside the model;
4. Fabrication/ shop drawings - Create drawings form BIM model to be used as tools in the construction site;
5. Communication - BIM promotes collaboration and communication between multiple stakeholders.
6. BIM 4D - Provides tools for a complete time schedule of construction phase, allowing better coordination in the construction site;
7. BIM 5D - Cost estimating and bid of quantity can be created with schedules and be automatically updated during the process;
8. Clash Detection: Coordination of collisions between multiples stakeholders, system to detect flaws in the model and to better communicate problems;

Table 2 - Summary matrix that positions BIM benefits for overcoming barriers in OSM processes. (Lawson and Ogden, 2010)
Yin et al. (2019) compile all literature reviews and analysis of BIM for Off-site construction. In this paper, they state that there are five summarizing topics in which BIM development can improve this matter: The interaction between BIM and Off-site Construction; BIM for DfMA; BIM enabled logistic planning; BIM enabled assembly planning; as-built BIM for construction control. The interaction between BIM and Off-site Construction can be pre-modelled as BIM objects into a BIM library, this process allows these objects to be parametric families containing information in regards of the modular object that can adapt in different context by changing some parameters.

BIM to DfMA is considered one of the most constrained process due to the needs of the integration of different stakeholders into the design stage. This methodology aims to improve the manufacturing and assembly of prefabricated construction elements. However, due to different configuration between off-site and on-site construction process, BIM tools face some difficulties. Considering that most elements in on-site are made cast-in-situ construction materials, as in off-site the elements need to be assembled in factory, this makes the base families worked in different way, as more information need to be added to off-site construction.

BIM enabled logistic planning, by easing the definition of a supply chain for the several construction stages, enhancing the integration of prefabricated building. The information about the building elements at each stage should be collected in real-time through cloud-system to control and manage the process in-site, this can also be applied in the management of the prefabricated pieces in off-site manufacturing, through the definition of codes that help to keep track of the elements. Thus, creating an overall identifying system for the assembly and positioning of the elements before and after delivery.

BIM enabled assembly planning - Scheduling the construction is one of the most important roles so the manufactures can do their role, as following along the assembly schedule. Assembly planning combines BIM 4D capabilities to track construction development by preparing scheduling and cooperation with stakeholders and with the contractors.

As-built BIM for construction control – The prefabricated elements need quality control and assessment on as-built information collection. In most projects, the quality inspection is conducted manually, which leads to low efficiency and accuracy. Laser scanning is a good tool to collect information on site, since the manual assessment data cannot be stored properly for later management analysis.

![Figure 5 – A typical supply chain of OSC projects (Yin et al., 2019)](image)

BIM is extendable to management activities and to their information exchange which improves the overall transition for offsite construction. It has a lot to offer to the overall switch to this paradigm and during the off-site construction management there are a new step in the construction part that needs to be considered during the overall process, such as manufacturing, storage, and transportation. This processes in addition to the existing ones (design, construction, operation) demands effective communication, technologies, and tools to improve cooperation.
The number of papers related with Off-site construction and BIM are scattered and does not contain new inputs to the matter. This shows how unique the subject is for the construction industry. With the urge to create this change, there is a barrier that block the transition to mind the gap. The fact there is a lack of expertise in the subject, but more important, the ability to address the issue without compromising the design part or construction.

Despite the advances that BIM has introduced in the design process and in the construction industry, it still does not provide tools that focus on Off-site construction, makes this transition harder. As shown previously, Off-site construction is a decision that needs to be taken since the beginning, because it does affect the overall phases of the building, not allowing the user to make changes in later stages. The idea of BIM as a tool with parametric capabilities is not the main point of the overall use of it in the Off-site construction, but it provides a better design decision, automatic correlation between parts of the project, cost detection and quantification of the elements, allowing the early stage to be more accessible to all the stakeholders and providing the clients with decision making information.

2.3. Design for Manufacturing and Assembly

Design for Manufacturing and Assembly (DfMA) can be described as a set of design guidelines combined with an evaluation and optimization methodology for improving the design of a product regarding how it is made. (Kuzmanovska and Aitchison, 2019)

DfMA is a design process in which the elements of the building will be standardized and design to be as effortless and cost effective to be produced. This process is a design decision empowered by the architecture, architects can design a building to be enabled to be or not DfMA if it is thought since the design stage. However, architecture is a service where the main goal is to match client desires and generates design proposals, on the opposites manufacturing is non-service that maximize productivity and money/cost average per element by maximizing the output.

DfMA convert a building into a prefabricated design driven which elements needs to be modular and repetitive to be mass produced. Exploit designs rationalize, materials optimization, scheduling deliveries or on-site management to maximize productivity makes this a solution in Off-site construction. Manufacturing and Prefabrication will not get overtaken by DfMA, the process and techniques might differentiate between different components of the building. Leveraging digital tools in parametric design, architects have taken mass customisation as a design strategy to realize greater individual artistic expression. (Smith, 2019)

Embracing the principles of manufacturing – standardisation to mass customisation – has the potential to empower architects to be able to respond to the current demand and have greater impact on delivering democratic housing design for the masses. (Smith, 2019)

After literature review, it was necessary to analyse the process of standardisation and customisation by evaluating which types of process exist and how they are applied in the construction site. Smith (2019) create the following list is a result of the different types of customisation and manufacturing processes and how they directly affect the construction industry and architectural design of customized elements:
1. Made-to-Stock - As stated by the name, this process stock elements as strategy by lowering complexity and increase repetition;
2. Assembled-to-Stock - Customisation is introduced in design and standardisation. The concept of assembly line production and mass customisation are established in this process;
3. Made-to-Order – Elements are made to be deliver in site on time. This process has a determined design and engineering option apply to the process that allows to be customized without changing the production line;
4. Engineered-to-Order – Customizable elements that can’t be mass produced due to the unique application. This process thrives to provide competitive prices and delivery time to their output;

![Classification of prefabricated systems used on construction](Teribele and Turkienicz, 2019)

The figure 6 shows the types of prefabricated elements that can be mass produced using DfMA. This process is the ones that can be assembled-to-stock to be applied in construction site. This element can be unique and at the same time being produce in assembly line, making it a good fit for DfMA using BIM tools. However, since this element is not considered a made-to-stock components, it’s not easily fitted inside the BIM modelers software, making the process of manufacturing components easier than generating it in BIM. There is a gap between these type of elements compared to family-based components: Made-to-Stock elements contain a base of restrictions and dimensions and contain some cases where the structural frame is system inside, which is frequently used for manufacturers; Assembled-to-Stock can be used in certain elements inside the building, which usually don’t get standardized firstly because of the in-site process currently existing, second because they are more frequently used to extract information, rather to be used as a base for DfMA.

Following Smith (2019) research, the application of components as DfMA in the construction requires to go through three levels of manufacturing, following phases to generate the prefabricated modules in the building: parts, sub-assembly and assembly.

1. Parts: Stand-alone material or components of the construction that need to be sub-assemble in factory before moving to the construction.
2. Sub-assemblies: This refers to components, panels or modules that are pieced together with parts to create elements to be assembled on site.
3. Assembly: This is the act of setting sub-assemblies together on site in their final location and stitching.
2.4. BIM in Design for Manufacturing and Assembly

The DfMA assessment consist of a linear iterative optimization process based on already defined design details. This process can only be applied after their formal characteristics, such as design and structural parts being formally defined to be applied in the construction part of the building. The figure 7 shows how important the work process of DfMA operates in the architectural team. The process considers the architecture and engineering team working collaboratively together to maximize and formalize all the parts of the building before advancing to the next stage.

![DFMA-oriented architectural design team](image)

*Figure 7 - DfMA -oriented architectural design team (Yuan, Sun and Wang, 2018)*

The figure 7 is a schema presenting the role position for DfMA and the framework for collaboration. After analyzing the role of the architect and engineering as promoters of the process the split designer and the assembly technician, will manufacture and assembly the components for the building. BIM allows the communication and management of the process during the design for manufacturing procedure, to generate components of the building and to manage and control them in the assembly phase. The exchange of information between multiple stakeholders is one of the biggest advantages of BIM especially during all the process.

BIM is a key technology capable of supporting DfMA, and DfMA makes BIM more suitable for prefabricated buildings. DfMA-oriented parametric design, a new design philosophy, is the organic combination of DfMA and BIM parametric design. (Yuan, Sun and Wang, 2018)

The automation of DfMA is the most crucial step that turns the information in design, since it’s a time-consuming task involving elements, parts and assembled components. Towards achieving this procedure, it is important to define a process which combines BIM functionalities to maximize the output and provide a better performance. The first step in achieving DfMA is by establishing a reference model with all the stakeholder’s information, then to proceed towards the detail design analysis of the basic model. This fundamental step allows the elements to be later added in the process as part of the
manufacturing and assembly process. From the parametric precast components and assembly functions in BIM, there is a need to check the elements that will be manufactured. The elements contained inside the BIM library can be adapted to be prefabricated using the BIM re-development or BIM family template. The last step is exporting the information as drawing and optimized prefabricated building information model.

Parametric modelling improves the design and modelling productivity by providing an effective and optimized method, improving building manufacturing with the use of parametric objects retaining design content in response to external and internal spurs. Parametric modelling is limited in its applicability in DfMA for construction focus design detailing due to the complexity of the components and their haziness, since there is a lot of detail inside each component. These parametric elements need to be created in a hierarchical way to avoid the manual position of it, minimizing the number of manual inputs in the model.

Research on the subject focus in automatization of the process in executing parametric components for building manufacturing elements. These elements are considered in BIM as system type of families with specific roles in the construction, that don’t contain enough information to be exported as DfMA. Due to their layer based composed properties, the representation of the part of the assembly is not a part neither are shown as part of the components. One example of this elements is wall type system. The discoveries in this subject focus on process to develop and create a gap on the manufacturing process of this elements, minimizing the manual input.

The figure 8 shows a workflow process of generating frame system and boarding for wall created by Liu Et. Al. In this process, it’s possible to analyze the three stages of automation in system families, where the inputs are the BIM model and external factor provider for manufacturing. Then, the parametric design optimizes of the parts into assembly components using API to be exported as information for construction. However, the process of developing BIM for DfMA is not as linear. A model may not be suitable for such task if there is a variation of the components. As stated before, to maximize the potential of DfMA, it should exist a lot of repetition in the elements to maximize manufacturing. In the next chapter this idea will be analyzed with use of a practical case.

Figure 8 - System Architecture (Liu et al., 2018)
3. DFMA APPLICATION IN PRACTISE

The previous chapter makes an introduction of the BIM and DfMA which will be the main topic of this dissertation. To understand this process and to understand the problem, which was studied, this research was conducted with the help of Grupo Casais, a construction company based in the city of Braga, Portugal. This construction company has one split company named TopBIM which consist in a technical team that creates and develops DfMA. Inside the group there is a technical team which manufactures and assembles the prefabricated elements called Blufab.

This thesis main topic of research was proposed by the company to tackle a problem which they face when implementing DfMA process. The TopBIM team has a manual workflow of the procedure of assessment of the building, which lead to a time-consuming method and loss of information. The goal was to automate the process of generating information and use it as design driven procedure that contains data regards the building project and apply in an architecture project already developed without compromising this class.

3.1. DfMA in partition walls system

TopBIM developed a workflow for partition wall system which consist of manufacturing room walls in factory and deliver to the construction site. The idea was to apply all the principles learned before and apply the concept in closed room of the building. The type of room which was defined to be the tested was the bathroom since it can have multiple repetitive elements and can be standardized multiple types. However, bathrooms design deals not only with the layout of the bathroom furniture, but also with the infrastructural data, such as plumbing system that runs in between walls and the fact that there are multiple variation of bathroom depending of the dimensions.

Figure 9 – Blufab prefabricated bathroom by partition wall system
Bathrooms are complex compartments in the building, for being closed spaces which makes the process for DfMA an improvement of productivity in terms of collaborating in this space. The design of bathrooms has a mutual correlation and collaboration between architects and engineers since, there needs to have a structure, space disposition and plumbing system. Hence making it a priority in automatization using BIM.

Traditional methods of construction in bathroom develops around the collaboration of multiple employees inside the same space. The cut of the profiles and the assembly need to be done in site, to be later applied inside the room. The hot and cold water, that comes from the ceiling will be attached to the plumbing of the room to later pass underneath the profiles and connect to each sanitary. The elements that are connected to the wall will expel the waste through the sewer to later connect to the main sewer line of the building. To close all the space 2 panels of gypsum board will reinforce and surround all the space creating the finish face of the wall, the finish material will be applied on top of this walls.

The new process allows the fabrication of the frames of the wall to be conducted in factory and later transported with the board cut to the place it fits, since was already measured to fit in that specific wall with the fixtures marked. Later, the frames are carried and put on place, to then apply the infrastructure underneath that will be attached to a prefabricated piece to attach the sanitary, preestablished from factory. The boards are cut with desirable dimensions, to fit in the prefabricated component.

To develop a new workflow, it was used an in-house residential project with five levels, which contains approximately 500 bathrooms. This amount of bathroom made the company evaluate the number of different rooms which are contained inside the building, reducing the total number of variations of the design of the minimum bathrooms possible. However, since this process was not automated a technician use a CAD plan of the building exported from the BIM model, that was provided from the architecture firm, to be the assessment for DfMA.

The CAD plan was the only available resource, even if doesn’t contain enough information. However, it can serve as further improvement in the BIM model, then it was possible to detect the location of the rooms and walls, since it was the only file that was provided between the architecture firm and the construction company. Consequently, the task of the technician got more complex because of this huge barrier that the file takes from the workflow. However, the task liberation was developed with the use of this resource by creating a set of steps to achieve the design optimization for DfMA:

1. Map all the bathroom inside the CAD drawing and remove the one which are unique, since they will not be adaptable for DfMA;
2. Separate the Bathrooms in Groups by dimensions and disposition. Separate in the CAD file to then overlap in multiple blocks;
3. Find relation between bathrooms to reduce the number of different types;
4. Set similar bathrooms which may be inverted in new sub-types;
5. Find a fit modular bathroom of each type;
3.2. Process workflow using DfMA

In this chapter, the manual workflow will be analysed to be transpose to a digital process optimized with the use of BIM. The problem starts with the creation of a hierarchical approach to separate all the rooms in different types of categories, since all the room have different attributes and disposition. The bathroom has different types of organization, but the elements which are inside the room are similar with two elements being the mandatory to be considered bathroom: toilet and lavatory.

The first process starts with the separation of the rooms by selecting previously their geometry, through the number of faces. Consequently, the faces represent the number of walls inside the bathroom and can be splitted in different groups. Then all the bathrooms were selected by size and dimensions, then divided in another groups, so in the end, the selected few can be detected by the formal disposition of the space (Fig. 10).

This process was done manually with some uncertainties in some cases, some elements didn’t fit the criteria. This creates a problem of human error in the process that will generate future difficulties. Nonetheless, with the use of this process the 500 bathrooms that exist inside the model, could be sorted in 30 groups, reducing the gap of unique types. However, since the rooms belong in groups, there is a need to detect all the smaller variation in the BIM model which can be mass produced and manufactured, without compromising the architecture and structural part of the building.

![Figure 10 - TopBIM floor plan of the residential case study with the marks of each bathroom](image)
The process stands to find the number of similar compartments and why they are different, to later find a middle term block that will fit the position which they have in the project. Some block, as the figure 11 shows, can be a type with more than one variation. Some rooms are dependent of their spatial position, which can be inverted in relation with the spaces. In terms of grouping elements by type this doesn’t create a problem however, in DfMA the wall, which is inverted makes already a different component, that needs to be thoughtful in the design and assembly process. The reason sub-types are crucial is due to all the parts that belongs to the group be the same, yet the way they are assemble is different depending on the disposition of the elements.

![Figure 11 - Room type grid with final block](image)

The figure 11 shows how this process was created in manual form, where they pick each room similar in all floors of the building and stack them on side of each other to identify similarities. The table represents a typology, and the rows represent the subtypes of each selected type. The columns are the different variation of room with similar proportions and dispositions. The end column it’s the final block chosen, which is a block that can fit in all the spaces available by that sub-type, this is one of the most demanding parts of the work and one that can’t be easily achieve on BIM. However, the fact that these changes were done to be standardized and mass produced, could be more efficient if were done using BIM, since the new changes could be sent as IFC to the architecture and engineer office to request for modifications. This method will be more certain in the design optimization of all the parts, thanks to the detection system of elements code inside the file. Therefore, the changes were done as report and the drawing file was used as recognition system, making time consuming task with likelihood of hazards.
3.3. DfMA in partition walls system of bathroom walls

The manufacturing process which Blufab developed define prefabricated components for each element that exist in the bathroom. A toilet element is a standardized component that can be produced multiple times, independently of the type of bathroom that will be implemented. The only difference stands in the element toilet, since it might have different manufacturer specifications, that can lead to different cut holes for the fixtures.

The number of existing partitions walls system in the bathroom are directly correlated with the number of individual elements inside the bathroom. Elements like Toilet, Bidet and Lavatory are unique component that will be replicated multiple times. However since, they are prefabricated as a unique element they need to be assemble in a group of walls to be part of the bathroom type wall. To achieve this role wall needs to be split in three parts.

1. Profiles - Create the frame around the wall and the in-between in their spawn;
2. Structural panelling board - Attached to the profiles, creates the support for all the plumbing of each element and to the overall system inside the bathroom. The element profile of the bathroom enters in this category since they will be replicated more often, they are manufactured with the plumbing system of each element and with the mechanical system that might be needed to support the element;
3. Finishing panelling board – Attached usually in an opposite direction of the structural panelling, they contain all the finishing material of the bathroom and contain the fixtures for the elements to be assemble;

Figure 12 - TopBIM board panelling DfMA with the information for the fixtures
The figure 13 shows the composition of all the part together in the manufacturer process. Taking the consideration of the elements that belong to the group the interior board as seen, contains all the plumbing and fixtures for each component, as contains the flush for the toilet. These elements are then attached to this profile frame that add-up to another one in some cases. When the wall is empty this process, simplifies as just the space between profiles need to be taken in account, but there are two elements that need to be rethink: firstly, the wall which contains the door, and the walls that surround the shower and bathtub.

The element of door is a simple component, however its function that need stands as a connector to both side of the partition wall, as it’s a system that works inside the room, leaving the interior exposed. The door needs to be the element that will make the transition between the two partition walls closing the gap that exists in the construction detailing. However, when the wall is a sliding door, this element instead of not only unite the partition wall, but it needs to move along the space inside both. This creates a problem already in architecture, but when taken to DiMA it gets even worse, as new information has been added, these elements can collide with the substructure of the partitions walls and make them a barrier to standardize the process. The solution is changing and playing with the different type of doors to fight this problem on some occasions.

The bathtub and shower partition wall system make part of a bigger group that is assembled to protect from future infiltration. The bathtub and shower sink are a group composed of a wall system connected

![Figure 13 - Room type grid with final block](image-url)
by common corner that connects all the sides where they intersect. Blufab came with the solution of foldable wall, that takes these elements and connects in the corners and then unite all the side of the bath as a unique group to be easier transported to the site. This solution makes much easier to manufacture the component multiple times, as bath tube is a already manufactured components, makes it already a optimize to be replicated in the manufacturing process.

Shower and bathtub partition wall system are already more trackable inside the model and in the cad drawing, then other components families. This blocks usually have a fixed place in the bathroom, which can’t be moved and goes along with the model. The biggest turn back is the fact that when fitted in the corner, makes the element directly connected to the width of the bathroom. In an optimized solution, such as final blocks, this is a problem that needs to solved, or by accepting the manufacturer dimension or rather by the length desirable to the room.
3.4. Partition wall system tracking in DfMA

![Blufab tracking code with QR code in wall (WC24)](image)

**Figure 15 - Bluefab tracking code with QR code in wall (WC24)**

The elements detecting system is one of the most important parts of the process. All the elements that are created to DfMA need to have a code to be detected in the site. To keep the track on the components a code is assigned to each wall, that will fit in each room, the code represents the wall code and which room will be attached, the figure 15 shows the code created by Blufab to keep track of the wall of the project.

This process when done manually can lead to errors when keeping track of the position and location of the element. The issue being the outdated files and manually assemble of the code in the drawings, leading to concurrence of information, and lost and displacement of the elements. BIM can tackle this task much easier, by creating a code directly in the family wall system, make it readable in the site construction. The implementation of BIM makes the partition wall system always up-to-date and easily trackable by exporting as an IFC and opened in any software used on-site.
4. OPTIMIZATION OF BIM MODEL FOR DESIGN FOR MANUFACTURING AND ASSEMBLY

In this chapter the main goal was to define a design optimization strategy that automatize the manual process analysed in the previews chapters. The automatization starts with the use of BIM as the design resource tool to achieve the maximum optimization of the process, avoiding mistakes and human errors. With the resource of a BIM model, the process was taken using the same residential cased study stated in the process above, to compare the results and to use the accumulated knowledge in the creation of the process.

To maximize the output for DfMA the process was divided in three milestones: IFC Interoperability, Typologies Generation and Sub-Typologies. Each represents a group of steps to achieve certain functions. To achieve these milestones, the software selected was Revit, since it optimizes the process using parameters which can be created inside their interface, providing information and integration during the methodology. This software contains a visual programming extension named Dynamo, that can automatize using nodes with written code that are specified to work with Revit. These parameters are then exported as information inside Revit, which combining multiple codes will provide a solution to the problems stated above.

The figure 16 represents a diagram of the optimization process and the relation between all the nodes that were developed during the investigation. The code is divided in 3 phases being the first one the creation of the data and the working file; the second the creation of the typologies; last one the sub-typologies. The image represents the connection trough a dark line and using dash line the middle stages that were used to achieve a desirable result. In each sub-chapter of this chapter all the methods will be analysed in a direct correlation of the overall structure defined in the diagram.
4.1. The IFC Interoperability – Milestone 1

This chapter will focus on how to transform the information received and prepared to DfMA. When the project is transferred to the split designer a new BIM model will be created, that will work autonomously from the Reference Model. Since this new file will work only for DfMA, the changes and information that need to be added should be only applied to the new file. One of the preliminary works that needs to be done by the split design is to detect if every bathroom as the same name, to then pass to the second stage. The file needs to be attached as Link IFC to be introduced in the BIM software as necessary information. It’s important not to exceed the amount of information in the model, since there are a lot of operations that need to be done to achieve the result.

Figure 16 - Diagram of the relations of all the codes
To prepare the information and all the details towards reaching the results, it was generated a LOD 200 family types of all the sanitary pieces of the bathroom and door slides (Fig. 17). A simple and low detail family type of elements was helpful in creating relations with the elements by creating rectangular angles, that will further be analysed and will help in additional decision making in the model. The block of the bathtub and shower are independent family types, in opposite, all the other components are wall-based families. Consequently, and since the file is a new file, the only elements that will be added will be the bathtub and the shower in the beginning of the process.
4.1.1. Partition wall generating system

The first step was to develop an automated process of generating the panelling system from the interior wall of the room (Fig.18). When exporting the IFC as a linked file, the room volume, which is a representation of the space inside, generates a boundary independently of the surrounding walls, doors, or any other elements of the building. The two element families of the bathtub and shower, as shown in previews, are different elements that need to be concerned in terms of their relationship with DfMA. These two elements have different parts and assembly system compared to others, making this element the first one that needs to be added to the design.
After applying this family block to the BIM Model, a Dynamo code consisting in mapping the boundary geometry of the room and the boundary geometry of the bathtub and shower. The followings will generate the new wall system for the partition walls. The process works by developing a new wall system and then applying a generic wall type, that consist in three layers, to be used as base wall for DfMA.

The figure 19 shows the selection of the two components: room and furniture. In this code the elements that are equal to the following type or name will be selected from all sources of information. This allows the selection of all the rooms that are considered bathrooms, the example detects all the room with the name equal to “I.S.” (means WC in Portuguese). As for the furniture the two elements which are bathtub and shower will be select form the list of elements. The output of the code above is the selection made using the select node parameters to pick only these elements from the list.

![Figure 19 – Code with steps to generate partition wall systems](image)

The figure 20 is a visual representation of the next stage, using the bathroom perimeter curves and bathtub curve, two solids will be generated. These solids will be overlapped since the bathtub block will be inside the bathroom main volume. Then, by applying a Boolean operation know as slit, the elements of the bathtub will be divided from the main volume. The result is two blocks attached to each other, to extract the curves of the volume they need to select the bottom face of the solids and extract the perimeter curves.
The process used the previews list of elements as the source to achieve the result. From the room list it was used the node “Room.FinishBoundary” that allows to detect the inner line of the room geometry to be used to generate the base surface of the solid, then by just extruding the volume from their height the solid is generated. The block is a group of multiple volumes that needs to be unified as one volume, to be then intersect. However, the height of this block needs to match the height of the room, otherwise the outcome will not be the desirable one, since the room will go after the slab dimensions.
The next stage the process starts form outing the volume of the room on top, the one that needs to be split and the geometry of the bathtub on the bottom part to split then, then using plan surface the base surface of the model will then be extracted. The end part is an extraction of the perimeter curves of the surface to be used as base for the new wall elements that will be generated. Selecting the two lines from the bathtub volume base and from the new room boundary the two list were joined as a new list of elements.

![Geometry Intersection](image)

**Figure 22 - Step 3: Split the room lines**

Then two lines will coexist in the middle, are duplicated since the intersection of both create a collision that need to be tracked. Using an offset perimeter curve of the exterior boundary, when this new element intersects the new result, they will report with true value by simply removing the true value form the main list, the lines that are left are the exterior wall of the wall, that will be then used to generate the new wall system. This process makes the creation of wall much simpler, since often wall from linked files doesn’t contain information enough of information to simply create the wall or even has too much information, that make this process harder. To have a better DfMA the less information that is imported the better the workflow.

![Room Offset](image)

**Figure 23 - Step 4 and 5: Room offset and remove the interior lines**
The last step is combining the lines that were created and select each one by floor and apply the code “Wall.ByCurveAndLocation” created in the package WombatDynamo developed by Woods Bagot (Fig.24). That, consist in a code that basically generates a wall using Curve as the base, then the ask for a Level that the wall will follow, lastly it will ask for the Location line that will provide the boundary of the wall in relation with the desirable face of the wall. However, to proceed there was the need to create a generic wall for the elements, so the basic wall for DfMA is a partition wall with three parts: two boards of gypsum board that makes the finish face and metal profiles that makes the structure. All together these elements have 70mm of thickness.

![New Walls](image)

**Figure 24 - Step 6: Create walls from the lines**

The figure 25 shows the result of the components that were created and how the information shows as result in this step-by-step process. The result is a bathroom with smaller partition walls in the core area, which is the transition of the wall with the bathtub or shower. This process is important, not only helps to quantify all the number of walls that exist in the bathroom that need to be DfMA, but it does help in the manufacturing process by providing to these elements to work autonomously form the rest of their group. This action will help in the future part of the process, as the code develops in the transition to further information.

![Figure 25 - Result of the code](image)
Figure 26 represents the method to apply the partition wall in the room by dividing the initial boundary with new lines. However, due to the fact, that the file that was provided was a CAD drawing the process change to a more manually approach, since all the walls and room didn’t exist. Consequently, the file was saved as IFC and imported back to the drawing, to be then applied the steps stated above, to test the veracity of the code. The result is what is proofed above, even if the walls that were created manually and not from an initial IFC file or even “.rvt”. The process of splitting wall can also be done manually, however this solution is not recommendable, as the split command can lead to misplacements of dimensions, leading to discrepancies.
4.1.2. Apply wall-based families

After the generation of the wall, the wall-based families inside the room need to be attached to their new walls in this stage, since this process can’t be done automatically. The fact that the wall and the elements are directly connected makes each element created to be only attached to an existing wall, making this process work in manual way, since there isn’t a solution to exchange elements that were originally attached to a wall. The elements can keep it up on the wall, it’s important to attach these elements. Consequently, when new wall was generated inside the new file, made the reference that exist with the original wall disappear, removing any information that was created previously.

The figure 27 shows the room with all the wall-based families inside it. This task is one of the most time consuming as the elements need to be in the exact place as the original elements, making this one of the making each element to be applied individually in the process. The elements door and sliding door are the biggest concern, as further in the process was detect that if the door position was not correct, it will have implication if it belongs to the room or not. In remind, this method proofs how negatively affects the procedure by simply evidence human error as a problem in the design process.

4.1.3. Apply Element ID to Rooms and Walls

This step is one of the most useful in the control and tracking of all the process for DfMA, specially in keeping the trace of the elements not only in the procedure, but in on-site. In the previews chapter was the analyses the codification of the walls to be sent to the site, there was one point that stated that BIM can generate automated codification for each element, this code is the “Element ID”. This ID allows to detect the element inside the Revit interface and can be exported when send as IFC, making an asset in element detecting, not only during the DfMA, but also during the assemble on site.
The importance of the code is resumed in the automatic generation, since any new elements will automatically have an Element ID. However, this ID is not visible in the user interface, since it’s the code that the software uses to detect elements in his API. This process output uses this parameter as source, by using Dynamo to retrieve the information of the ID and apply to a selected parameter of the elements.

![Diagram](image)

**Figure 28 - Code to apply element ID to rooms**

The figure 28 represents the code to select the rooms and apply the Element ID in a new parameter, in this case the parameter chosen was the room number. The room number is a visible parameter in the room tag, making it detectable in all the process, and to keep visual tracking on the elements. The parameter needs to be always a shared parameter to export the information as when needed in the schedule, making this parameter already a shared one. The Element ID is always attached as a value which consist in a group of numbers, making it a good fit to be used as a code to detect element.

![Visual representation](image)

**Figure 29 - Visual representation of the result – Element ID to rooms**

In the wall the method was similar except the fact that, there isn’t a visual parameter which could be used to show the tag visible, therefore was named to a new parameter called “TypeID”. The most important aspect to retain from this code is the fact that the wall is more important in terms of assembly in site, since they will be the fabricated, transported and assembled. The ID from the room is more important to generate the needed information for DfMA. Therefore, the result pass from combining this two ID in different ways to maximize the output.
4.1.4. Apply Room ID to Walls

The next code represents the process to create a connection between the Room ID with the walls (Fig.31). This step is essential since both elements are not linked in between each other. The importance of this step relies on the information that can be provided, as DfMA needs to be exported as information for the construction company to assemble the modules. Using BIM as the source of information make it possible to dimensioning, export bid of quantities, stock control and provides guidance on site. This step is important to generate the codification to be assemble in the factory and on site.

To achieve this result, it’s important to apply a process of intersection between multiple elements to detect if they belong or not to the same room. However, this is a tough process that uses a lot of interaction to identify the potential outcome. The solution found pass by creating multiple intersection by level, reducing the time needed to achieve the result.

The code starts with finding all the elements that contains in the name “IS_” in the case of the wall type and “I.S.” in the case of the room (Fig. 32). These elements need to be divided by the level, reducing the number of intersections between both, making the process of thinking faster. The level is a number which is given between the top part of each slab, that often doesn’t detect which is the height limits, so to achieve that and to avoid collision between the room and the upper slab, it’s important to define the maximum height.
Figure 32 - Step 1: Selection of the wall that belongs to IS

Figure 33 - Step 2: Select wall by level

The code that is shown in figure 34 selects the slab from the model and apply a process of detecting the thickness. This thickness is given as a value, and changes between slabs. This small step is important since the elements will always try to connect to the next floor, colliding with the wall that might be on top. The reason to be used here instead of the previews one, was due to the room being created without height boundary when imported using the IFC. The fact that when operating the other code will give a direct height that is undefined, creating the need to be adjusted to the fit on the bottom of the slab. However, Revit the room height can’t be changed but the solid which will be created can adapt his height to the code created.
The next step was to create and generate the volume of the objects. In case of the walls the elements were linked using “linkElements” created by Bimmorph.Nodes which creates a solid form the wall which was selected. The room need to apply the height created with the connection to the slab and apply to the correspondent floor selection to unify all the height. The volume then will be created by applying the code “Room.FinishBoundary” which will be joined to create a polycurve to then taken the result and extrude as a solid with the height generated.
The next code picks the volumes of each element and intersect them in relation with their level and base (room) or base constraint (wall). The walls are the element which serve as the base for intersection as they will intersect with all the rooms to detect which wall belongs to. The result is a list of true and false, meaning the true is the element that belongs to this list. However, the next steps will define how the procedure of selecting the elements that are true works, as this part of the code will pally multiple time through the investigation. The figure 36 shows the steps taken to control this information, the procedure works by detect when all the true happens, this will select only the first level of the list, meaning the result will contain 230 elements instead of these elements multiply by the number of walls. Then the code will transform this first list in an index number to be taken from main list the elements that belong to. Then the room “Number” needs to be translated as a string which will be the value in a new parameter called “Room_ID”.

![Figure 36 - Step 5: Intersection of the elements and application to a parameter](image)

The figure 37 shows the result of the adding the component to the parameter type. In the room number we can sport the element ID of it and detect that in “Room_ID” it shows the same code. This makes the code useful during the process, because there is always the possibility to detect which room the wall belongs, even if the wall type might change, as it will happen in the next set of codes.

![Figure 37 - Result checking](image)

### 4.1.5. Conclusions

The codes that were developed during this chapters were important to elaborate information which parameters that can be used to guide on BIM, making them resourceful for the overall process of exchanging information. This set of codes are not dependent of each other, however the first one will need to be always the code to applied to the wall of the project, since without them all the other steps are not possible.
The result is already an optimization of the process of generating codes for assembly, since it’s a unique and unchangeable code that were assigned to the elements that belongs to the project in Revit API. The fact that these elements are unique makes the process easier to export information in a reliable way, by removing manually assign tasks, that can lead to human error. The base codes were already created, now the split designer needs to create the typologies, which will be analysed in the next chapter in order to fill the role for DfMA.

4.2. Typologies Definition – Milestone 2

This chapter will focus on how to transform the various types of information inside the model and define multiple typologies automatically. The process is an optimized procedure of chapter 3.2, where the split designer manually separates the elements and groups them, creating the typologies. The big problems being the fact that procedure was a time-consuming task and can lead to hazards, in the serialization of the rooms.

Finding the Typologies is the main part of this dissertation as it’s the most reliable asset in DfMA. This process as multiple ways to be achieved, not only because exist a certain number of parameters that needs to be created, but also needs to find a way to hierarchical position them to get the fittest result. The biggest problem was how to understand and detect the bathroom disposition, and how they affect the typologies. This is one of the most demanding process but certainly, the step to divide in fewer groups.

TopBIM manual process to create typologies found around 30 different types of bathrooms. The hierarchical process was often unclear and not straight forward, but the parameters that were used were the same: bathroom disposition, area, dimensions, and number of walls. These four parameters can be quantified using available tools and information inside the room to extract each one of them. The first step was to get the values for each parameter in relation with the room, the second part to collaborate all the parameter in a hierarchical way to achieve the typology.
4.2.1. Detect element families inside room

The first step is to identify elements position in the bathrooms and provide them with a unique identifier for each unique type (Fig.38). However, the position sometimes can be hypothetical, with a lot of small variation which will lead to different results. In DfMA, the fittest the information the better, and in this situation, the code needs to go abroad the parameter and need to define as a different type of wall, defined by the physical position of the elements in relation in the bathroom. Introducing this topic, the bathroom position can be detected by the surrounding elements, which will define what are the differences between the existing compartments.

Figure 38 - Diagram with Typologies relations
One important aspect to notice in this process is the fact that there is only one way that a room can be considered a bathroom and its by having a toilet and lavatory. These two elements are the ones who define the bathroom, they can contain more elements inside or not, but these ones are obligatory. Therefore, the maximum elements that a bathroom can contain are by having a bathtub or shower and a bidet. There is a relation between the elements and the type of bathroom, since lower areas tend to have a fewer number of elements and larger area more elements.

The main problem is how this information can be extracted, and how it can be helpful in the process of generating typologies. Therefore, all the results should contain a certain solution to quantify all the elements, creating the correlation between the type with a parameter. To achieve this result, the code needs firstly to detect what types of bathrooms exist and create a process to export this information to be used in DfMA. In previews chapter 3.3 it was examined that the partition wall system can have multiple solutions, but a wall is always a combination of multiple elements or not, since some wall can be empty. The figure 40 shows four different bathrooms organizations:

![Figure 39 - Different bathrooms organizations](image)

The bathroom organization is correlated with the occupation and disposition of the elements. However, not all the bathrooms are equal and even with similar organizations the outcome might be different, the important aspect is not the size and dimension, but what makes them similar. Therefore, the wall occupation is the unique element that can be equal and different in all the bathroom, containing similar walls in different areas. This concept allows similar walls in different type of bathroom to be detected and mass produced while serves as information to further bid of quantities and supply management.
Taking this process and apply to a code, the next step was to convert the wall that exist in the model, and if they contain one or more elements, to detect them and report as a different wall that declares what encompasses inside it (Fig.40). The creation of this parameter steps away from the analysis of what is inside the room and considers how many elements are gather in the same wall. The code will use a group-based ideology, where wall with components will be taken first, then the door types and in the end the bathtub and shower. Each group have different process for DfMA, since components are attached to wall and contain prefabricated modules for each element; doors are different, since they need to be subtracted from the main wall and sometimes works inside other walls; and bathtub and shower are a unique type of prefabricated modules that works by themselves.

The first step in the code is to select all the walls that belong to the bathroom and provide a list that will be intersect for all unique items. Each individual component that belongs to the bathroom (toilet, bidet and lavatory) will be selected and detect in each wall using the code “Get Host Elements” that finds in which wall they are connected, since it’s a wall-based family. This result will show which wall the elements will be connected, but since they will intersect all the existing walls without taking in consideration if there are more elements inside, they need to pass from a serialization.
Figure 41 - Step 1 and 2: Get bathroom wall and select all index of Toilet

The figure 42 represents the five types of walls with the different types of components inside the room. In bathroom, there are two elements that can be on wall separately toilet and lavatory, they can also be together in the same wall, but the bidet can only be near the toilet or with all of them together, the following list shows the combinations that exist, and how they were classified “TBL” Toilet, Bidet and Lavatory.

1. “TB” Toilet and Bidet;
2. “LT” Lavatory and Toilet;
3. “T” Toilet;
4. “L” Lavatory;

Figure 42 - Different walls inside bathroom

After analysing the different wall, it’s possible to detect that in the code there are walls with more combination and the process to achieve that uses the node “List.SetIntersection” to create a list with the common element which are equal. When the three components are intersected together a unique list that will be defined as “TBL”, which means that contains all the elements inside it, will be created. Then the second list will be a intersection with the list before subtracted using the node “List.SetDifference”, that provides as output the result of the intersection of the list with toilet and bidet, the result on “TBL” will
be subtracter with the result in “TB”. Therefore, the same procedure will be applied to “LT” by combining the Lavatory and Toilet and apply difference from the results on “TBL” and “TB”. Lastly the “T” (toilet) and “L” (lavatory) will be subtracted to all the previews items intersected.

**Figure 43 – Step 3: Hierarchical selection of walls**

The next step was the creation of Wall Types with the name that represent their unique types and use them to be an identifier of the change that were done. Then, by using the node “Element.SetParameterByName” the elements that were selected form each list will be then replaced by this unique family types, thus helping not only in visualizing the result, but also to be detectable in the model.

**Figure 44 - Step 4: Substitute the wall for IS_Wall_TB**

The next step was the creation of Wall Types with the name that represent their unique types and use them to be an identifier of the change that were done. Then, by using the node “Element.SetParameterByName” the elements that were selected form each list will be then replaced by this unique family types, thus helping not only in visualizing the result, but also to be detectable in the model.
Figure 45 - Step 5 and 6: Identify the wall with the component sliding door and change them to a related family

The next step is to change the wall near the bathtub and shower to their unique wall type. However, this families are not wall-based, so the process to achieve this result needs to use an intersection between solids to export of the detected walls. Therefore, the step that was created in the beginning of splitting the room with the bathtub and shower was important for this procedure, because this module is autonomous in relation with all the bathrooms. This means that as opposite of the DfMA walls created by the components, this wall will never go work and be autonomous. The process starts by creating a solid from the family of bathtub or shower and create a unique volume to be later intersected with the room solid.

Figure 46 - Step 7: Create a solid form the component

After creating the solid from the module of the bathtub and shower, it was needed to generate a solid for the bathroom walls. The code above shows which elements need to be taken from the list of walls, then it was need to apply the node “LinkElement.Solids” created by Bimorph Nodes that virtually creates the solid from the following walls.
The last step in this code was to intersect the volume of the walls with the volume of the family and get as result a list of walls. Then the wall that contain this element need to be changed for the respective type. All the empty walls will keep the generic wall type, but now all the rest have a unique type that defines them, this process is still not complete, since more variation might happen with the fact that might exist wall with doors and components. However, this doesn’t apply to this case, due to the walls with components being opposite of the ones that serves as the entrance. The figure 49 shows all the rooms with colour on coarse mode of all the changes that were made in the file to each wall type.
4.2.2. Room Disposition

The next code is a continuation of the previews one, that detect four types of disposition in the bathroom in regards of the type of wall that exist in the model (Fig.50). This code further improves the use of the wall in a combination of four variations to export as four types of wall disposition, regards the spatial position of them. The principle is to detect the combination of wall that are inside and combine with other parameter to group the multiple parameters inside the room.

The code selects all the wall inside the model and use the types that were previously created to define a new parameter. From the previews code there were five wall types, and a combination one of two together makes the room be spitted in four dispositions, where “TBL”, “TB” and “TL” are already unique types of walls with a lot of information that defines them as compartments, and the wall “T” can also be consider, since it doesn’t need to find the pair.
The first step was to pick the walls in the model and get their “Type”. Then the value needs to be transformed in a string to be picked from the list individually. The selected wall type family will be then transformed in a string to be later detected all the index of this parameter value in the list of walls. Therefore, the list needs to be connected to the main one and all the elements that are in the index will be shifted into four sub-list of elements.

**Figure 51 - Step 1 and 2: Wall type detection and list partition**

The next stage is a process to select all the rooms that belong to the bathroom and find their “Element ID”. Consequently, this output will be intersected with the information inside the “Room_ID” parameter in the walls, since it was created to detect where the wall belongs in the room. The result will be given as true or false, being true the walls which belong to that room. The last step is to detect in the index the empty list and apply a node to clean all the elements that don’t belong in the list providing as output, the rooms that contain that specific wall.

**Figure 52 - Step 3 and 4: Get the room Id and find the wall that belong to the group**
The last step is the application of each result to a shared parameter named “Disposition”, where each one of the four results will have a unique identifier to detect what are the bathroom composition. The figure 54 shows the parameter applied in the room “400426”, that will serve as guideline to all the process and future additions.

![Figure 53 - Step 5: Apply value to parameter](image)

![Figure 54 - Parameter applied to the room](image)

4.2.3. Detect number of sides of the room

The next step was to create a layer in the definition of typologies by detecting the number of wall that each room contains. With this process it’s easier to separate the multiple elements that exist inside the wall and export the information as a parameter that contains the data related. This code allows to split rooms that contain four or more walls in sub-list of values.

This process works by selecting all the wall that belongs to the bathroom and then extract the perimeter curve by using the node “Room.Boundaries” developed by Archilab. After extracting the curve, they will be joined as polycurve to be then transformed as a surface. The surface purpose was to clean the curves and extract only the edges that quantifies the room, since there are split walls inside the bathroom. Therefore, another clean code was applied named “/W CurveLoop.Simplify” created by Spring Nodes which reduce the number curves inside the surface. The result is exported as a quantification of the number of curves using “PolyCurve.NumberOfCurves”.

![Diagram](image)
The last step was to create a shared parameter named “Sides” and export the number of rooms as a string with the information for each room. The figure 57 shows the result of the addition of the parameter to the process to achieve the typologies.

4.2.4. Detect area of the room

The parameter “Area” of the room already exists and can’t be changed since its already connected to the room information, so the problem was how to get the value as rounded so it can be grouped form approximately value. The following process is a code to transform room area into a new parameter that can group bathrooms.

The first step was to select all the rooms that belong to the bathroom. Consequently, it proceeds to select the “Area” parameter of the selected rooms, later it needed to detect the number string and apply the node “Math.Round” to get the approximately area of the compartment. However, the number that came
as an outcome contains some repetition of “0”, so they were taken of the list and replaced with nothing, giving them an integer number as result.

![Select Type of Room by Area](image)

**Figure 58 - Select area parameter and round**

Last step was to create a shared parameter for the room named “Area Code”, that will export the information values into room properties in the model with the value equal to the “Area”. However, the parameter generated is a string and the predefined in the room is a numerical string which when added as tag of the room can appear with the value rounded. The figure 60 shows the result of the applied code parameter.

![Add to Code Parameter](image)

**Figure 59 - Apply value to the parameter**

![Parameter applied to the room](image)

**Figure 60 - Parameter applied to the room**
4.2.5. Detect maximum length of the room

To detect the dimensions of the room it was necessary to identify what was the maximum distance of it, since it will translate to the length of the bathroom. However, it’s not recommendable to detect the width of the room, since in cases where the room have different number of walls, the boundary can’t be simplified to a unique value, in matter of facts the “Area Code” parameter can untie this problem by combining with the maximum distance, it’s possible to have an overall concept of the dimension of the room.

To generate the code all the bathroom walls were selected and then the same process of generating the number of sides was applied. The code joins the curves from the room boundary, transforms into a surface, and then extracts the curve simplified with the use of the code “\W CurveLoop.Simplify” created by SpringNodes, makes possible to extract the curve lengths of the room.

To generate the code all the bathroom walls were selected and then the same process of generating the number of sides was applied. The code joins the curves from the room boundary, transforms into a surface, and then extracts the curve simplified with the use of the code “\W CurveLoop.Simplify” created by SpringNodes, makes possible to extract the curve lengths of the room.

![Select Type of Room by Maximum Length](image)

Figure 61 - Select room curves

The code extracts from the list of curves of each room, the element with maximum value and round it to a decimal case. Then it needs to be transformed into a number integer using “Math.Floor”, the result will be then export into a new shared parameter named “Length”. The figure 63 shows the application of the code in the room parameter list.

![Maximum Length](image)

Figure 62 - Select curve with maximum length and add as parameter
4.2.6. Sequential code to define typologies – parameter

The next code combines all the previous parameters and merges them as a unique list to create the typologies (Fig.64). Typologies are by all the means the process of divided the multiple compartments in different room areas, where they will have closer and unique characteristics that can’t be transposable. To generate this code, it will be used the four parameters created in the previous chapters and based on the case studied process done by TopBim.

The figure 64 shows the process for generating the hierarchical approach of the code, this compiles of four steps and a last one will contain the list subdivided that will attributed to a shared parameter. To start, all the parameters of the room will be selected one by one in sequence, the logic of the steps that were firstly created started with “Sides”, “Length”, “Area Code” and “Disposal”.

The figure 65 shows a repetition of each different parameter in a different step. To better understand the concept two nodes are key to settle this hierarchical list “List.SortByKey” and “List.GroupByKey”, there function is to take from the list of rooms the specific parameter and sort them by the value, to be then grouped by the result in a new list. What this code creates is multiple sub-lists of each different result, that will be stacked on top, since when applying again the same process, they will create a sub-list from the sub-list that was sorted before. Making this a hierarchical code, because as further information goes the more the number of sub-lists will be generated, making the final parameter being a sub-sub-sub-list of all the rooms.
After creating the final list, the last list will be counted to create a range of number that starts on 1 and will extend to the number that will be given in the node “List.Count”, in this case 27. Then, by applying the sequence of number in a code block they will generate the value for the parameter “Typology”. The last step was to flatten the list to the last one and introduce in the node “Elements.SetParameterByName” with the list sorted as was generated and then applying the value to the shared parameter “Typology”.

Figure 65 - Step 1, 2, 3 and 4: Short room list by parameter
Figure 66 - Step 5: Apply parameter to the room

During this code the four parameters were tested in different position and different sequence, but no matter which code goes first the result will always be 27, so it means the hierarchical code disposition doesn’t alter the code and it’s only affected by the values of the parameters. The code disposition by sequence is more likely to be an intuitive way to stack similar room together with smaller number ranges between them, rather than an uncontrollable number generated for the typologies (Fig.67)

Figure 67 - Parameter applied to the room

After analysis of the rooms, it was detected that some rooms could be consider from the same typologies, due to problem that exist inside the parameter. During the investigation there was an understanding that dimensions are directly correlated with the occupation of the room, since the big area usually contains more elements inside. However, there is no boundary to this limitation since there is not a specific area boundary that defines if belongs to a new typology.

The figure 68 represents the problem of the code, it shows 2 room with different colour schemas, which were generated for the bathroom typology, each colour schema represents a different typology “T6” on the Left and “T7” on the right. The problem can be detected in open eyes, as the parameter of area shows a round number of four on the left and three on the right, this is the main cause for the generation of different typologies. The fact that these typologies were created was caused by the math round, which
trick the program to think that they are different, when it’s the opposite. Therefore, to test the limits of the software understanding the spatiality of the room, a different code was created to solve this problem.

![Figure 68 - Identical bathrooms, different typologies](image)

#### 4.2.7. Sequential code to define typologies – point coordinates

The next code was developed to solve the problem that was found in the previous chapter, even if the smallest difference exists, the idea of DfMA is to uniformise all the elements in a unique component that will be mass produced (Fig.69). The typologies serve as first layer to take all the compartments and unify them in a unique group, since previously there was a problem which led to the creation of more typologies there was the need to solve this problem with a different solution.

The code developed stacks all the bathrooms on top of each other and then, by finding the limit point of the room will group all of them by the dimensions. This means that if the elements are near or even on stacked the code will split them in multiple groups and will use the room parameter “Disposition” as tiebreaker between elements that are not clear in the group that they belong.

![Figure 69 - Code to generate typologies overview](image)

The code starts with use of creating a bounding box in all the rooms that belong to the bathroom. This process creates a cube around all the boundaries of the room. Then, with the use of the code “Cuboid.Width” and “Cuboid.Length” it’s possible to get the dimensions of the cuboid. However, most of the elements are rotated, since they don’t face all the same direction, it was necessary to create a new list using “List.Transpose” to get the first item in the list as the lower one. Then by math round the elements, to 1 decimal case all the elements will be position in a grid with 0.1 of space between all the points.
Figure 70 - Step 1: Create point by coordinates

The first item of the list will be then position as the “x” and the last item will be position as “y” of the room. Therefore, by using the two dimensions, a list of point will be created with the coordinates provided. The figure 71 shows all the room rounded and stacked on top of each other then. It’s possible to detect all the groups of point that are almost touching, by creating a node with circumference around the point and giving a 0.05 radius, the circles will intersect in the tangent between each other. Through simply looking in naked eye it’s possible to detect all the rooms that are almost touching in the list.

Figure 71 - Room stack overview (left); Point in the grid with rounded numbers (centre); Points in the grid without round number (right)
The next step was to intersect all the circles and take a result which consist in true if they intersect, then a list of all the intersection will be created, for each point that was intersect an x number of results will appear on the list. Then a Python code as shown in the figure 73, created by the user Howard in Stack Overflow, takes the common intersection of a group, and detects as a list of indexes the circles that intersect each other. To later take the value from the list of points which belong to each room.

![Points Intersection](image1)

**Figure 72 - Step 2: Circles intersection and sub-list creation**

![Python Script](image2)

**Figure 73 - Python script to detect intersections**

The codes generated to detect the “Area”, “Sides” and “Length” were substituted by the point location code. However, the code of “Disposition” will be used as the decider of the typology’s selection, by creating a sub-list with the same process of the previews chapter. The same process applied to the previews code is applied to this one, since it works by creating sub-lists. The result will be then extracted as the total number of different typologies, in this case, 25 different variations were detected. The result will be then exported with the parameter “Category”. The figure 75 shows the same room that were shown in the previews chapter with the new parameter applied.
Figure 74 - Step 3 and 4: Sub-list from the parameter “Disposition”; Create parameter with the value “Category”

Figure 75 - Analysis of the results in the bathrooms

Concluding, both processes were important to understand better the results of this method of reducing the number of typologies. However, it’s not a finished process, as the sub-category which are the variation on disposition, inside the room will be extremely important and will create more variation. In DfMA if a wall is inverted, it will contain the same elements but a different process of assembly. The results of this code were limited by the number of results that exist, if there are more variation inside the
room, it could not be useful as in this case, since the more element exist in the model, less the number of variations between the two. There isn’t a viable solution to the problem so the combination of both codes can be adaptable to each type of assignment.

4.3. Sub-Typologies Definition – Milestone 3

Since the number of typologies are a generic approach to the multiple bathrooms that exist in the building the next stage is taking this step a in DfMA further, by detecting what are the differences in the disposition of the room, that makes them unique in comparison with other groups. Taking in consideration all the typologies that were created during this process, there is a need to detect further relations between elements through a code that can link elements and then divide them in multiple sub-groups.

The idea of this code is to understand the spatial disposition of the elements and consider the relation between them, since in DfMA the elements that exist inside the room can be produced as the same when a wall is different, the relation with them in the wall is something that correlates to the assembly part. Consequently, this unique code will group these elements by detection them, in relation with their axis, gathering information that will formalize a sub-typology group. The code will start by creating a generic code to detect in which position the room is facing by combining the direction in x and y axis.

This process is an approach of what was analysed in the chapter 3.2 and the unique subcategories that were created in the room detection system developed by TopBIM. Therefore, the biggest role is to divide into step-by-step process. The detection of the relation between door and lavatory will get, not only the direction of the room, but the location of the lavatory in relation with the door; Further it will be analysed the toilet position in relation with the lavatory to detect the place of this element in relation with it; Lastly it will detect the door type in each room.
4.3.1. Element Position

The next code will create two parameters to later create a relation between them, this operation uses the principle of cartesian coordinates to detect where the room is facing (Fig.76). The relation with the elements will be created through the wall types that contain doors and lavatories, allowing to develop a relation between elements and their directions with others. The code is divided in two processes, the door position and the lavatory position that will be combined in two different outputs to be related in relation with the related direction that are facing.
The figure 77 shows the all the code steps, the underneath part will work separately to get two different results. The principle of the code was to divide by level the rooms, since due to the amount of information that exist in the model, it’s better to reduce the number of iterations. After this process the composition worked by creating the same code applied to all the walls that contain lavatory and doors. The walls that contain doors, will be selected by the wall types containing them, and in the rooms with the wall type of lavatory the following wall types were selected “L”, “LT” and “LBT”. The result will be given by two new parameter that will have a value of geographic coordinates, that will further understand.

Figure 77 - Lavatory position code overview

The figure 78 show a group of codes that selects all the rooms that belong to the bathroom, then it uses a group of nodes to detect the level which they belong, this way it’s possible to group the elements by floor. Then the second code detects the room boundary and generates a curve that will be extruded as a surface. After getting all the surfaces of the solid a node was used to identify the middle point of the surface. Then spheres were generated in this point using “Sphere.ByCenterPointRadius” with a small radius. This code will intersect with the output of the rooms, to detect which surface belong to each wall. This process was created to always have the surface normal, the direction of the surface, faced always to the inside of the room.
The codes in the figure 79 selects all the wall types that exist inside the model that belong to the door and lavatory. Then, with the value of the parameter “Room ID”, it’s possible to detect which wall belong to that specific room. Therefore, the wall elements will be then sorted not by their element ID, but by the “Room ID” that was created, thus sorting the two groups of elements using this information, to generate a sub-list that can be attached to them. The walls will be later distributed by floors using the predefined parameter “Base Constraint” which will separate then by the floors.

Figure 78 - Step 1 and 2: Select rooms by level and surface creation

Figure 79 - Step 3 and 4: Select wall types and divided them by floor
The codes in figure 80 will pick all the elements in the multiple groups and divide them by floor, generating a list of elements sorted by the room ID. Since the walls need to intersect the spheres that were created, the next step was to generate a room solid from the existing elements to intersect the objects. However, since the rooms that contain doors have an open in the door location, it was necessary to use a different method to generate the volume. The code uses “Geometry.BoundingBox”, which is a node that creates a box that fits all the elements inside it, then by converting to a “Geometry.BoundingBox.ToCuboid” the elements will create a physical volume of the bounding box created.

Figure 80 - Step 5 and 6: Select the room ID in each level and create a solid from the selected elements.

After the creation of the spheres and the solid, these two elements need to be intersected using “Geometry.DoesIntersect” being the spheres the priority, since the outcome desired is the use of the surfaces created using the room boundary. After the intersection there is a serialisation process combing true and false and the output will be given to the surfaces. Consequently, the output needs to be grouped and sort again using the “Room_ID” to go to the next stage. The elements that belong to each floor need to be join in one unique list, by combining then in two groups, one with all the surfaces and the other one with the list of “Room_ID”. Therefore, the elements that belong to this group now need to be sorted using the parameter, making it a list with all the surfaces in the parameter order.
Figure 81 - Step 7 and 8: Intersect surfaces with wall and detect surface normal

The track of “Room_ID” is the most important part of the code and the key factor, since the elements need to be exported as a room parameter, the track of this information makes the process be detected and can lead to the last stage of the code. The extraction of the surface normal gives a vector with the direction of the line, this line will move in an axis and the value which will be provided from this vector will help to detect the direction of the room.

Figure 82 - Cartesian coordinates system detection and output as parameter
The last part of the code is unique, since combines cartesian coordinates with the use of the x and y axis, due to the software not being able to detect the angle of the direction which the element is pointing. Subsequently, it doesn’t detect the angle of rotation of the elements, to detect the relative position of the elements, proving that the use of angle doesn’t give proper information, since the result shows the angles at 0, 90 and 180 degrees, never going abroad the last value. If a room faces upward or even downward the result will always be equal, due to the detecting of the angle to the shortest rotation.

Giving the fact that the angles doesn’t provide enough information, the process created works by extracting two values, the vector in x and the vector in y, these two coordinates will provide a list with values equal to -1, 0 and 1. Taking in consideration the cartesian coordinates the coordinate (0,0) represents the centre point, then the point (-1,0) and (1,0) represent the x axis, if the x is positive the room element is facing right since x positive moves right, and if it is negative it moves to the left. Taking on this representation and converting to geographic coordinates when the element faces the right direction its facing East, and when facing left is facing West, by doing this process in the room door, dictates the spatial position of the room in relation with the entrance. This process can be applied to North when y (0,1) is positive and to South when y (0,-1) is negative.

![Figure 83 - Parameter applied to the room](image)

To continue the code there is a need to create two new shared parameter “Organization” and “Organization1”, that will take all the information in regards of their geographic coordinate system and split all door and lavatory by their direction (Fig.83). This process when applied to both selection lavatory and doors, will always give the spatial position of the elements in the overall context of the project. The next stage is how these two groups will then correlate and create a spatial relation between them, detecting if the lavatory is on the right or left in relative with the door.
Figure 84 - Step by step process representation of the following code

1. Intersect point with surface
2. Remove surfaces that don’t contain any elements
3. Surfaces left after cleaning
4. Get surfaces direction through the points
4.3.2. **Lavatory Position**

The next code created to add a new parameter named “Lavatory Position” which consist in the relation between the two parameters of the previous chapter (Fig.85). The parameter named “Organization” refers to the door position and the “Organization1” to the lavatory position. This code will divide all the elements that are facing each geographic coordinate and relate the other element in relation with the spatial position in relation with the door, providing the information of the element faces right front or left.

The process works by selecting all the room in the project that belong to the bathroom and by selecting firstly the parameter “Organization”, which are related with the door position. Then by selecting the elements in the parameter a sub-list of elements will be created composing of four different value that each belonging to a different room, then by isolating them by each coordinate it’s possible to create a correlation with each one of them.

![Figure 85 - Overall view of the code with the steps](image.png)

Selecting all the elements inside each room a sub-list using the parameter “Organization1” (lavatory position) will give the direction of each element in relation with the first one. Therefore, the result was given as three different values, since no element is near the door, neither was detected before any elements in room that shares the same wall type of the door.
Figure 86 - Step 2 and 3: Select the element that belong to “Organization” and “Organization1”

The next step is the most important since the elements will be judge by the relation to each geographic coordinate. The process starts by isolation each sub-list of elements in relation with the value of the parameter “Organization1” and creates a methodology process of isolating the components and compare them with the previous selection. Taking the element in the coordinate East the value West will faces in opposite direction since, it’s considered in front of the element. The figure 87 show all the relation between all coordinates, for example, in the East, North is on the right side and South on the left. To the other parameter the same principle is applied, with different procedures.

Figure 87 - Relation between the elements in the geographic coordinates

To achieve the last result and define this new parameter, the elements on each sub-list need to be isolated in a unique coordinate. Then, by applying the principle above, it was needed to detect if exist three different values for the elements, therefore they can be separated in sub-list of elements. The next stage was to select the components and give a unique value in a new parameter named “Lavatory Position” that will have three different outputs “F”, “R” and “L”. With this new information added, this parameter
serves to detect if an element in a category is on the same position or not, since it provides more information. However, as stated before this code only applies to one element of the room, there is the need to apply a different code to detect the other element of the room, which is the toilet.

Figure 88 - Step 4: Separate the element by coordinates and export as a value

Figure 89 - Parameters applied to the selected room
4.3.3. Toilet position

The next code was created with the same principle of the previews one, with the difference of instead of using the walls as reference it will use the elements as the core of the process (Fig.90). Working on collaboration this code will pick the elements that belong to the lavatory and toilet and use them in a list containing all the reference, to then detect the spatial position of the toilet in relation with the lavatory. To do that, most of the wall elements need are in different wall and since the typology already detects if the element sits in another wall, the principle of this code was only to detect if the toilet is on the right or left of the room, since it will represent if that specific wall is mirror in relation with other similar wall of the same category.

![Figure 90 - Code overview with each step](image)

The code starts by once again selecting all the room that belong to the bathroom. Then works by choosing the element Lavatory and detect where exist in each room using Archilab node “Elements in Room”, that detect exact place where it was taken. The code works by finding a point on the surfaces of the element that was selected, and use it as base line. To generate this, point the first part need to recreate the solid form the elements, then explode the geometry, to be get the selected surface that attach to the wall. After detecting it the node will try to find the position on the list where the surfaces stand and export it as output.

![Figure 91 - Step 1: Select lavatory inside the room](image)

The next code selects the surface direction and then detects a point on the surface to be then exported as vector points. A similar process as the previous code, where the vector point will be detected in the surface when finding the point on the surface. Then, the point information will be exported as vector in x and y axis to be later correlated as cartesian coordinates for the elements.
Figure 92 - Step 2: Get surface normal and vector value

The code detects the elements in vector x and divides them as positive or negative and exports them as a sub-list from the room, with the information of the surface direction. Then the same process is applied to the vector y. This process will detect the direction where the lavatory is facing. Consequently, the vector x will represent the coordinates of East and West, and the vector in y will represent the coordinates of North and South.

Figure 93 - Step 3: Get the geographical coordinates of the elements

The next code will apply the selection process for the toilet and apply the same process as for the lavatory. The output will be cartesian coordinates in relation with the room, all the elements that belong to wall-based family toilet and lavatory need to pass again for the same process of detecting which direction they are facing since what will connect them will be a line between points. For this reason, the element needs to be sorted always by the parameter “Room_ID”, to keep always of their room position.
The code now needs to use the element solid of toilet and explode to find the surface which attach to the wall element. However, instead of taking the point as vector, it will be a normal point on the surface, since the two elements will be connected not by spatial position, but by line direction between them. Consequently, a middle point in the surface was created to pass the line coming from the lavatory to detect the direction where the element stands.

The last step was to create a line by the two points on each element of the room. Consequently, the output will be a line in spatial relation with three coordinates (x, y and z), that will serve as direction which the line will take. The values will be different from the previous code, since exist more numerical values the 0 or 1. Subsequently, the typology parameter defines already the type of room, and the lavatory position the room position, then it need another information to detect the relation between the elements in the wall, so if the elements is on one direction it will be positive and if goes for other it might be negatives. So, instead of detecting the coordinates, the elements will identify if they are position on the right or left of the lavatory, since the wall are established, and the lavatory position already placed. The principle of coordinate play with the idea if the lavatory is on East and West the value of x defines and if it is position in North and South the value of y will detect. Later the information was exported as a shared parameter named “Toilet Position” with the added value of “R” (right) or “L” (left).
4.3.4. Door type

The figure 98 shows the last parameter of the code to detect the sub-categories is the door type. This code will select all the wall that contain a different door type and creates a list of elements to split them in a new parameter. Since, the doors have a direct relation with the type of organization inside the model, such as sliding door can have a higher impact in surrounding elements since it run inside the wall, for this reason this parameter should be visible and be detectable in the sub-category.

The code works by selecting all the wall types that contain doors and then detect the “Wall_ID” of each elements type. Using the list intersection, it’s possible to detect all the element in the bathroom. Then, by using the “Room_ID the element will provide a list of the walls and the room which they belong. This process is applied to both types of walls as the code progresses.
After selecting all the rooms that belong to the bathroom, the code takes the parameter “Number” which contains the Element ID and creates a string with that information. Connecting both codes and creating an intersection, the code will detect which walls belong to each room, since a string can’t be transferred directly to ID. However, since the code is made by the room list, the list of indexes that will be generated from this code will pick the elements in the list that contain that specific wall. The same process was applied to both wall types. The later part of the code was the process to export the information as output for a shared parameter named “Door Type” and give them a value as “S” (sliding door) or “D” (door) depending on the wall selected.

Figure 100 - Step 2: Detect the walls inside the room and export as a parameter

Figure 101 - Parameter applied to the room

4.3.5. Create sub-category

The next code combines the multiple parameters in a hierarchical approach with all the information that was gathered during the preview’s codes (Fig.102). The following parameters were used in the creation of the last one: “Lavatory Position”, “Toilet Position” and “Door Type”. This code follows the same ideology of the one shown in the chapter 4.2.5. Consequently, the following element needs to be exported as a new parameter called “SubCategory”.

Figure 102 - Step 3: Create sub-category
The code follows with the selection of all the elements that belong to the bathroom, and they will be split by the first parameter “Lavatory Position”, since it’s the first code that will detect how the spatial position of the bathroom will work, this code gives an output of three values, and then they need to be divided in sub-list divided by each value of the parameter.

Next, the introduction of the “Toilet Position” to divide the elements in two list in base of the value of the parameter, making a total of 12 different sub-list off elements.
Then the code needs to be split in halfway since by the list the code had the doors in odd number and sliding doors in pair number. By picking the elements in three level of the list, it was possible to divide them in multiple groups, to be later divided according to the door type. The value was created with the range to six numbers and applying and the end of the sequence the type of the door as value “S” or “D” in the new shared parameter “SubCategory”.

![Create Parameter Value](image1.png)

**Figure 105 - Step 4: Apply parameter to the room**

After getting all the list of rooms, the sub-categories might not contain all the information. However, the, since the room need to be firstly separated by typologies to work, making this new parameter further information to the rooms, to detect how it’s distributed without takins in consideration how the elements are physically position (Fig.106). The use of this information works in regards of the parameters created to help to make better design decision in further improvement of the process of DfMA.

![Parameter applied to the room](image2.png)

**Figure 106 - Parameter applied to the room**
4.4. Export information

This chapter will focus on elaborating the information exported and manipulating it to be readable, helping to make better decisions for DfMA. To export this information two schedules inside Revit were created, with the information necessary to understand all the project, one containing the wall schedule and other the room schedule. These schedules were exported with the main information that is relative to the parameter created through the dissertation that not only helped to identify typologies but serves as information to the graphical part.

Table 3 - Schedule of the parameters applied to each room and wall

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Category</td>
<td>SubCategory</td>
<td>Number</td>
<td>Area</td>
<td>RoomLength</td>
<td>Perimeter</td>
<td>Name</td>
</tr>
<tr>
<td>B1</td>
<td>IS_35</td>
<td>400414</td>
<td>5m²</td>
<td>3</td>
<td>9.74</td>
<td>1S</td>
<td>Level 0</td>
</tr>
<tr>
<td>B1</td>
<td>IS_10</td>
<td>400418</td>
<td>18m²</td>
<td>3</td>
<td>9.70</td>
<td>1S</td>
<td>Level 0</td>
</tr>
<tr>
<td>B1</td>
<td>IS_33</td>
<td>400415</td>
<td>18m²</td>
<td>3</td>
<td>9.80</td>
<td>1S</td>
<td>Level 0</td>
</tr>
<tr>
<td>B1</td>
<td>IS_10</td>
<td>400411</td>
<td>18m²</td>
<td>3</td>
<td>9.61</td>
<td>1S</td>
<td>Level 0</td>
</tr>
<tr>
<td>B1</td>
<td>IS_35</td>
<td>400413</td>
<td>18m²</td>
<td>3</td>
<td>9.60</td>
<td>1S</td>
<td>Level 0</td>
</tr>
<tr>
<td>B1</td>
<td>IS_10</td>
<td>400412</td>
<td>18m²</td>
<td>3</td>
<td>10.00</td>
<td>1S</td>
<td>Level 0</td>
</tr>
<tr>
<td>B1</td>
<td>IS_35</td>
<td>400577</td>
<td>18m²</td>
<td>3</td>
<td>9.74</td>
<td>1S</td>
<td>Level 1</td>
</tr>
<tr>
<td>B1</td>
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<td>400568</td>
<td>18m²</td>
<td>3</td>
<td>10.00</td>
<td>1S</td>
<td>Level 1</td>
</tr>
<tr>
<td>B1</td>
<td>IS_15</td>
<td>400564</td>
<td>18m²</td>
<td>3</td>
<td>10.40</td>
<td>1S</td>
<td>Level 1</td>
</tr>
</tbody>
</table>

Schedules that were created on Revit will be exported as “.txt” to be later add to the Excel (Table 3). The tool used to elaborate and work with the desirable information was Power Query, since allows to import the information as data. All the parameters and chosen to allow to have further information inside the data and at the same time create comparison between the multiple results achieved. One point which was crucial in the connection of both schedules was the parameter “Number” in the room schedule and the “Room_ID” in the wall schedule. This parameter contains the same value, which makes the elements on the wall list to be inside the wall schedule, this process opens new exploration of the data that was added. Power Pivot worked the information inside the model and create multiple sources of information generation by transforming the values in number and names.

The power of using Excel, beside the work with the Power Query and PowerPivot, consist of the availability of the software in-house. Since, it is part of a must have package inside any company the use of this as part of the process makes it the more reliable solution. With the combination of information and graphic power it was possible to extract a complete list of elements and information (added as appendix) and dynamic tables as shows in the next figures.
The table 4 show the number of rooms that exist in each category. This graph represents the number of rooms divided by their subcategories, created by the codes to detect the different variation between all of them. With the use of this schedule, it’s possible to detect the bathrooms that can be standardized, and mass produced, since there is a lot of repetition on the number of subcategories in that category. The following categories stand out to be the more successful for DfMA: IS_1, IS_19, IS_3, IS_4, IS_5, IS_7 and IS_8. Consequently, this will be the rooms that will be focused in the optimization for DfMA.

Table 4 - Number Rooms in the same category

<table>
<thead>
<tr>
<th>Category</th>
<th>S_6S</th>
<th>S_6D</th>
<th>S_5S</th>
<th>S_5D</th>
<th>S_4S</th>
<th>S_4D</th>
<th>S_3S</th>
<th>S_3D</th>
<th>S_2S</th>
<th>S_2D</th>
<th>S_1S</th>
<th>S_1D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Repetitions</td>
<td>12</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>NUMBER OF REPETITIONS</td>
<td>IS_1</td>
<td>IS_3</td>
<td>IS_5</td>
<td>IS_7</td>
<td>IS_9</td>
<td>IS_11</td>
<td>IS_13</td>
<td>IS_15</td>
<td>IS_17</td>
<td>IS_19</td>
<td>IS_21</td>
<td>IS_23</td>
</tr>
<tr>
<td>1</td>
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<td>1</td>
<td>1</td>
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<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

The table 5 shows the walls with the biggest repetition in relation with the length. This connection was created by the amount of wall types that contain each room, and cross with the length of the various compartments to be later mass produced the ones with more repetition. These walls can be assembled in factory and even if they don’t belong to a category they can still be mass produced to go to the site. The following walls can be mass produced due to their amount of repetitions independently of their multiple lengths: Walls that belong to bathtub and shower (IS_Wall_BT and IS_Wall_B), as analysed before can be multiplied in every single room making them a great fit in DfMA; Then there are a lot of...
“IS_Parade_Geral (Generic wall) with the same dimension that can be mass produced; Some Sliding door walls and door (IS_Wall_SD and IS_Wall_D) also fit the criteria; Finally all the other bathrooms that contain the wall based components encompass some fewer duplications, but mostly there are elements that can be mass produced in factory using by the following result.

**Table 5 - Number of walls similar**

<table>
<thead>
<tr>
<th>Length</th>
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<th>IS_Wall_T</th>
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The table 6 shows average the walls in each category. This process serves to help the rooms that belong to the categories to detect the average wall size in a way to mass produced the entire room. The following ones were selected as the room that could be standardized and mass produced: IS_1, IS_19, IS_3, IS_4, IS_5, IS_7 and IS_8. The flowing list shows the rooms selected above, and what is the average wall length for each type of wall inside it. This process allows to a room to be adjust in the BIM model software the specific category to fit in all the similar compartments.
The data of the model can also be transferred as detail drawing with all the information that was shown in previous chapter. This concept allows to export the information to be used directly in the fabrication and assembly of the elements, providing documentation to assemble each partition wall. The process works by selecting all the room and exports as drawing with elevation and plan. However, the
optimization of this process happens by developing fewer different elements in factory and more repetition of wall. The result will be new information added to the model such as the profiles position and the panelling for each type of wall.
5. CONCLUSIONS

In conclusion of this dissertation, DfMA as a lot of potential when developed in BIM. During the study all the information analysed was important to have a broad knowledge of the state of the art of both topics, and how they can intersect and collaborate to achieve a more efficient, economical, and sustainable design and construction process. The change to off-site construction and to DfMA improves and makes it more accessible the transition for a modular and prefabricated construction systems. Therefore, the focus on the understanding of the process with an experienced construction company, provide in-bounds how the process is conjugate with the technicians.

The process developed in-house was already suitable and proofed, when connected with BIM the solution resembles what was achieved. The amount of experience provided by the construction company allowed to have an insight how to detect and group all the typologies, making the information more helpful, since it optimizes not only the rooms that belong to the bathroom, but to all the compartments that fits inside the building. The digitalization of the process is more demanding when the partition walls contain infrastructural elements that elevates the level of information inside it, making bathrooms a better fit to test the solution. However, kitchen can be considered as a group of walls that contains some installations but, in all the case it´s still consider a broader space and besides the demand of structural elements in regards the modularity of their cabinets doesn´t contain the direct relation of infrastructure that bathrooms contain. This compartment, usually surrounded by walls, makes it harder not only to work inside but to install the sanitary, being a better fit for DfMA.

The codes created to the digitalization of DfMA were often inaccurate due to limitation and lack of solution that could solve the problems, so as lack of programming skill, being one of these examples is the walls generation. This process of creating walls using Dynamo creates a concurrence of events in relation with BIM since the wall elements need to be generated using a line as base reference. The ideal process was to select the wall that intersect that room and convert it to a partition wall, by simply changing the type of wall. The code generated could be improved in a way that doesn’t create problems, but due to the walls being split, it wasn’t possible to do that. Consequently, the problem of not allowing the software to splited wall, is a bit step back in DfMA, since one of the criteria is being able to transport the wall to the site, if the software can’t detect where the wall need to split, how can an element be split to be carried to the construction, without compromising the overall process. This process is something that should be available since the current methods is done by using wall to break another wall.

Another functionality to be computationally implemented was the definition of typologies by points of location. For this code multiple solutions were created until a final proposal was achieved. One of the reason this code had a problem due to the points that are connected in an intersection chain, touching multiple elements in continuality, making the points that are touched a unique group, even when the extremes are further from each other. Acknowledging that, different solutions were experimented to face this issue, by finding central point or divide them by cores. However, none of the solution tested was near the use of the parameter “Room Disposition” as the solution which divide the points chain in new groups, allowing the elements to be divided in multiple typologies.
The final block, a type of bathroom of each typology that can be replicated multiple times was not solved, as multiple problems were found in the process. The final block should be the fittest type of bathroom, but since inside each typology there are a lot of small variations makes this process a bit complex. Consequently, the room to fit in the criteria, needs to be equal or approximate to most common dimension, that will be gathered and analysed in groups with all the information in regards off the room.

The idea of developing a final block is the desirable goal for DfMA, as the more repetitions there are, the more optimized and standardized the process will be. However, find this value come with certain boundaries, the first problem faced was Revit and Dynamo constrains. Revit wall types are an element that can’t be moved beside the interface of the software. To create different walls the process, need to pass from a component where the elements will be developed using the boundary line to be later transposed to wall. As shown previously in the chapter 4.1.1 where from the room boundary the walls were created.

The walls in this code were developed with the use of the node of room boundary and then the wall attach to the line to be later replicate the wall as DfMA. Consequently, the process to create a single-family type pass from the idea of taking the element in this code and detect in the list of elements, the line that can be expandable or retractable to fit in these criteria. This implementation faces some difficulties such as detecting the lines that need to be fit in the criteria. Since all the rooms have different positions and some walls are closed between each other, the software do not detect this kind of information.

Project Refinery is an extension of Dynamo that allow to optimize design solutions with the use of information to find the fittest result for a given goal. However, this extension comes with the problem stated before, the information that need to be fitted need to be added in the software before even making the calculation. The fact that the rooms are line that are already implemented in the model, and there isn’t any value which can be manipulated to provide a better solution such as point location, makes it a setback. Since, the representation of the walls are lining that don’t have enough information of the point limit to move and to fit in the room. The last part of the problem is the fact that to move a wall, it needs to be modelled again, since the software can’t move an element using Dynamo everything that was done before need to be done again to detect if the result was the desirable, leading to concurrency of process.

Without further developments in this research on this topic and no following solution found for the problem stated above, the better answer was by making manual adjustments in the model and use the data created to be a guideline in the decision making. With the resource of other BIM software and tools it is possible to detect the fittest result of a compartment working in collaboration with the stakeholder, without forcing changes that could affect the state of the building. The use of clash detection as a source to detect when a room is more suitable or not, or if doesn’t collide with other elements, optimizes all the typologies in comparison of using Project Refinery. Consequently, it was important how the information gathered in the project could be helpful in making decisions, hence the solution found in this investigation.
The investigation delegated bridges the gap in digitalization of the process of DfMA to Architecture, Engineering, Construction and Operation (AECO) industry, since the goal was to optimize the methodology and digitalized more the workflow, improving collaborating with the use of information. The steps developed during this dissertation were the beginning of the process, where only information is manipulated, further developments come with the transition to a model-based process, where the partition wall will be transformed in families with more information. These families will contain profiles disposition, the elements places, the fixtures, and panelling mapping.

The walls as an assemble components with information and model objects, can be exported as detail drawings to be produced in factory and be transported to the site. However, the next stage for this process, is a collaboration between BIM and automatic robotic manufacturing or BIM and CNC. The advantages the automatization for manufacturing and assemble is the mass production of custom solution. CNC process allows the information to be exported from the model to be able to collaborate with machinery but leaving the assemble stage to human intersection. Additionally, this process is more likely to be adopted as the cutting of the panelling and the profiles can be done automatically by adding the information relatable in the machine to cut the elements in series.

As the AECO industry is always evolving, this work results are a little step in DfMA implementation with BIM and also a contribution to pave the way to structure information management for the shift to prefabricated construction. Therefore, the research developed will provide assets to bridge the gap for Industry 4.0 and create a process which can still be customisable but optimized to be more efficient and more resourceful.
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## LIST OF ACRONYMS AND ABBREVIATIONS

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<th>Acronym</th>
<th>Description</th>
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<td>API</td>
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APPENDIX

APPENDIX 1: TABLE WITH ROOM SCHEDULE WITH CATEGORY AND SUBCATEGORY EMBEDDED

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### Table: IS_5, IS_6, IS_7

<p>| IS_5/S_1D | 400488 | 6 m² | 3 | 10.80 | I.S. | Level 0 |
| IS_5/S_1D | 400591 | 6 m² | 3 | 10.62 | I.S. | Level 1 |
| IS_5/S_1D | 400619 | 6 m² | 3 | 10.77 | I.S. | Level 1 |
| IS_5/S_1D | 400630 | 6 m² | 3 | 10.84 | I.S. | Level 1 |
| IS_5/S_2D | 400650 | 6 m² | 3 | 10.77 | I.S. | Level 1 |
| IS_5/S_2D | 400679 | 6 m² | 3 | 10.80 | I.S. | Level 1 |
| IS_5/S_1D | 400679 | 6 m² | 3 | 10.60 | I.S. | Level 2 |
| IS_5/S_2D | 400679 | 6 m² | 3 | 10.62 | I.S. | Level 1 |
| IS_7/S_3S | 400416 | 4 m² | 3 | 8.36 | I.S. | Level 0 |
| IS_7/S_1S | 400422 | 5 m² | 3 | 8.80 | I.S. | Level 0 |
| IS_7/S_1S | 400439 | 4 m² | 3 | 8.40 | I.S. | Level 0 |
| IS_7/S_2S | 400440 | 4 m² | 3 | 7.77 | I.S. | Level 0 |
| IS_7/S_2S | 400444 | 4 m² | 3 | 7.82 | I.S. | Level 0 |
| IS_7/S_4D | 400446 | 4 m² | 3 | 8.40 | I.S. | Level 0 |
| IS_7/S_2S | 400450 | 4 m² | 3 | 8.29 | I.S. | Level 0 |
| IS_7/S_2S | 400458 | 4 m² | 3 | 7.88 | I.S. | Level 0 |
| IS_7/S_1S | 400460 | 4 m² | 3 | 7.82 | I.S. | Level 0 |
| IS_7/S_2S | 400462 | 4 m² | 3 | 7.82 | I.S. | Level 0 |
| IS_7/S_2S | 400465 | 4 m² | 3 | 7.88 | I.S. | Level 0 |
| IS_7/S_1S | 400470 | 4 m² | 3 | 8.40 | I.S. | Level 0 |
| IS_7/S_6D | 400477 | 4 m² | 3 | 8.40 | I.S. | Level 0 |
| IS_7/S_2S | 400481 | 4 m² | 3 | 8.27 | I.S. | Level 0 |
| IS_7/S_4D | 400483 | 4 m² | 3 | 8.40 | I.S. | Level 0 |
| IS_7/S_6D | 400484 | 4 m² | 3 | 8.40 | I.S. | Level 0 |
| IS_7/S_1S | 400579 | 4 m² | 3 | 8.20 | I.S. | Level 1 |
| IS_7/S_1S | 400581 | 4 m² | 3 | 8.02 | I.S. | Level 1 |
| IS_7/S_1S | 400583 | 4 m² | 3 | 7.97 | I.S. | Level 1 |
| IS_7/S_1S | 400592 | 4 m² | 3 | 8.02 | I.S. | Level 1 |
| IS_7/S_3D | 400595 | 4 m² | 3 | 8.40 | I.S. | Level 1 |
| IS_7/S_5D | 400596 | 4 m² | 3 | 8.40 | I.S. | Level 1 |
| IS_7/S_1S | 400601 | 4 m² | 3 | 8.02 | I.S. | Level 1 |
| IS_7/S_2S | 400604 | 4 m² | 3 | 8.29 | I.S. | Level 1 |
| IS_7/S_2S | 400605 | 4 m² | 3 | 7.82 | I.S. | Level 1 |
| IS_7/S_2S | 400607 | 4 m² | 3 | 7.92 | I.S. | Level 1 |
| IS_7/S_2S | 400610 | 4 m² | 3 | 8.02 | I.S. | Level 1 |
| IS_7/S_3D | 400623 | 4 m² | 3 | 8.40 | I.S. | Level 1 |
| IS_7/S_2S | 400624 | 4 m² | 3 | 8.02 | I.S. | Level 1 |
| IS_7/S_2S | 400627 | 4 m² | 3 | 8.00 | I.S. | Level 1 |
| IS_7/S_3S | 400631 | 4 m² | 3 | 8.36 | I.S. | Level 1 |
| IS_7/S_2S | 400638 | 5 m² | 3 | 8.80 | I.S. | Level 1 |
| IS_7/S_1S | 400647 | 4 m² | 3 | 8.14 | I.S. | Level 1 |
| IS_7/S_5D | 400654 | 4 m² | 3 | 8.40 | I.S. | Level 1 |
| IS_7/S_6S | 400655 | 4 m² | 3 | 7.77 | I.S. | Level 1 |
| IS_7/S_2S | 400661 | 4 m² | 3 | 7.82 | I.S. | Level 1 |
| IS_7/S_5S | 400663 | 4 m² | 3 | 7.82 | I.S. | Level 1 |
| IS_7/S_2S | 400666 | 4 m² | 3 | 7.88 | I.S. | Level 1 |
| IS_7/S_1S | 400670 | 4 m² | 3 | 8.40 | I.S. | Level 1 |
| IS_7/S_6D | 400677 | 4 m² | 3 | 8.40 | I.S. | Level 1 |
| IS_7/S_2S | 400680 | 4 m² | 3 | 8.27 | I.S. | Level 1 |</p>
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## APPENDIX 2: TABLE WITH WALL WITH TYPE OF WALL AND DIMENSIONS

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BIM In Design for Manufacturing and Assembly: Bridging the gap in AECO Industry 4.0

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BIM In Design for Manufacturing and Assembly: Bridging the gap in AECO Industry 4.0

Erasmus Mundus Joint Master Degree Programme – ERASMUS+

European Master in Building Information Modelling BIM A+
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Erasmus Mundus Joint Master Degree Programme – ERASMUS+
European Master in Building Information Modelling BIM A+ 131
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**Notes:**
- The table above represents a performance analysis or data collected from a specific context, likely related to a project or study involving IS_Wall_L, IS_Wall_LBT, IS_Wall_LT, IS_Wall_SD, IS_Wall_T, and IS_Wall_TB categories.
- The 'Total Geral' column sums up the values in each row, indicating a cumulative score or metric for each category.
- The values in the table range from 1 to 12, suggesting a scale or scoring system applied to the categories listed.
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Erasmus Mundus Joint Master Degree Programme – ERASMUS+
European Master in Building Information Modelling BIM A+ 141
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**Erasmus Mundus Joint Master Degree Programme – ERASMUS+**

**European Master in Building Information Modelling BIM A+**
APPENDIX 6: AVERAGE SIZE OF WALL OF EACH TYPE
BY CATEGORY

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| S_2D | 0.40 | 1.13 | 2.20 | 2.10 |

### IS_24

| S_1D | 2.00 | 1.60 |

### IS_25

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### IS_3

| S_1D | 1.19 | 2.15 |
| S_2D | 1.17 | 1.99 |
| S_3D | 0.65 | 1.12 | 1.63 |
| S_4D | 1.10 | 1.70 |
| S_5D | 1.09 | 1.67 |
| S_6D | 1.07 | 1.17 | 2.10 |

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| S_1S | 1.53 | 1.13 |
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| S_3S | 1.60 | 1.13 |
| S_4D | 1.90 | 1.07 | 1.30 |

### IS_5

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| S_2D | 1.78 | 1.07 | 1.36 | 2.96 |

### IS_6

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### IS_7

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| S_1S | 1.61 | 1.07 | 1.30 |
| S_2D | 1.85 | 1.10 | 1.70 |
| S_2S | 1.57 | 1.13 |
| S_3D | 1.80 | 1.09 | 1.68 |
| S_3S | 1.80 | 1.10 |
| S_4D | 1.80 | 1.10 | 1.70 |
| S_5D | 1.87 | 1.11 | 1.73 |
| S_5S | 1.50 | 1.03 |
| S_6D | 1.80 | 1.10 | 1.10 | 1.70 |
| S_6S | 1.60 | 1.60 |

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| S_3S | 1.80 | 1.10 | 1.50 |
| S_4S | 1.80 | 1.02 | 1.45 |
| S_5S | 1.80 | 1.13 | 1.90 |

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| S_5S | 1.70 |

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