

## PROJECTE O TESINA D'ESPECIALITAT

### Títol

Estudi del potencial de la tecnologia BIM i la seva implementació dins  
l'àmbit de la construcció

### Autor/a

Francesc Xavier Echegaray Jaile

### Tutor/a

Climent Molins Borrell

### Departament

Enginyeria de la Construcció (EC)

### Intensificació

### Data

13 de Maig de 2014

**Title:** Study of the potential of BIM technology and its implementation in construction

**Author:** Francesc Xavier Echegaray Jaile

**Advisor:** Climent Molins Borrell

## ABSTRACT

The work presented herein is intended to treat the main theoretical and technical concepts that compose *Building Information Modelling* (BIM) in an organised and comprehensive way. In the initial parts of this work the very fundamentals of this new approach are addressed, putting special attention in the technological shifts that support BIM and the main efforts and challenges that are to be faced.

In essence, BIM technology allows the generation of accurate virtual representations of a project, which include all of their physical and functional characteristics. These BIM models are then used to simulate the conception, design, construction, operation and eventual demolition of a facility. The combination of these models with specific simulation and analysis tools allows BIM users to take solid informed decisions throughout the whole lifecycle phases of the project. But beyond technology, BIM unfolds a whole new set of design and construction capabilities with regard to traditional practices. These workflows encourage all project stakeholders to collaborate from initial design stages, creating changes in roles and relationships amongst them.

In this line, the work visits the path towards collaborative workflows, pointing out the main changes that appear at a business and organisational level. In order to contrast how BIM differs from traditional approaches, current AEC industry practices are overviewed. This puts in evidence the areas in which BIM provides new or improved capabilities. The advantages resulting of BIM implementation are then described, emphasising on the obstacles that have to be overcome beforehand.

Finally, after an adequate knowledge base is acquired, a set of practical examples are developed in an attempt to contrast and evaluate the capabilities of BIM technology. In these examples, a generic building project is developed in a realistic and consistent way. The developed example emphasises on simulating a design process by exploring the roles of owners, structural engineers, architects and contractors. The concepts that have been reviewed throughout the length of the work are put into practice in this final part. To conclude, several lines of development for future works are proposed based on the gained experience.

**Keywords:** Building Information Modelling, Building Information Model, parametric modelling, object based design, Interoperability, workflows, stakeholders, collaboration, Integrated Project Delivery.

**Título:** Estudio del potencial de la tecnología BIM y su implementación en el ámbito de la construcción

**Autor:** Francesc Xavier Echegaray Jaile

**Tutor:** Climent Molins Borrell

## ABSTRACT

Esta tesina está enfocada a tratar los principales conceptos teóricos y técnicos que componen el *Building Information Modelling* (BIM) de una manera organizada y entendedora. En las primeras partes del trabajo se tratan los principios fundamentales del BIM, poniendo especial atención en los avances tecnológicos que lo hacen realidad y en los puntos clave que aún precisan desarrollo.

En esencia, la tecnología BIM permite generar modelos virtuales de un proyecto que incluyan con precisión sus características físicas y funcionales. Estos modelos BIM permiten simular la concepción, el diseño, la construcción, la operación y la demolición de cualquier obra de construcción. Combinando estos modelos con herramientas de simulación y análisis, los usuarios BIM son capaces de tomar decisiones bien fundamentadas acerca del proyecto a lo largo de todo su ciclo de vida. Pero más allá de la tecnología, el BIM despliega toda una serie de nuevas capacidades en el ámbito del diseño y la construcción en comparación con los métodos tradicionales. Estos nuevos flujos de trabajo alientan a todos los agentes involucrados en un proyecto a colaborar a partir de los estadios iniciales de su diseño. Esto implica cambios importantes en las relaciones que se dan entre estos agentes y los papeles que éstos desempeñan.

En esta línea, la tesina explora el camino a recorrer hacia los flujos de trabajo basados en la colaboración, indicando los cambios más importantes que surgen a nivel organizativo y empresarial. Para resaltar estos cambios, las prácticas que actualmente caracterizan al sector de la construcción son analizadas brevemente. Esto permite desvelar las mejoras y nuevas capacidades aportadas por el BIM. A continuación, el trabajo se centra en las ventajas de implementar el BIM, poniendo énfasis en los obstáculos que deben superarse previamente.

Finalmente, después de asentar los conocimientos propicios, se desarrollan una serie de ejemplos prácticos para contrastar y evaluar las capacidades de la tecnología BIM. Los ejemplos constan del desarrollo de un proyecto de edificación de una manera realista y técnicamente consistente. El ejercicio pone especial ahínco en simular un proceso de diseño desde el punto de vista del cliente, el ingeniero estructural, el arquitecto y el contratista. Los conceptos que se han ido viendo a lo largo del trabajo se ponen en práctica en esta última parte. Para concluir, se exponen unas líneas de desarrollo para futuros trabajos basadas en la experiencia adquirida.

**Palabras clave:** Building Information Modelling, Building Information Model, modelado paramétrico, diseño basado en objetos, Interoperabilidad, flujos de trabajo, partes implicadas, colaboración, Integrated Project Delivery.

# TABLE OF CONTENTS

<b>INTRODUCTION AND OBJECTIVES .....</b>	<b>9</b>
 <b>CHAPTER 1 – INTRODUCTION TO BIM.....</b>	<b>12</b>
1.1. Definition.....	12
1.2. BIM History.....	14
1.2.1. Origins.....	14
1.2.2. Graphical representation .....	15
1.2.3. Data based design .....	16
1.2.4. From research projects to commercial software .....	18
1.2.5. Interoperability and collaborative building construction.....	21
1.2.6. Simulation and assisted design .....	22
1.2.7. Current practices .....	23
1.2.8. Building Information Modelling as a term .....	24
1.3. Implementation in the AEC industry.....	25
1.3.1. BIM: A growing reality .....	25
1.3.2. North America: Industry reports and BIM surveys.....	26
1.3.3. Western Europe: Industry reports and BIM surveys.....	29
1.3.4. Spain: BIM awareness .....	32
 <b>CHAPTER 2 – BIM FUNDAMENTAL PRINCIPLES.....</b>	<b>33</b>
2.1. Introduction .....	33
2.2. Setting a BIM knowledge framework.....	33
2.2.1. Introduction.....	33
2.2.2. BIM fields.....	33
2.2.3. BIM implementation stages .....	35
2.2.4. Measuring BIM implementation .....	38
2.3. BIM Technology.....	39
2.3.1. Introduction.....	39
2.3.2. Object oriented design .....	39
2.3.3. Parametric modelling beyond design.....	44
2.3.4. Building Information Models.....	46
2.3.5. BIM software platforms.....	47
2.3.6. Enabled key aspects .....	47

2.4. Interoperability .....	47
2.4.1. Introduction.....	47
2.4.2. Interoperability fundamentals .....	48
2.4.3. Exchange formats and schema languages distinction.....	50
2.4.4. Ways to interoperability.....	50
2.4.5. Open product data model exchange formats .....	51
2.4.6. Beyond data interchange .....	51
2.4.7. Information management and server repositories .....	52
2.5. Integrated Project Delivery (IPD) .....	53
2.5.1. Introduction.....	53
2.5.2. Integrated Project Delivery .....	53
2.5.3. Redefined project lifecycle phases.....	55
2.5.4. The Mc Leamy curve.....	57
2.5.5. Contractual implications of Integrated Project Delivery.....	57
2.5.6. Constructions Operation Building information exchange (COBie).....	58
<b>CHAPTER 3 – BIM IMPLEMENTATION .....</b>	<b>59</b>
3.1. Introduction .....	59
3.2. Current state of the AEC industry .....	59
3.2.1. Current practices .....	59
3.2.2. Inefficiencies of current AEC industry practices.....	61
3.3. BIM Implementation advantages.....	62
3.3.1. Introduction.....	63
3.3.2. Advantages for the project.....	63
3.3.3. Advantages for BIM user firms .....	68
3.4. BIM Implementation challenges .....	68
3.4.1. Introduction.....	68
3.4.2. Efforts towards interoperability and collaboration.....	69
3.4.3. Contractual arrays for integrated BIM use.....	69
3.4.4. Adaptation to new practices .....	70
3.4.5. Investment for implementation .....	70
<b>CHAPTER 4 – BIM PRACTICAL EXAMPLE.....</b>	<b>71</b>
4.1. Development of a building project with BIM.....	71
4.1.1. Introduction.....	71

4.1.2. Tools and methodology .....	72
4.1.3. Building description .....	72
4.1.4. Model development: Design process simulation .....	74
4.1.5. Summarised model reviews .....	75
4.2. Structural model.....	76
4.2.1. Introduction.....	76
4.2.2. Structural design methodology .....	76
4.2.3. Practical examples.....	77
4.3. Architectural model.....	82
4.3.1. Introduction.....	82
4.3.2. Architectural design methodology .....	82
4.3.3. Practical examples.....	83
4.4. Construction model.....	86
4.4.1. Introduction.....	86
4.4.2. Practical examples.....	87
4.5. Coordination model .....	90
4.5.1. Introduction.....	90
4.5.2. Practical examples.....	91
<b>CONCLUSIONS .....</b>	<b>92</b>
<b>FUTURE WORKS.....</b>	<b>97</b>
<b>REFERENCES .....</b>	<b>99</b>

## LIST OF FIGURES

<i>Figure 1: BIM adoption rates for North America [31]</i> .....	9
<i>Figure 2: AEC industry project lifecycle phases assisted by BIM [16]</i> .....	12
<i>Figure 3: Parametric definition of stair steps in the GLIDE interface [17]</i> .....	17
<i>Figure 4: Main participants involved in AEC industry projects [63]</i> .....	22
<i>Figure 5: Use of field management and augmented reality BIM capabilities [11]</i> .....	24
<i>Figure 6: BIM adoption rates for North America [31]</i> .....	27
<i>Figure 7: BIM adoption rates by type and size of firm [31]</i> .....	27
<i>Figure 8: BIM implementation levels [31]</i> .....	27
<i>Figure 9: BIM team use of IPD [31]</i> .....	28
<i>Figure 10: BIM ROI for users by level of engagement [31]</i> .....	28
<i>Figure 11: BIM adoption rates [30]</i> .....	30
<i>Figure 12: BIM engagement rates by years of experience [30]</i> .....	30
<i>Figure 13: Perceived ROI North America vs Western Europe [30]</i> .....	31
<i>Figure 14: BIM fields of activity [39]</i> .....	34
<i>Figure 15: BIM stages of implementation [39]</i> .....	35
<i>Figure 16: BIM stage 1 of implementation [39]</i> .....	36
<i>Figure 17: BIM stage 2 of implementation [39]</i> .....	37
<i>Figure 18: BIM stage 3 of implementation [39]</i> .....	37
<i>Figure 19: Organisational schema for object families, classes and instances</i> .....	41
<i>Figure 20: BIM models and their deliverables [16]</i> .....	45
<i>Figure 21: Amount of data attributed to information interchanges [19]</i> .....	48
<i>Figure 22: Cartoon of poor communication in project development [37]</i> .....	54
<i>Figure 23: Traditional project lifecycle stages</i> .....	55
<i>Figure 24: IPD project lifecycle stages</i> .....	55
<i>Figure 25: The Mc Leamy curve [4]</i> .....	57
<i>Figure 26: From left to right: Updated linked CAD file; Approach to foundation and column design</i> .....	77
<i>Figure 27: Hollow core section slab geometric data implementation process: Paper based; CAD; BIM</i> .....	78
<i>Figure 28: From left to right: Parametric definition of void forms; Resulting slab edge trims</i> ...	78
<i>Figure 29: Composite metal deck family class' structural layers</i> .....	79
<i>Figure 30: From left to right: Analytical model defined in Revit; Analytical model exported to RSA</i> .....	79
<i>Figure 31: Steelwork framing system: connection details</i> .....	80
<i>Figure 32: Import of steel reinforcement from RSA to the Revit structural model</i> .....	80
<i>Figure 33: External wall class properties dialogue</i> .....	81
<i>Figure 34: Definition of material appearance dialogue</i> .....	81
<i>Figure 35: Modelling of interior walls based on linked CAD file</i> .....	83
<i>Figure 36: From left to right: Model view of commercial reception desk; Rendered view of commercial reception desk</i> .....	84
<i>Figure 37: Day light simulation for Eastern façade window: Interior and exterior views</i> .....	84
<i>Figure 38: Parametric definition of wall openings</i> .....	85

Figure 39: From left to right: Interior ‘camera’ model view; rendered interior model view ..... 85

Figure 40: Modelled site conditions: Inclusion of construction-related object instances ..... 88

Figure 41: Evaluation of scaffolding layout in the construction model..... 89

Figure 42: Rendered view of building’s surrounding urbanisation..... 90

Figure 43: Clash detection for ventilation duct: Colliding elements are highlighted in orange .. 91

Figure 44: The Mc Leamy curve [4] ..... 93

Figure 45: BIM workflow curve [23] ..... 94

Figure 46: Dynamic Fire Simulation with CFD software [14]..... 97

Figure 47: BIM model of building site and machinery [28] ..... 98

LIST OF TABLES

Table 1: Building design aspects categorised by field: Treated aspects are highlighted in green  
..... 75



## INTRODUCTION

When *Building Information Modelling* (BIM) was first introduced, few could have imagined the large impact that this term would reach in the years that followed. BIM has gone from being a barely known academic development to capturing the attention of the whole architecture, engineering and construction (AEC) industries.

*Building Information Modelling* has its origins at the start of the computer era, during the early 1970's. Forged by the hands of remarkable visionaries, BIM technology has continuously pursued the ambitious objective of simulating the capabilities of a 'designer' instead of reproducing those of a 'drawing board', as is the case of most Computer Aided Design (CAD) solutions. Although the first commercial software titles of this original technology were released thirty years ago, it has not been until the recent overcoming of technological barriers that they have taken off. BIM solutions are currently the key technology provided by all the major AEC industry software developers which initially offered CAD products. These developers are now heavily investing in the extension of BIM application capabilities, which are growing at an exponential pace due to an ever increasing demand of the industry. [19]

The adoption of BIM is having a major acceptance amongst practitioners. It is claimed that BIM presents many advantages to both the outcome of projects and to AEC industry firms. Leading firms which are now using BIM in almost all of their projects have perceived remarkable profits and healthy returns on investment. In front of these competitive advantages, other firms are being drawn to undertake their own transition. As matter of fact, surveys show that BIM adoption in North America expanded from 28 percent in 2007 to 71 percent in 2012, demonstrating an impressive growth despite the recent economic pressures. [31]

### Levels of BIM Adoption in North America

Source: McGraw-Hill Construction, 2012

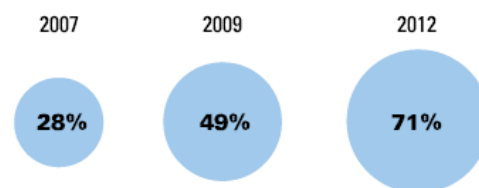


Figure 1: BIM adoption rates for North America [31]

BIM implementation has grown all over the world, and even some countries such as North America, the United Kingdom, Norway, Sweden and Germany are putting forward plans for its mandatory adoption. For instance, the United Kingdom's government has made it a national issue and will request it in all of its projects by 2016 with the objective of "*reducing capital cost and the carbon burden from the construction and operation of the built environment by 20%*" [10].

In accordance with these trends, it is said that *Building Information Modelling* represents one of the most important transformation opportunities for the AEC industry, which has long been reluctant to change. In fact, it carries along a new way of focusing how building projects are designed, constructed and managed.

In this line, BIM technology allows the generation of accurate virtual representations of a project, which include all of their physical and functional characteristics. These BIM models are then used to simulate the conception, design, construction, operation and eventual demolition of a facility. The combination of these models with specific simulation and analysis tools allows BIM users to take solid informed decisions throughout the whole lifecycle phases of the project. With BIM, designers are capable of visualising and exploring several alternatives in a simulated environment, detect any potential conflicts with other disciplines and manage design information in an efficient manner. Once design models are complete, contractors can take advantage of the included information to carry out procurement, fabrication and construction activities more effectively. At final project lifecycle stages, owners can have at their disposal an intelligent and data-rich digital representation of the facility's as-built conditions for its operation and maintenance.

But beyond technology, BIM unfolds a whole new set of design and construction capabilities with regard to traditional practices. These workflows encourage all project stakeholders to collaborate from initial design stages, creating changes in roles and relationships amongst them. Therefore, BIM can be better understood as a *process* towards innovative practices rather than a mere set of tools and technologies.

Up to date, *Building Information modelling* has been a latent topic of discussion that has drawn many opposed positions around it. While some state that it will certainly be the future, others say that it is another ephemeral trend that will not prevail. Either way, BIM sure deserves the attention of students, academics, developers and professionals related to the AEC industry, as it represents an interesting proposal to approach traditional industry practices in a renewed and innovative way. Therefore, this work has been developed with the motivation to provide a clear and useful insight into this interesting and extensive topic.

## OBJECTIVES

The main objective of this work is to **provide a clear and useful insight into *Building Information Modelling***, focusing on the relevant and practical aspects which will help to better understand this new approach and its implications in the engineering, architectural and construction industries.

In line with this main purpose, the objectives which will drive the development of this work can be listed as follows:

- Set a contextual background for BIM, overviewing how it surged and what is the current scenario of its adoption.
- Review the fundamental principles of BIM in order to understand how it works and the capabilities that it enables.
- Layout the main changes that BIM presents in front of traditional practices.
- Review the advantages and drawbacks of BIM adoption and evaluate it as a business investment.
- Familiarise with the use of a main BIM software platform to a satisfactory level.
- Develop several practical examples putting into practice the reviewed theoretical concepts in order to evaluate them.
- Put forward proposals for future works based on the gained experience.

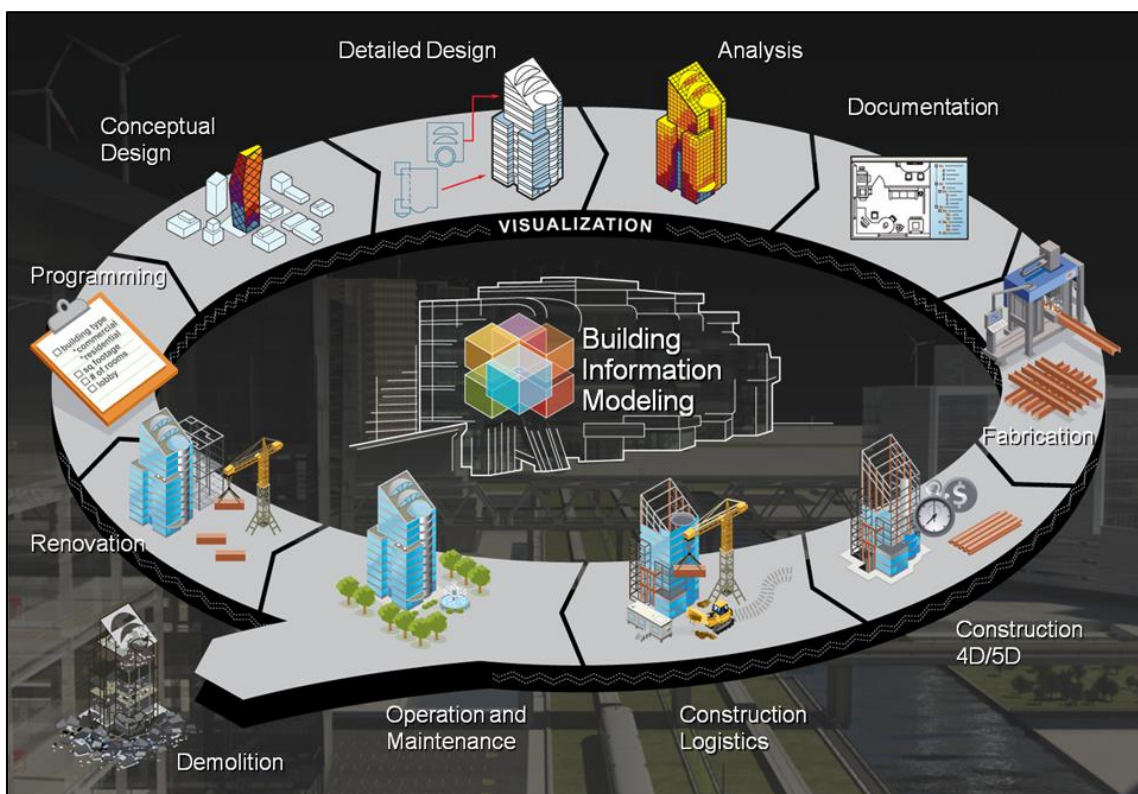
In summary, the work presented herein intends to offer a consistent knowledge base for both students and professionals so that they can understand the major implications of this development. It aims to objectively explain how they can be affected, what opportunities arise and which challenges are to be faced whenever attempting to implement BIM.

Furthermore, the development of practical examples in this work aims to serve as an academic content of reference to prove what can be achieved through the use of BIM. Hopefully, it will encourage and be of some assistance in future researches and developments on the topic.

# CHAPTER 1 – INTRODUCTION TO BIM

## 1.1. DEFINITION

BIM is an acronym for Building Information Modelling, and describes a **process** which involves the generation and management of digital representations of physical and functional characteristics of a facility. This process allows coordinated, collaborative and multidisciplinary workflows between multiple players involved in a project to create, manage, run simulations and analyse a virtual model of the facility through **BIM software tools**. The resulting **building information models** are data-rich, object-based, intelligent and parametric digital representations of the facility. These models become shared knowledge resources to support decision-making about a facility from earliest conceptual stages, through design and construction, through its operational life and eventual demolition. [50][13][24]



*Figure 2: AEC industry project lifecycle phases assisted by BIM [16]*

Building Information Modelling is a vast and extensive field, and therefore it may be pretentious to give a unique and global definition. It is interesting nevertheless to clearly define the basic processes and elements that compose it to avoid confusion. In this line,

BuildingSMART, a non-profit organisation working towards BIM interoperability, has published its own definition:

*“BIM is an acronym which represents three separate but linked functions:*

***Building Information Modelling:*** *Is a BUSINESS PROCESS for generating and leveraging building data to design, construct and operate the building during its lifecycle. BIM allows all stakeholders to have access to the same information at the same time through interoperability between technology platforms.*

***Building Information Model:*** *Is the DIGITAL REPRESENTATION of physical and functional characteristics of a facility. As such it serves as a shared knowledge resource for information about a facility, forming a reliable basis for decisions during its life-cycle from inception onwards.*

***Building Information Management:*** *Is the ORGANIZATION & CONTROL of the business process by utilizing the information in the digital prototype to effect the sharing of information over the entire lifecycle of an asset. The benefits include centralized and visual communication, early exploration of options, sustainability, efficient design, interaction of disciplines, site control, as built documentation, etc. – effectively developing an asset lifecycle process and model from conception to final retirement.”*  
[13]

Yet, another clarifying definition can be extracted from *The BIM Handbook*, by Chuck Eastman et. al.:

***“Building Information Modelling (BIM):*** *We use BIM as a verb or an adjective phrase to describe tools, processes and technologies that are facilitated by digital, machine-readable documentation about a building, its performance, its planning, its construction and later its operation. Therefore BIM describes an activity, not an object. To describe the result of the modelling activity, we use the term “building information model,” or more simply “building model” in full.*

***Building Model (or Building Object Model):*** *This consists of a digital database of a particular building that contains information about its objects. This may include its geometry (generally defined by parametric rules), its performance, its planning, its construction and later its operation...”* [19]

To finalise, only some distinctions regarding BIM technology have been made necessary to avoid misunderstandings:

**BIM software tools** are the technological support which drive the Building Information Modelling process, and must not be used to define the whole meaning of Building Information Modelling.

They are **NOT BIM software tools** the ones that support models which:

- **Contain 3D data only and few or none object attributes:** They are mainly used for 3D visualisation.
- **Have no support or behaviour:** They have object attributes but cannot adjust their positioning or proportions because they do not utilize parametric intelligence.
- **Models that are composed of multiple 2D CAD reference files that must be combined to define the building:** Consistency and intelligence are not ensured.
- **Models that allow changes to dimensions in one view that are not automatically propagated to other views.** [19]

## 1.2. BIM HISTORY

### 1.2.1. Origins

The first ideals of BIM as we understand it today arose in the early beginnings of **computer aided design** (CAD), at the start of the computer era. The very fundamental functionalities and concepts of **object oriented design** appear mentioned in *Augmenting Human Intellect*, by Douglas C. Engelbart in 1962, through a fictional example of an architect's working scenario:

*"Let us consider an augmented architect at work. He sits at a working station that has a visual display screen some three feet on a side; this is his working surface, and is controlled by a computer (his "clerk")...He is designing a building..., the architect next begins to enter a series of specifications and data—a six-inch slab floor, twelve-inch concrete walls eight feet high within the excavation, and so on. When he has finished, the revised scene appears on the screen. A structure is taking shape. He examines it, adjusts it, pauses long enough to ask for handbook or catalogue information from the clerk at various points, and readjusts accordingly... These lists grow into an ever more-detailed, interlinked structure, which represents the maturing thought behind the actual design.*

*Next he begins a functional analysis... All of this information (the building design and its associated "thought structure") can be stored on a tape to represent the design manual for the building. Loading this tape into his own clerk, another architect, a builder, or the client can manoeuvre within this design manual to pursue whatever details or insights are of interest to him..."* [20]

The author pictures a future scenario where an architect works alongside his computer, or his 'clerk', as he names it, allowing him to develop the design of a building from start to end. Engelbart defines some features regarding this computational assistance, rather fictional for the time being, but nevertheless visionary of what BIM systems would be. He talks about object-oriented design, parametric design interface, relational database and model-based analysis, all concepts that will be explored later on [20].

Object oriented design has been also heavily influenced by the work of other design researchers, such as Christopher Alexander, who sets the theoretical basis for object oriented programming in *Notes of The Synthesis of Form*:

*“To match the growing complexity of problems, there is a growing body of information and specialist experience. This information is hard to handle; it is widespread, diffuse, unorganized. Moreover, not only is the quantity of information itself by now beyond the reach of single designers, but the various specialists who retail it are narrow and unfamiliar with the form-makers’ peculiar problems, so that it is never clear quite how the designer should best consult them. As a result, although ideally a form should reflect all the known facts relevant to its design, in-fact the average designer scans whatever information he happens on...*

*... The technical difficulties of grasping all the information needed for the construction of such a form are out of hand - and well beyond the fingers of a single individual.” [3]*

Alexander mentions how design refers not only to the final form of the design, but to the complex set of data that has been involved in its creation, and the need to organize and analyse it in order to make improved rational-based decisions in design [3].

### 1.2.2. Graphical representation

Although the early fundamentals of BIM had been set, technology had to follow up very tight to bring it to life. Graphical interfaces are basic to make computer aided design possible. They are the door for the designer to interact with the model, allowing him to develop his work in a fully intuitive work-environment.

The first graphical representation tools appeared as research projects, pioneering in **human-computer interaction** (HCI) [8]. The tedious and stiff barriers of early human-computer interaction based on batch processing<sup>1</sup> had to be broken, leading into a more affordable and intuitive working interface [64].

In the course of his PhD thesis in 1963, Ivan Sutherland wrote a revolutionary computer program called Sketchpad. Unlike earlier computer applications, which were batch oriented, Sketchpad was interactive. Using a light pen, which directly controlled a cross cursor in an oscilloscope screen, and some input buttons, basic elements such as lines, points and arcs could be drawn. In addition, several geometrical constraints could be applied when sketching. Amongst them were perpendicular, parallel, equal size, fixed lengths and angles, and many more [61] [64].

Sketchpad pioneered some of the most essential concepts in computing, including the graphical user interface and non-procedural programming. But, most important, Sketchpad pioneered in **object-oriented programming** [8].

In big terms, object oriented programming in Sketchpad consisted in working and saving the design model in a master file, from which all instances or duplicates of the model were sourced. If any change was made to the master model, it would automatically be transmitted and shown in all of its instances and duplicates [61].

---

<sup>1</sup> Batch Processing is execution of a series of programs on a computer without manual intervention. Punched cards and magnetic tape were used in the beginnings of batch processing.



Although Sutherland is believed to be one of the fathers of **computer-aided design** (CAD), it is interesting to remark that he never intended Sketchpad to be a computer-aided design program in the first place. Being very aware of this, Sutherland described Sketchpad as a program for computer-aided drafting; not being far from what modern CAD software is. Later on, Sutherland developed a second version of Sketchpad issued for complete design, instead of drafting uniquely [64]. In fact, Sutherland's latter project inspired Douglas C. Englebart in the development of oN Line, a computer collaboration system which exploited the possibilities of human-computer interaction [60].

Later on, computer-based graphical representation of geometry gained force. Around the 1970-80's there were two main representation methods, which were Constructive Solid Geometry (CSG) and Boundary Representation (BREP) [8].

Constructive Solid Geometry consists in creating complex geometric shapes by combining and modifying basic and primitive solid bodies. This is accomplished through basic Boolean operations such as intersection, union and subtraction [48]. Although working with CSG may be somewhat tedious, it proves to be very consistent in the creation of completely defined solid shapes. This results in an effective clash detection capacity and reduces the need for consistency checks, which is very useful in engineering design [54].

In Boundary Representation, solids are represented as a collection of connected surface elements. Based on a much richer set of operations, boundary representation offers wider geometrical possibilities to design in comparison to constructive solid geometry. Although consistency checks are needed, reliable BREP methodology turns out to be more appropriate for CAD software operation [49].

These representation methods were later combined and improved. CSG would account for editing and BREP for visualization, measuring and clash-detection. But these efforts were mostly oriented to implementation in CAD software. Although these methodologies are an essential part in the graphical side of design, it has to be acknowledged that BIM software builds upon other fundamental aspects. When speaking of a virtual building model, not only is its graphical three-dimensional representation referred; the database that sustains it is also to be considered. This database is the one that sustains all the information that may involve the building's design, from geometric parameters to material properties.

### 1.2.3. Data based design

In the construction industry, any kind of work is made up of basic constitutive elements put together in a certain sequence and location. Viewing a building through the lenses of a database encourages breaking the building down to its basic components. This exercise requires a listing and organisation of these elements, assigning them whichever parameters are necessary to define them.

The first program that successfully worked with an **object database** for building design was Building Description System (BDS), developed by Charles Eastman in collaboration with the



Advanced Research Projects Agency (DARPA)<sup>2</sup> [8]. Like preceding research projects, BDS worked with a graphical interface and allowed various representation views of a model. But, what BDS innovated in, was the use of an element library, from which the designer could add or delete elements to the model. These elements had a set of data-based parameters that could be sorted, consulted and modified by the designer [18].

Eastman, current BIM expert and teacher at the Georgia Tech School of architecture, was an architect by the university of Berkeley that later moved on to the field of computer science at the Carnegie Mellon University [8]. With his development of BDS, Eastman anticipated the inefficiencies and challenges of the AEC industry that BIM would have to overcome in the future. As he stated in his paper *An Outline of the Building Description System: -“Many of the costs of design, construction, and building operation derive from the reliance on drawings as the description of record of the building”* [18]. These inefficiencies had to do with the documentation support used at the time, which was paper based. Eastman claimed that paper drawings were redundant in representing the same elements from different perspectives and with different scales. Moreover, they were not capable of representing and keeping up to date with a building’s further construction and modifications. He defended that by using BDS, the cost of design would drop by fifty per cent [8]. But being BDS a research project realised before the age of personal computing, no building projects could be done to back up his statements.

Eastman later developed Graphical Language for Interactive Design (GLIDE) at Carnegie Mellon University in 1977. His new project intended to provide an efficient computer representation for physical systems in sufficient detail for their design and construction [8]. The program works with object elements, whose representation goes beyond shape and includes functional information. GLIDE also was designed to be extensible and presents many modern BIM applications such as data consistency checks, cost estimation and evaluation of element properties. It also presents solid graphical representation capabilities, generating reliable two-dimensional drawings from three-dimensional models [17].

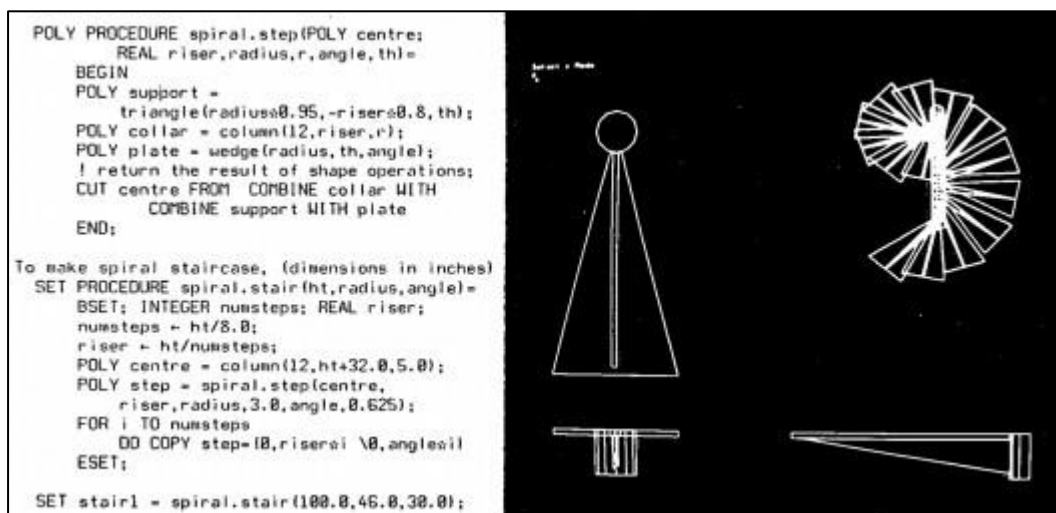


Figure 3: Parametric definition of stair steps in the GLIDE interface [17]

<sup>2</sup> Formerly known as ARPA, the Defence Advanced Research Projects Agency (DARPA), under the U.S. Department of Defence, was founded in 1958 in response to the Soviet Block’s technological advances.

In the early 1980's data based design programs were developed and began to gain traction in the United Kingdom, to the point that some were used in building projects. Amongst them were GDS, EdCAAD, Cedar, RUCAPS, Sonata and Reflex [8].

But still, these computational systems needed to fulfil the representation of an essential aspect of the AEC industry: Phasing of the construction process. RUCAPS, developed by GMW Computers in 1986, was the first software system to consider time and construction sequences in the design of a building. The first infrastructure project designed with the assistance of a four-dimensional model was Heathrow Airport's Terminal Three in London [19] [8].

The development of four-dimensional models was later boosted by the foundation of the Centre for Integrated Facility Engineering (CIFE) in Stanford, 1988 by Paul Teicholz. The centre's foundation later gave birth to two main research lines that would carry on for the next two decades. On one side, the development of applications for various disciplines related to the AEC industry, meant to improve efficiency in construction. On the other side, creating design assisted tools by viewing the building model as a prototype, which can be analysed and tested in performance [8].

Building Design Advisor, developed by Lawrence Berkeley National Lab in 1993 is an excellent example of an assisted design tool. This software uses an object-based model of a building and its surrounding conditions to perform simulations in order to give feedback and suggest design solutions. This program was one of the first to integrate graphical analysis and simulations to provide information about how the project might perform given alternative conditions regarding the projects orientation, geometry, material properties and building procedures [8].

By the early 1990's many software programs had been developed and could perform in many ways as how we understand BIM software today. But what began as ambitious research projects in the early 1960's had to take a leap into a more functional and practical ground once the personal computer area began in 1980.

#### 1.2.4. From research projects to commercial software

CAD commercial software was first used and further developed by big companies in the automotive, aerospace and electronics industries [8]. These industries were the only ones to afford computers with enough capacity to run these programs. Later developments of CAD, written in more openly used code languages, allowed its use in more affordable computing devices [53]. But it was not until the 1990's that CAD software irrupted massively in the market with AutoCAD, which could be run in personal computers [45].

BIM software had an early and rather singular entry in the personal computing domain. While in the United States progress was rapidly made, two computing developers achieved remarkable advances in the Soviet Block. They were Gábor Bójar, founder of Graphisoft, and Leonid Raiz, co-founder of Charles River Software. Both software firms gave birth to ArchiCAD and Revit respectively, which would later shape the BIM software market as we know it today [8].

ArchiCAD was founded in 1982 in Budapest by Bójar, who was a physicist. Computer exporting to the Soviet Block was very restricted for a long time, so Bójar found himself pawning his wife's jewellery in order to smuggle some Apple computers into Hungary. With these contraband devices and with high computing skills he wrote the first lines of Radar CH that would later be ArchiCAD [8]. With similar technical resources as Eastman's Building Description System, Radar CH was released for Apple's Lisa OS in 1984. This first version makes ArchiCAD the first BIM software to be implemented in a personal computer [38].

Although greater computational skills had been used to program ArchiCAD in limited performance hardware, it was very slow to run. This is the main reason for which at first ArchiCAD was not used in big projects. Later on, many improvements and several releases have made ArchiCAD a main BIM software title in today's market. Despite its prominent position, the software still lacks some basic features. Amongst them are a lack of time consideration in design and a complicated programming environment for element design. [8]

In the United States the first version of Pro/ENGINEER was released in 1988 by Parametric Technology Corporation (PTC) shortly after its foundation in 1985. Unlike Radar CH, Pro/ENGINEER had a wide market acceptance and is considered to be the first commercially successful solid modeller based on parametric design [8].

Leonid Raiz and Irwin Jungreis, who worked together in the development of Pro/ENGINEER, decided to take all their knowledge and experience in parametric modelling to the building industry. They split from PTC and founded Charles River Software in Massachusetts, 1997 [8]. They hired experienced software developers and architects and started writing their new software in C++ for the Microsoft Windows OS. Revit was first released in January 2000, and motivated the change of the corporation's name to Revit Technology Corporation. Two years later, in 2002 Autodesk purchased the company to further research and develop the software [46].

The developers of Revit were aware that their software had to support big and more complex projects in order to succeed in the market. Moreover, they designed Revit to fulfil the greater deficiencies of their main competitors [46].

Revit included time consideration in design, giving the model a fourth-dimension. This allowed designers and contractors to simulate the construction process and create schedules based on the model [46]. The first project to base its schedules on the software was the Freedom Tower in New York. Through various linked BIM models bonded to a schedule, it was possible to estimate costs and quantity take-offs. This resulted in an increase of efficiency and coordination and would later motivate the further development of applications to coordinate the work of the various disciplines involved in the construction process [8].

Revit also offered a revolutionary and far easier way to design basic elements in comparison to ArchiCAD's parametric solid modeller Geometric Description Language (GDL). Basic elements (also called families) could be designed parametrically in a visual programming environment, without the need of writing any code line. This made its use affordable to architects and engineers without advanced programming skills [46].

But, the major difference that Revit presented was its parametric change engine. This feature propagated any change made to the model to its various views, duplicates, schedules, quantity

take-offs and any other documents generated from the model. Using object-oriented programming it also kept relationships and constraints between elements. This ease of change and model consistency inspired the software's name as a contraction of 'Revise-It' [46].

Experienced engineering firms also provided their specific knowledge to the BIM environment. Although they did not start as research projects, some BIM software started off from the need of computational support in civil engineering. This is the case of Nemetscheck Allplan and Tekla Structures.

Georg Nemetscheck founded the 'engineering firm for the construction industry' in Munich, 1963. At first, the firm specialised in structural design and construction, and shortly after developed engineering software for their own use. Taking advantage of their experience in computer use, Nemetscheck Engineering released Programmsystem Statik 97/77 for desktop computers in 1977. The software would later be integrated in a software package for calculation and design of standard elements for construction, being one of the first computer-assisted engineering (CAE) programs [35]. In 1984 the first version of Allplan was launched. In its first versions this CAD software only allowed three-dimensional modelling. It was not until Nemetscheck launched their data-based supported platform in 1997 that their software could be considered as BIM. This platform was introduced as Object-oriented Product Model Engineering Network (OPEN) and allows the delivery of requested model data in a consistent and open format to all those involved in the construction process [36].

Allplan is considered to offer extensive modelling capabilities and tools for multidisciplinary tasks. Although its file formats allow their interoperability with all their products, their management may be a drawback when working with the model. Allplan saves the model in many files to ease the distribution of work to multiple disciplines, but this approach does not permit the automated update of changes made to the model. This is its main deficiency compared to other BIM software like Revit [59].

Tekla by itself comes from a grouping of engineering firms that founded a joint software company. *Teknillinen laskenta Oy* or 'technical computing' was founded in Helsinki in 1966 and would later see its name contracted to Tekla. Their first software was developed in close liaison with civil engineering and was focused in structural engineering and linear works [42]. In 1986 the company developed their virtual database technology which allowed faster use of relational databases. Not long after that object oriented design was successfully achieved by their systems: in 1987 their relational database could be operated through a graphical interface. In 1993 the first version of their main structural steel engineering software Xsteel was released. Later on, Tekla Structures was launched in 2004 based on Xsteel. This time, the software would not be focused in structural engineering only, but on the whole construction process. This makes Tekla Structures a fully operational BIM software. [43]

Tekla Structures outstands in structural design modelling. It supports very complex structural schemes and allows the modelling of a wide range of materials. It also permits precise detailing design features like being able to define customized structural re-bar, for instance. Although it does not fulfil many multidisciplinary feature needs by its own, its open file format allows interoperability with other BIM software. This foments easier and more integrated

workflows. Nevertheless, Tekla Structures focuses in the management of the full construction process by adding time consideration in planning to the model. [62]

By the beginning of the 2000's, many BIM commercial software titles were on the market. Although its implementation was not widely spread, professionals involved in the AEC industry who wanted to work with building information modelling found themselves with serious **interoperability** issues. This happened because project stakeholders did not necessarily use the same software.

#### 1.2.5. Interoperability and collaborative building construction

The construction of a project is a complex process that involves activities of various nature carefully organized in time and space. If building information modelling wanted to represent the building process in all its depth, it would have to integrate the work of engineers, architects contractors and all disciplines involved. This was the main reason why BIM software titles started to develop own versions focused on a certain area of the AEC industry. In 2005, Autodesk launched the first version of Revit Structure focused on structural engineering, and in 2006 launched Revit MEP with its focus on systems [46].

**Integrated Project Delivery** (IPD) as a concept appeared in 2000, and was later academically defined in 2007 by the American Institute of Architects California Council [57]. Integrated project delivery aims to increase to the maximum the efficiency of the construction process by coordinating and bringing together the work of all stakeholders early in the design phase. Close collaboration between multiple disciplines in this initial stage allows better informed decisions in design. Moreover, unnecessary coordination costs can be tackled if every participant notices the implication of their work in the whole process. In traditional contracts for instance, where design is apart from construction, a lot of resources are spent on coordination issues and design feasibility errors. Increased collaboration has taken the industry apart from these traditional design-bid-build contracts towards IPD. [8] [19]

IPD requires the sharing of information between the parts involved in a project. BIM allows multidisciplinary participants to work on a same project by sharing a set of models. Usually these models are linked to a master model, and every participant can claim ownership of its work and modify the elements in the model relevant to its discipline [57]. The tools for management of privileges over the model, based on user's ID, were first featured in Autodesk's Revit in 2006. Later on, major BIM software titles allowed these functions and offered additional tools for control, revision and management of the model's workflows. These tools are basically used to know who created or changed what in the master model [8].

But considering the multidisciplinary nature of construction is not enough. To make IPD possible, an effort had to be made to overcome the barriers of different software file formats. Due to the hierarchic and singular nature of information in a BIM model, fidelity was lost every time it changed from one BIM platform to another. [8] [56]

In 1995 the Industry Foundation Classes (IFC) file format was created by the International Alliance for Interoperability (IAI). This open format was meant to allow open workflows for all

those involved regardless of the software tools used, creating a common and reliable language for the industry [56]. Otherwise, the work made by different project stakeholders could not be put together with the efficiency that Integrated Project Delivery requires. The existence of commercial viewing software like Autodesk's Navisworks added difficulty to this purpose. Navisworks is essentially a viewing tool to coordinate across different BIM file formats and detect any inconsistencies [8].



*Figure 4: Main participants involved in AEC industry projects [63]*

All these efforts put on the upgrading of the AEC industry's efficiency follow one of the schools of thoughts promoted from CIFE. As mentioned before, the Centre for Integrated Facility Engineering gave birth to another line of research, which considered the BIM model as a prototype to be tested in performance. Simulation-based assisted design saw great advances in the meantime.

#### **1.2.6. Simulation and assisted design**

The main advantage of visualising a project without building it is that designers can actually test it and take more solid decisions on how it could be upgraded and optimized based on sound simulation results. Following the steps of Building Design Advisor, many software applications have been developed to assist the design in BIM platforms.

Structural analysis tools have been adapted to import BIM models, analyse them and export the results back to the BIM model for interpretation and review. Some BIM platforms go a step further and integrate the analysis on the same interface [62]. There are also applications for mechanical engineering which can simulate pressure drops and flow calculations in pipework systems [8]. Although many of the mentioned simulation and calculation processes had



already been developed in stand-alone software, BIM platforms' Application Programming Interface (API) permit its integration to BIM [8] [47].

The discipline which has seen major advances in simulation and perhaps the most promising one is sustainable design. Three-dimensional models that offer information on the material's thermal conductivity, building orientation and other relevant data allow energetic performance analysis of a project. Software titles like Ecotect, Energy Plus, IES and Green Building Studio develop their simulations by importing the BIM model to their own platforms. Other programs like Autodesk's Vasari (Beta) are integrated straight into the BIM platform and run solar studies and insulation levels allowing the modification of the model for iteration. [8] [47]

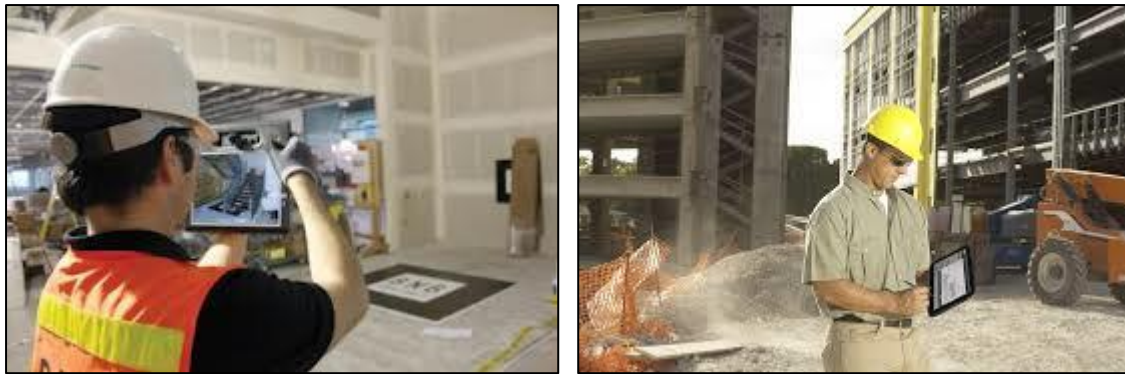
It is interesting to highlight that when collaboration is accomplished in early design stages, the building model approximates reality and thus only then energetic simulations are reliable. With consistent models and solid energetic simulations, a project's design can be energetically qualified in sustainability [47]. This adds value for the client and is one of many recalls for adopting BIM.

#### 1.2.7. Current practices

As progress towards Integrated Project Delivery is made, BIM software and their applications are being adapted and developed respectively to lead the way. Every single process involved in the AEC industry can be supported in BIM platforms and new and revolutionary solutions constantly surge. Current avant-garde practices involve cloud computing, augmented reality and field management software, generative design and virtual object commerce amongst many others [8].

Cloud computing allows designers to run simulations using the cloud server's computational power. BIM cloud environments also allow all users involved in a project to access the BIM model any time anywhere with internet access. This facilitates in great measure the collaboration of wide spread teams and solves many common informatic difficulties. In 2009 Graphisoft launched BIM server, followed by Autodesk 360, launched in 2012 [47] [55].

Field management software is currently used to permit access to the model while being in the field. Applications for portable devices such as smartphones or tablets have been developed to view and modify the model anywhere. But augmented reality really appears in applications that allow the user to view the model as if it was already constructed by orienting the portable device in any direction inside the building site. Contractors can benefit from these applications, accessing the whole model to reduce errors derived from paper drawings, creating checklists for quality control and other tasks, and in summary establish better communication with the field.



*Figure 5: Use of field management and augmented reality BIM capabilities [11]*

Generative design is an advanced design process that uses Multi-Criteria Design Optimization (MCDA). Initially used in industrial processes and design, it has now moved into Building Information Modelling. With multiple parameters to be optimized in design and numerous variables to be modified, MCDA techniques work with an evolutionary process<sup>3</sup>. Through the use of genetic algorithms, genomes are iteratively modified to reach a determined value 'score' calculated from fitness parameters. The main limitation of this practice is that in some cases local maximums are reached instead of total optimization. [5]

Current trends in architecture have given birth to a virtual marketplace (or library) of products and materials for construction [8]. These new type of libraries allow designers to select products from a catalogue and import them as parametric objects to the BIM model. By importing the product's representation, their properties and behaviour are also imported, allowing designers to have a better understanding of it. A good example of these libraries is the National BIM Library, supported by the UK's National Building Specifications. The NBL offers a wide range of objects covering all fields of the AEC industry in an open IFC supported format. It is expected that objects figuring in these libraries will have to meet industry specification certificates in the near future [33].

It is indeed a crucial time for the AEC industry, as it is facing quite a revolution in how the building process can be upgraded. Since the decay of the industry's efficiency in the 1960's, changes have been slowly adopted in comparison to other and more dynamic industries [38]. As technology is currently opening many doors, the main challenge lies in adopting the practices that are appropriate to take maximum profit out of it. BIM is not only about buying software licenses, but transforming the whole construction process into an integrated, holistic and sustainable practice [19].

### **1.2.8. Building Information Modelling as a term**

The fundamentals of BIM have been forged and described by various researchers and visionaries since the early 1970's. As the concepts and ideas came to practice, the whole definition of BIM began taking form.

<sup>3</sup> In MCDA, parameters to be optimized are called fitness parameters, and have a certain score associated. In the same line, modifiable variables are known as genomes.



Building Information Model as a term was first mentioned in 1992 in *Modelling Multiple Views on Buildings*, a paper by G.A. van Nederveen and F. P. Tolman [50]. But it was not until Autodesk released its white paper *Building Information Modelling* in 2003 that the term and its acronym BIM became popularly used [7].

However, various BIM software firms already had their own terms for describing the digital representation of the construction process. Graphisoft's ArchiCAD, recognized as the first functional BIM software implemented in 1987, operated under its 'Virtual Building' approach. Bentley Systems adopted the description of 'Integrated Project Models' and Autodesk's Vectorworks coined 'Building Information Modelling'. Other firms adopted terms like 'Single Building Model' and 'Project Lifecycle Management'. [50] [26]

Under these differing terminologies 'Building Information Modelling' prevailed thanks to the work of Jerry Laiserin. He is recognised to have popularised and spread the term, but most important, convincing major BIM software firms (other than Autodesk) to describe and analyse their products under the same terminology [26]. This has allowed BIM vendors to compete in a common ground and allowed users to better compare them. Laiserin has made a notable effort to define and put together the concepts and processes that compose BIM, with the aim of standardizing the term and thus facilitating the existence of a common knowledge for this growing industry [50].

## 1.3. IMPLEMENTATION IN THE AEC INDUSTRY

### 1.3.1. BIM: A growing reality

This section intends to give a quick view on the growing reality of Building Information Modelling in the AEC industry. With current use and implementation in projects all over the world, industry reports show BIM adoption rates and tendencies over the past few years. To better reflect this reality, some reports further indicate in which measure all stakeholders in the construction process have adopted BIM as a process in close collaboration. [31]

In order to understand adoption tendencies it is important to know which benefits motivate this change. Therefore, surveys also indicate the implications of adopting BIM, resulting in a generalized increase of productivity which is measured as an increase of Return on Investment (ROI). [30] [31]

In response to the improvements in efficiency and added value to the construction process that the adoption of BIM implies, governmental entities with competence within the AEC industry are starting to take legal action. As matter of fact, the UK Government has stated its intention to require collaborative 3D BIM, with all project and asset information, documentation and data in electronic open format on its projects by 2016 [10]. In order to do that, they have founded a BIM Task Group which will be designated to promote and supervise a four-year program for the modernisation of the industry. The main objectives behind this initiative are to reduce capital cost and the carbon burden from the construction and

operation of the project's built environment by 20%, and most important, to be ahead and lead the change in the AEC Industry. [10] [15]

But many other national governmental organs are beginning to be aware of the new change of scenario in the international industry. As HOK's CEO, Patrick Mc Leamy states in the 2011 UK Government Construction Strategy:

*"BIM is the first truly global digital construction technology and will soon be deployed in every country in the world. It is a 'game changer' and we need to recognise that it is here to stay - but in common with all innovation this presents both risk and opportunity. "* [44]

In front of these risks, a long list of countries have created their own BIM specific bodies to manage the transition of its adoption and take advantage of the opportunities BIM has to offer. Included in this list are Hong Kong, India, Iran, Singapore and South Korea for Asia; France, Norway, Switzerland, the Netherlands and the United Kingdom for Europe; and finally, Canada and the United States of America for North America. In terms of expertise, the United States and Sweden have a long run and experience working with BIM environments. So it comes as no surprise that they lead the BIM adoption ratios in the international scene. [50]

Apart from these countries, there are many others which do not have specific BIM proactive bodies, but in compensation they support international BIM standards. BuildingSMART, the organization which represents those industry standards has chapters all over the world and partially covers the function of these bodies [51].

### 1.3.2. North America: Industry reports and BIM surveys

Industry reports and BIM surveys cover the construction markets which have enough implementation to collect relevant data. Therefore in this sub-section only North America<sup>4</sup> will be issued. Afterwards, Western Europe and Spain will be overviewed.

#### Adoption

BIM adoption and implementation by the AEC industry's users has seen a **significant increase from 28% in 2007 to 71% in 2012**. This increase of adoption is led by contractors, which represent 74% of adopters, followed by architects (70%) and engineers (67%). It is interesting to highlight that medium to large and large organizations have much more higher grades of adoption (90%) than small retail ones (49%). This may have been caused by the 2008 economic recession, which may have reduced the investment capabilities for BIM implementation of

---

<sup>4</sup> The following information has been extracted from The Business Value of BIM in North America, a study research carried out in 2012 and driven by Mc Graw Hill Construction; open to 582 construction industry professionals from the U.S.A. and Canada representing firms of varying size and type. For further information consult the full report. [31]

smaller firms of the industry. In addition, small companies are in disadvantage in front of large ones as they usually have no experience in implementing new technologies and later standardize business processes to optimize them.

### Levels of BIM Adoption in North America

Source: McGraw-Hill Construction, 2012

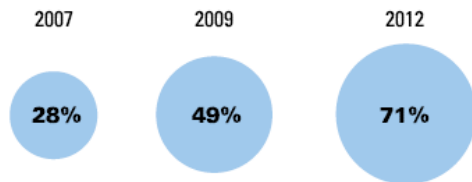


Figure 6: BIM adoption rates for North America [31]

### BIM Adoption by Type and Size of Firm (2009 and 2012)

Source: McGraw-Hill Construction, 2012

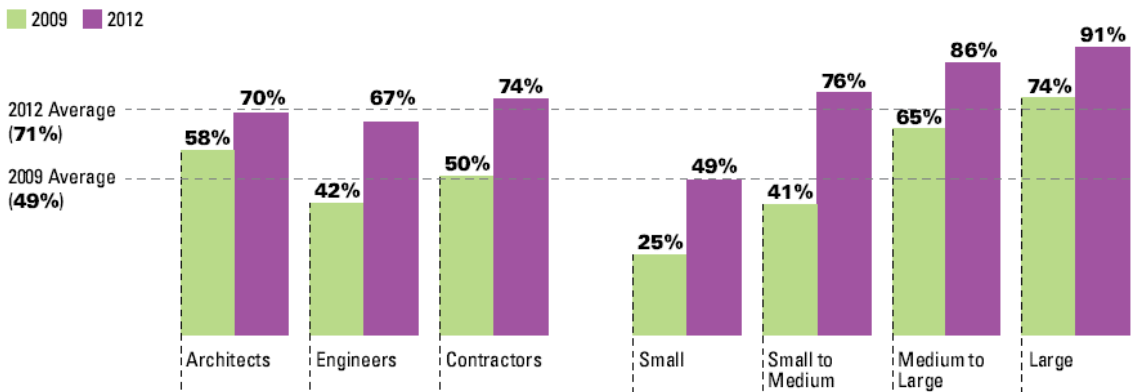


Figure 7: BIM adoption rates by type and size of firm [31]

Expertise in BIM implementation has significantly increased, with **almost twice the proportion of users with five or more years of experience in 2012 (36%) than in 2009 (18%)**. Moreover, **58% of current users, regardless of their experience, expect to use BIM in most of their projects by 2014**.

### BIM Implementation Levels (2009–2014)

Source: McGraw-Hill Construction, 2012

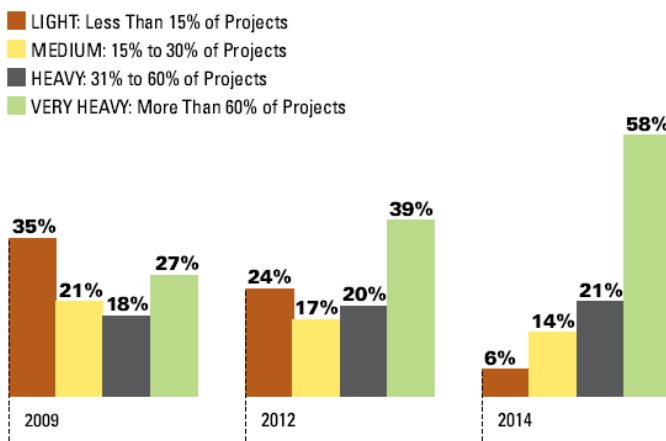


Figure 8: BIM implementation levels [31]

### Collaborative processes

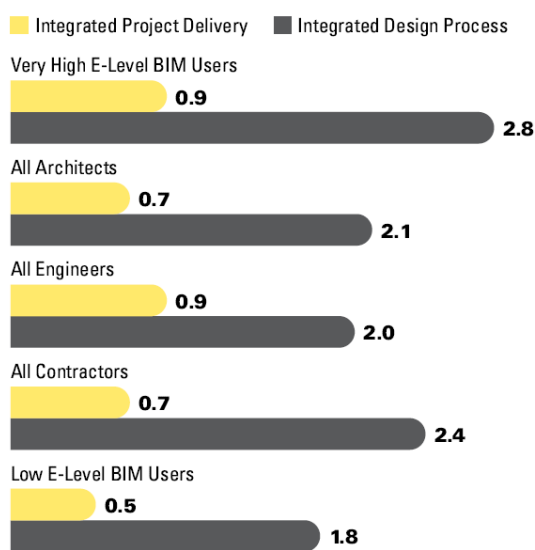
**Integrated Project Delivery is reported to have very low implementation by BIM users.** As IPD has a legal and contractual implication, all parties involved in a project need to have a high grade of experience in collaborative processes. Nevertheless, there are alternative non-contractual collaborative ways of working that will help companies gain the experience needed to reach IPD. This intermediate collaboration step can be called **Integrated Design Process**, in which all parties involved in a project declare their intention to collaborate as much as possible and set common goals to the benefit of the project.

As appreciated in *Figure 9*, users have rated in a 1 to 10 scale the frequency in which they use IPD and IDP. Engineers seem to be more involved in typical IPD contracts. High engagement level BIM users lead the way in collaborative ways of working.

Collaboration is usually measured by model sharing activity amongst project players. The highest level of model sharing activity is taking place between contractors and fabricators due to the benefits in coordination it implies. Opposite to contractors are architects and engineers, who are less likely to share their models due to strong intellectual property concerns. Once more, this indicates the need of legal and liability regulations for collaborative BIM processes.

#### **BIM Team Use of Integrated Project Delivery** Frequency Index (1–10)

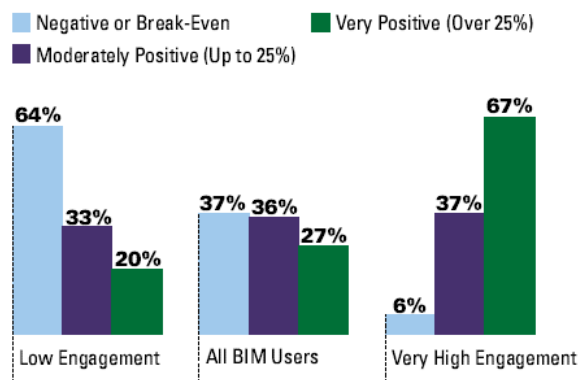
Source: McGraw-Hill Construction, 2012



*Figure 9: BIM team use of IPD [31]*

#### **BIM ROI for Users by Level of Engagement**

Source: McGraw-Hill Construction, 2012



*Figure 10: BIM ROI for users by level of engagement [31]*

### Benefits

Behind these growing grades of adoption several major benefits of BIM implementation are encountered.

- Major long term benefits: Consulted users claim noticeable increased profits, reduced construction cost and reduced project duration as the major long-term BIM benefits, along with maintaining repeat business with past clients (which requires completed project models for re-use).

- Major short term benefits: As short term benefits, fewer document errors and omissions are encountered, and companies seem to have an increased capability of marketing new projects to new clients.

#### Return on investment (ROI)

Although **almost two thirds (62%) state to have positive ROI with BIM adoption**, it is not evenly perceived across different firm types and BIM engagement levels. If analysed by firm types, 74% of contractors perceive a positive ROI in front of 37% of engineering firms. But even if separated by firm typology, **ROI strongly correlates with BIM engagement levels**, as shown in *Figure 10*.

#### User's investment areas

It is well known that BIM is not only about buying software licences, but adopting and engaging the whole process. Therefore, BIM ROI rewards companies with higher skill, experience and implementation levels. In this line, **experienced firms are investing substantially more in improving communication and collaborative processes than in mere software technology**.

#### Non-users

The percentage of non-users has shrunk from 51% in 2009 to 29% in 2012. Amongst them 30% of non-users declare that they will not use BIM in the future. Major reasons for refusing to BIM implementation are high software licence and hardware improvement costs, and most important; **there is not enough demand of BIM from contractors, owners or other AEC industry players**.

### **1.3.3. Western Europe: Industry reports and BIM surveys**

#### North America vs Western Europe

The underlying economical and historical differences that have defined the distinct practices in the construction industry of both western economies have also had its effect in the adoption of BIM and on its business value. In this subsection Western Europe<sup>5</sup> will be issued, comparing whenever possible the relevant facts and trends with those of North America.

---

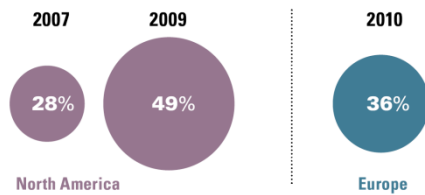
<sup>5</sup> The following information has been extracted from The Business Value of BIM in Europe, a study research carried out in 2010 and driven by Mc Graw Hill Construction; open to 948 construction industry professionals from France, Germany and the United Kingdom representing firms of varying size and type. For further information consult the full report. [30]

### Adoption

In 2010, **approximately one third (36%) of participants stated having adopted BIM**. Compared to a 49% adoption rate in 2009 in North America (NA), Western Europe (WE) falls behind. Architects lead adoption rates with 47%, followed by engineers (38%) and contractors (24%).

#### **BIM Adoption—North America vs. Europe**

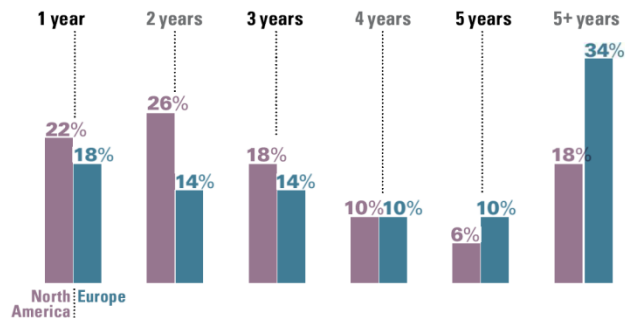
Source: McGraw-Hill Construction, 2010.



**Figure 11:** BIM adoption rates [30]

#### **Years Using BIM**

Source: McGraw-Hill Construction, 2010.



**Figure 12:** BIM engagement rates by years of experience [30]

Although overall adoption rates are lower, the BIM adoption process in Western Europe has been dramatically different. With a much earlier adoption in Western Europe, BIM users are more deeply committed than their counterparts in North America. In 2010, **over a third of WE BIM users (34%) stated to have over five years of experience, compared to only 18% of NA BIM users**. This high grade of commitment is reflected from the start by early adopters. Around 46% of WE BIM beginners use BIM in 15% or more of their projects, in front of only 20% of NA beginners. Furthermore, 45% of BIM users in WE consider themselves to be experts or advanced in its use. Yet, if analysed by firm type, another relevant difference appears. **Contrary to NA, where adoption among contractors in 2009 was about 50%, only 24% of contractors adopted BIM in WE.**

### Expected adoption growth

Regarding BIM engagement levels, **frequent users** (use BIM in 30% or more of their projects) **are expected to grow from 60% in 2010 to 75% in 2012**. These expectations exceed frequent BIM users reported in NA in 2012, which represent 59% of all BIM users. If analysed by firm type, contractors anticipate the most aggressive increase in implementation, with a growth of frequent users from 11% to 54% in 2012.

### Benefits

BIM adoption trends respond to the benefits it implies. As expected, experienced users enjoy higher benefits from BIM use. In line with the NA BIM users, WE BIM users also report increases in productivity, with reduced errors and omissions in construction documents and fewer costs in time and work in repetitive processes. Although NA BIM users report very positive impact of using BIM in marketing themselves as a firm to clients, these are not as important benefits for WE BIM users.

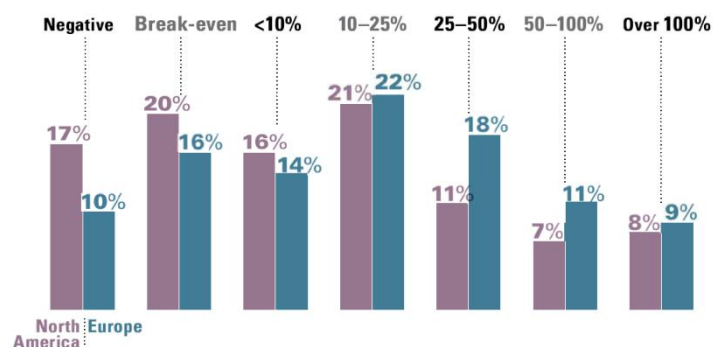
WE BIM users also report increased project value, with improved collective understanding of design intent, greater project quality and reduced conflicts during construction as major benefits. In contrast with North America, the processes in which BIM adds more value are design stages instead of construction phases.

#### Return on investment (ROI)

In 2010, **circa three-quarters of WE BIM users (74%) perceived positive ROI in front of 62% of NA BIM users.**

#### **Perceived ROI North America vs. Western Europe**

Source: McGraw-Hill Construction, 2010.



*Figure 13: Perceived ROI North America vs Western Europe [30]*

High BIM engagement levels by users in Western Europe explain the high rate of positive perceived ROI compared to North America. This difference is accentuated by the fact that Western European companies are more committed to formally measuring ROI in contrast to less than a third of North American BIM user companies. Usually, formally measured ROI is higher than perceived ROI.

In consistency with the North American BIM users, **ROI strongly correlates with BIM engagement levels.** In fact, **80% of WE expert BIM users report positive ROI.**

If analysed by firm type, a major difference is encountered. Opposite to NA BIM users, **in Western Europe a higher percentage of engineering firms perceive positive ROI in comparison to contractors:** 70% of WE engineering firms perceive positive ROI in front of 37% in NA; and 74% of NA contractors perceive positive ROI in front of 40% in WE. Although perceived ROI by contractors is low, it is expected to grow in the near future.

#### User's investment areas

It takes certain effort and investment to engage BIM prior to perceiving positive return on investment. **WE BIM users see a top priority in developing internal collaborative BIM procedures.** Even though WE BIM users are more engaged in BIM use, software and hardware improvement are still high investment priorities.

### Non-users

Non-users seem to be open-minded about BIM, with almost 70% of non-users aware of BIM and willing to use or evaluate it. The other **30% of non-users are not interested in using BIM**. This reluctance may keep a relation with the abundance of small projects that are not best fit for BIM. These kinds of projects often involve re-use or modification of existing buildings or infrastructure which are more abundant in Western Europe. Like in North America, Western European **non-users claim not enough BIM demand from clients or other firms as a major reason for not adopting it**. Other major reasons are expensive software and not enough time to evaluate BIM adoption.

#### 1.3.4. Spain: BIM awareness

Even though BIM implementation amongst the Spanish AEC industry is still not important enough to be surveyed, awareness is growing especially among contractors with international presence in countries where BIM is heavily implemented.

In its homeland, governmental bodies like Catalanian *Generalitat de Catalunya* have taken the first steps towards BIM adoption. Through its public company *infraestructures.cat*, a public education institute has been tendered with special positive evaluation of the use of BIM in the elaboration of the project and in the project management [25]. Thus, not only a BIM model is valued, but also a collaborative way of working.

Furthermore, in response to a request made by the author to *infraestructures.cat* regarding their BIM implementation policy, they stated that it was their intention to gradually implement BIM as a process, first requesting it in projects and later in construction and facility management. [65]



# CHAPTER 2 - BIM FUNDAMENTAL PRINCIPLES

## 2.1. INTRODUCTION

As BIM covers a vast and extensive field of knowledge, it is important to lay out the fundamental principles, concepts and tools that compose it. In order to do so, a **BIM framework** of knowledge will be provided to present information in an organised and comprehensive way. Technology tools and concepts will be explained in order to understand the changes and effects BIM can have on the industry's business processes and policies.

## 2.2. SETTING A BIM KNOWLEDGE FRAMEWORK

### 2.2.1. Introduction

Building Information Modelling embraces an enormous and unquantifiable set of concepts, processes and ideas which can be at first overwhelming. Such amount of information of diverse nature calls for a need of organisation. For the scope of this work, a proposed research framework will be set in order to present collected BIM domain knowledge in an organised way.

BIM is agreed to be a process that involves a wide range of players related to the AEC industry and their workflows inside and between its respective fields. According to this, a conceptual frame is proposed to describe **the fields related to BIM activity** on one side, and another one regarding the **BIM process itself and its implementation** on the other side.

### 2.2.2. BIM fields

BIM fields of activity identify its players and their work outcome, known as 'deliverables'. Three interlocking fields will be considered: **Technology**, **Processes** and **Policy**. Each field will include two subfields each: Players and deliverables. A diagram is shown in *Figure 14*. [39]

- **BIM Technology Field:** This field gathers players which are specialised in developing software, hardware, net-working systems and equipment to increase the efficiency, productivity and profitability of the AEC industry.
- **BIM Process Field:** The process field groups all players directly or indirectly related to the AEC industry. It includes engineers, architects, contractors, subcontractors, facility managers, owners and all other stakeholders who procure, design, construct, manufacture, use, manage and maintain facilities.

- BIM Policy Field:** Policies are understood as a set of agreed rules to drive decision-making. This field includes all those bodies that focus their work on delivering research, preparing BIM practitioners, distributing benefits, allocating risks or minimizing conflicts within the AEC industry. These players may be represented by research or educational institutions, insurance companies or industry regulatory bodies. Although their products are not necessarily construction-related they play a divulgater, preparatory, regulatory and contractual role for the AEC's industry practices.

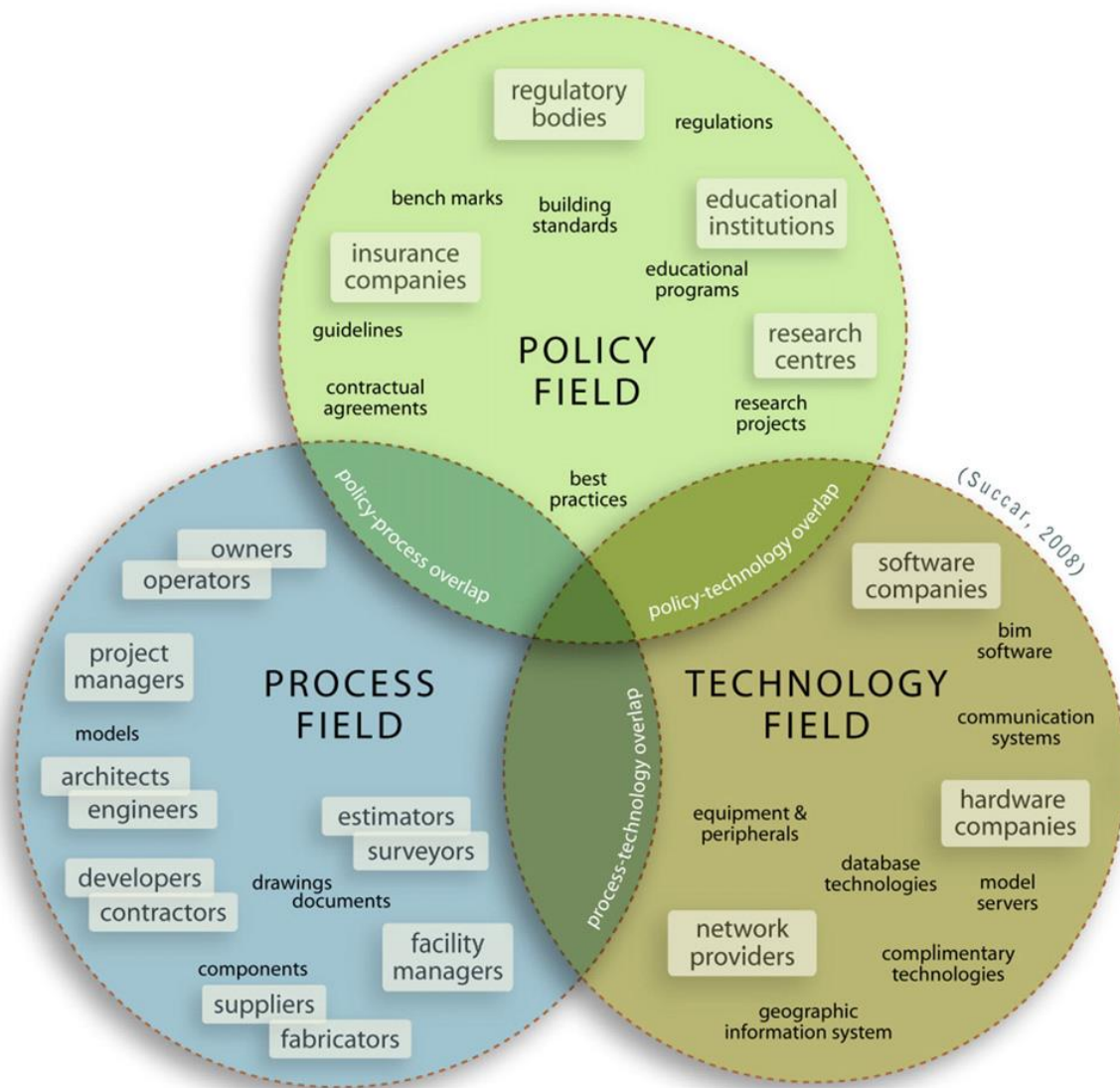


Figure 14: BIM fields of activity [39]

### Interaction<sup>6</sup>

As the described fields and sub-fields overlap with one another, a dynamic interchange of work and deliverables takes place between their players. These relations are denominated push-pull interaction. Push interaction transfers knowledge from one to another field or sub-field, while pull interaction is knowledge transference in response to a feedback request. [39]

### Overlaps

In BIM Fields overlapping, certain deliverables call for the joint effort of players from different fields, or perhaps certain bodies composed of players from different fields. Some examples of these overlaps are exposed [39]:

- Process-Policy: Industry bodies (BIM player) ex. BuildingSMART
- Policy-Technology: Interoperability standards (BIM deliverable) ex. IFC Standards
- Technology-Process: Communities of practice (BIM player)
- Process-Policy-Technology: BIM Implementation (BIM deliverable).

### 2.2.3. BIM implementation stages

There is a long path of challenges and achievements that AEC industry players have to overcome in order to take full advantage of BIM's capabilities. Many of the concepts that will be treated in this work can only take place when a certain grade of BIM domain and mastering has been achieved. As project stakeholders are more experienced and engaged with BIM, new possibilities arise. Therefore, it is necessary to set a basic time-linear frame of the BIM implementation process and briefly explain its stages.

Each stage is reached consecutively and in a gradual way through various steps. Current AEC industry practices prior to BIM use are considered as a starting point scenario, and through three intermediate stages, a final and ideal BIM adoption stage, known as Integrated Project Delivery (IPD), is found. The difference between stages and steps is that stages are radical changes and steps are incremental changes in the path of reaching a next stage. [39]



**Figure 15:** BIM stages of implementation [39]

<sup>6</sup> For further information and examples on field interaction consult *Table 1* in *ANNEX D*.

The defined BIM implementation stages are as follows:

- **Pre-BIM**

Project stakeholders are awarded design-bid-build contracts, which encourage risk avoidance. Project information is often based on 2D CAD documentation. Workflows are in general linear and asynchronous. Few collaborative processes are encountered and data flows often lack interoperability. [39] [19]

- **BIM Stage 1: Object-based modelling**

BIM implementation begins with BIM software use in the production of models responding to a single discipline. These authoring models are in general developed by a single player and used in only one project lifecycle phase (ex. Architectural design model, structural design model). Models are primarily used to automate 2D drawing generation and export of basic documentation such as construction schedules or quantity take-offs.

Collaborative processes and multidisciplinary model interchange in this stage are scarce. Pre-BIM contractual aspects and behaviour persist. Data flows are still linear and communication between players is still asynchronous. The main change to be noticed is a need of detailed design information in early design stages to produce the models. [39]

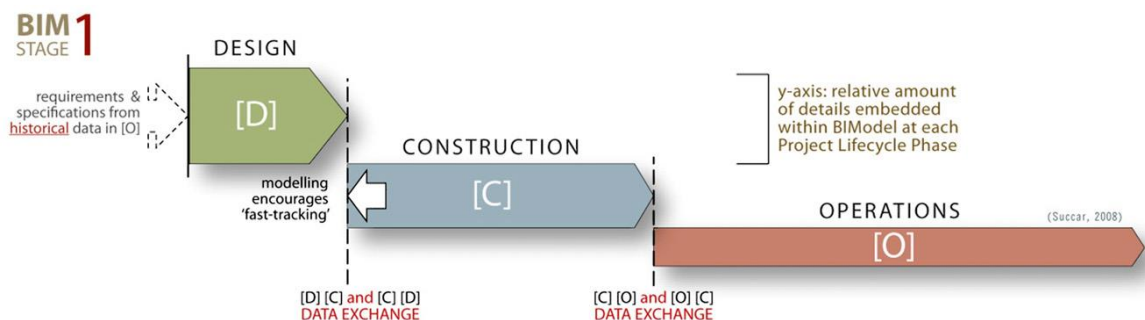


Figure 16: BIM stage 1 of implementation [39]

- **BIM Stage 2: model-based collaboration**

As players have reached maturity within stage 1, they realise the potential benefits of collaborating with other players using BIM. In this second stage, model-based collaboration takes place between players of distinct disciplines through BIM model interchanges. These model interchanges may occur in a same project phase (ex. Design-Design: Architectural model – Structural model), or between different phases (ex. Design-Construction: Structural steel models; Design-Operations: Architectural model – Facility maintenance model). Valuable deliverables like 4D time analysis and 5D cost estimating can be generated from these interchanges. Communication between players is still asynchronous but Pre-BIM behaviour starts to fade. Contractual amendments become necessary, as document-based communication is gradually replaced by data flow through model interchanges. Intellectual property concerns regarding models also arise.

As model interchanges take place, models gain in detail and project lifecycle phases begin to overlap. Construction players offer design services in response to designer's demand of detailed construction and procurement information. This translates in richer and improved construction models, which have been developed through better assisted and informed design decisions. [39]

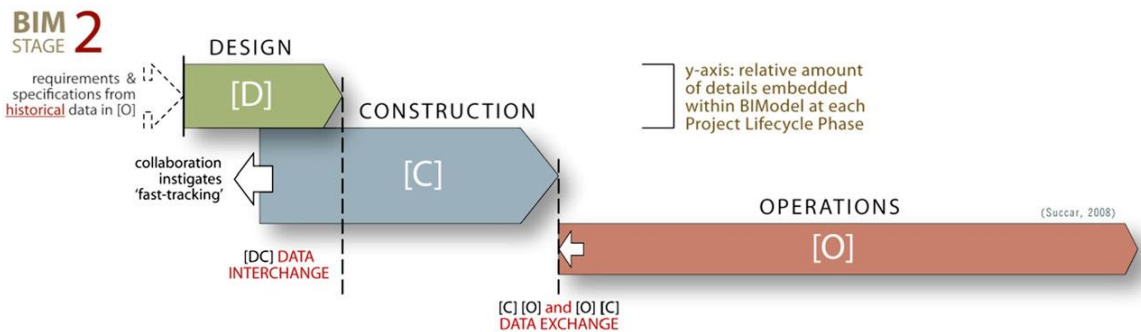


Figure 17: BIM stage 2 of implementation [39]

- **BIM Stage 3: network-based integration**

In this third stage integrated and semantically-rich models appear. They are created, modified, shared and maintained collaboratively across the project's lifecycles. Network and software technology (ex. Servers, shared data-bases and cloud services) is essential to allow model access and integration amongst project stakeholders.

Models in this stage are interdisciplinary and n-dimensional, allowing valuable complex analyses in early design and construction phases [27]. As every player is involved in the design phase, the resulting model incorporates solutions that respond to every discipline and which do not interfere with others. Integrated models also allow projects to comply with design, construction and operation scopes and objectives from the very beginning, and in the meantime optimize constructability, operability and other relevant attributes (ex. Green building, safety, etc.).

Phases totally overlap in this stage and data flow between them is synchronous. All project players work upon a shared model which is iteratively improved [1]. In order to reach this implementation stage, contractual, risk allocation and intellectual property issues have to be seriously reconsidered. [39]

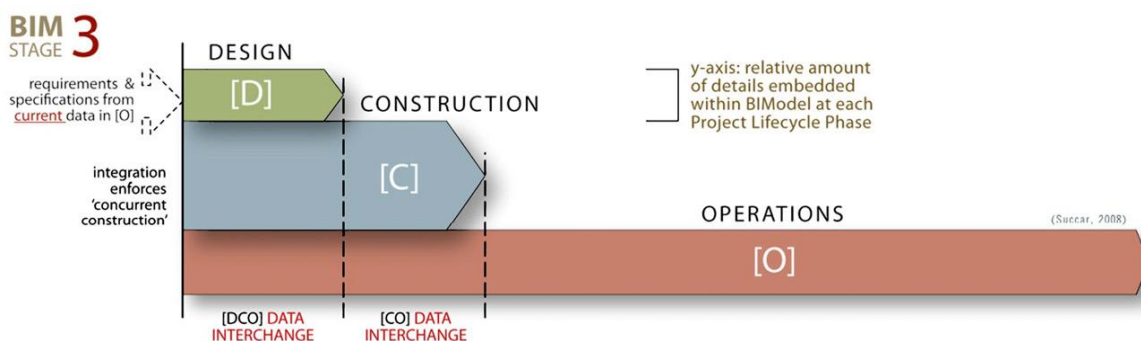


Figure 18: BIM stage 3 of implementation [39]

- **Integrated Project Delivery**

Integrated Project Delivery, a concept defined by the American Institute of Architects California Council, represents the ultimate BIM implementation goal. Although other implementation visions exist, IPD is open enough to incorporate future BIM implementation tendencies.

The AIA defines IPD as:

*“Integrated Project Delivery (IPD) is a project delivery approach that integrates people, systems, business structures and practices into a process that collaboratively harnesses the talents and insights of all participants to optimize project results, increase value to the owner, reduce waste, and maximize efficiency through all phases of design, fabrication, and construction.*

*IPD principles can be applied to a variety of contractual arrangements and IPD teams can include members well beyond the basic triad of owner, architect, and contractor. In all cases, integrated projects are uniquely distinguished by highly effective collaboration among the owner, the prime designer, and the prime constructor, commencing at early design and continuing through to project handover.” [4]*

#### 2.2.4. Measuring BIM implementation

In order to quantify and measure BIM implementation, three main variables are of great value:

- **Project Lifecycle phases**<sup>7</sup>: Projects go through three main phases which are **Design, Construction and Operation**. Each one of these may be divided in sub-phases and contain all tasks and workflows performed in a project’s lifecycle. It is valuable to have a clear diagram of these phases, as BIM implementation will change tasks and relations within them. [39]
- **BIM Data Flows**: What enables BIM to be a powerful tool is the ‘I’ for ‘Information’. Truly effective collaborative BIM practices, which improve efficiency, happen when this information is transferred. Data can be found in structured and computable formats (ex. database), semi-structured (ex. schedules) or non-computable (ex. Images). Transference may happen also in various ways. The importance of data flows relies in whether there is relevant information loss in transference or not. In **data exchange**, part of its information is lost when transferred (ex: export of only the geometry of an attribute-rich object). In **data interchange**, data transferred is structured and computable and can be used without relevant information loss in respect to an intended use. [39]
- **BIM Players**: BIM use and activities amongst stakeholders clearly defines the level of BIM engagement within a project. This variable puts in context the previous ones and gives them meaning, as data flows happen between players and project lifecycle phases.

---

<sup>7</sup> For further information on project lifecycle phases consult *Table 2* in *ANNEX D*.

## 2.3. BIM TECHNOLOGY

### 2.3.1. Introduction

**BIM technology** is the set of tools and both physical and digital resources that support the BIM process, allowing for building information model creation, management and interchange.

As described in the definition for BIM, a difference exists between BIM technology and BIM understood as a business process. When referring to BIM technology further distinctions between BIM software titles and **Building Information Models** are necessary.

In this section the very fundamental principles of BIM technology will be treated. These principles are the ones which rule the procedures, methodologies and the way information is managed in the design process inherent to BIM software tools. These tools, then, are the ones that will later be used to create, manage and share the final deliverable; the Building Information Model.

### 2.3.2. Object oriented design

Parametric objects are fundamental to understand BIM. They are differentiated from traditional 3D objects, as they contain additional information else than their geometry, and can be manipulated through parametric rules.

For the purpose of this work parametric objects are defined as those which:

- Have **geometric, data** and **parametric attributes**
- Their **geometric data is non-redundant**, resulting in a well-defined geometry. All 2D views of an object must be consistent with its 3D definition.
- **Parametric rules** attributed to the objects **will automatically change certain geometric parameters** when inserted into a model or when changes are made to another component parametrically linked to that object. For example, a window will automatically be fit into the closest wall, and a wall will automatically vary its height when the ceiling above is moved.
- They can be **defined through different levels of aggregation**. Parametric objects can be treated and modified at many different hierarchy levels. A roof for instance may be defined as a congregation of several layers of various components. If the thickness of one component is changed, the overall thickness of the roof will also change.
- They can **detect** inconsistent or unrealistic **changes that contradict their parametric rules**. These changes may contradict manufacturability, constructability, geometric feasibility, etc.
- They have the ability to **be assigned, transmit when requested, and export data attributes** in order to be used or reused in other models or by specific applications. For example, basic geometric data is transferred when used in other models or structural properties can be modified when used in structural analysis tools.



### Parametric modelling fundamentals

In order to analyse the basic features of BIM technology it is essential to understand the key concepts of parametric modelling. Basically, these are the incorporation of data attributes that turn 3D shapes into objects with properties, and the parametric attributes that rule their behaviour within the model.

What motivates the development of parametric modelling is the exploration of data attributes and parameters that go beyond 3D geometry. This is what ultimately transforms shapes into objects. The incorporation of information has unlocked many modern BIM software capabilities such as model analyses, quantity take-offs, cost estimates and so forth.

In the first steps of parametric modelling, the 3D geometry of a shape could be defined parametrically. As mentioned, in the '*BIM History*' section, representation methods such as CSG and BREP used dimensions that defined shapes as parameters. Later on, these parameters could be modified by user's request and would automatically generate the modified shape. But a major step for parametric modelling was the recognition of the need for **change management**. When an object is modified, these changes should propagate in their model accordingly to their connectivity to other objects. Basically, change propagation is applied to linked parameters between different objects. As an example, if a ceiling is moved upwards, the columns supporting the upper floor should extend to accommodate this change. This calls for a resolving capability that analyses these changes and applies the most efficient and parametric coherent update sequence. This capability is now seen in BIM software titles and finds itself in current development, as it is one of the basic features of Building Information Modelling.

### Object families, classes and instances

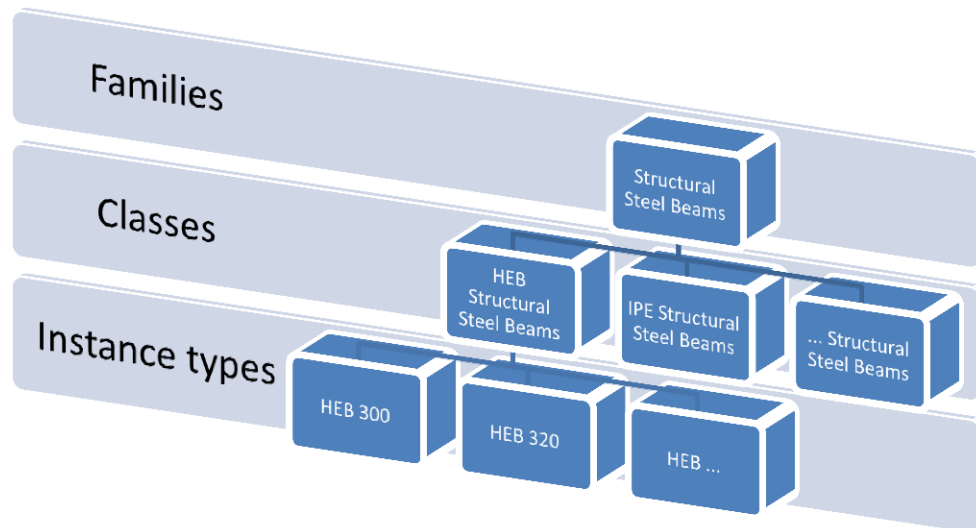
Virtual models of buildings are made up of basic building components. In BIM software titles these components don't have to be drawn and designed each time they are placed, as happens in 2D CAD design. Instead, these components can be categorized in **families** and **classes** and placed in the BIM model as object **instances**.

**Families** group similar components used in the AEC industry. Walls, slabs, columns, frames, doors, windows and many more are considered as families. They contain all types of components that serve a same basic function. Inside these families, object **classes** are found. Different classes within a family gather components with a same composition nature or behaviour. Therefore, components of a same family but pertaining to differing classes share a same basic purpose, but differ in relevant properties. To illustrate this, consider IPE structural steel columns and structural concrete columns, or exterior walls and interior walls. Both pertain to a same family, but their nature is different and their specific use varies respectively.

Contained in object classes, **object instances** are found. When defining a class, a wide range of properties and parametric attributes can be used to model the desired building object components within it. To create a class, an initial set of rules for object instance generation has to be determined. This process consists of setting a combination of fixed attributes, which are usually geometric and editable parametric attributes. These editable parameters allow the



generation of diverse object instances within that class. For instance, when defining an 'HEB structural steel columns' class inside the 'structural columns' family, a fixed parametric condition is set so that the base of the beam profile is equal to its height. Nevertheless, the height of the beam's profile is left as an editable parameter and allows for the definition of HEB300 beams, for example, inside the HEB beam class.



*Figure 19: Organisational schema for object families, classes and instances*

A very important part of class definition is the setting of parametric attributes that will rule an **object instance's behaviour**. The form of objects within a class will vary accordingly to its context. Their faces can be constrained through geometric parametric rules to other objects in the model. For instance, a wall class will adapt its height to the top and base levels it is connected to. Its length will be controlled by its end and starting points, which can either be independent or be attached to other elements like columns and other walls. Its faces can also be constrained to align with other elements' faces or gridlines. Parametric rules also apply to other objects placed inside or related to another object. For example, when a wall is moved and it has an inserted window, it will re-accommodate its position with respect to the wall's internal coordinates so they move as a unit. This preserves as much as possible the original design intent.

As found in the parametric object definition previously given, parametric rules regarding a component's **feasibility** can also be set. For example, if wall width underpasses a certain established minimum width, a warning can be given to the BIM user. This responds to a violation of the predetermined material widths that compose walls in that particular class. These rules can also apply to positioning feasibility, warning the BIM user when a door is placed outside a wall boundary, for instance.

Parametric systems also allow the **extensibility** of parametric object classes. This allows for BIM users to further customise their building object component instances, adding additional parameters for their generation. Taking back the example of HEB structural steel columns, BIM users can add new parameters to their object classes, like the thickness of fire-resisting coating

applied to beams, for instance. This additional property could even be further extended by adding a coating type as a parameter. Each coating type could then be assigned a specific thermal resistance that would be used to compute the beam's fire resistance time. As exposed, the possibilities of parametric customisation are certainly wide.

### Object structure

Parametric systems allow the definition of object families, classes and customised instances. Ultimately, building object components are generated, defined and modified through these systems.

Generally, the internal structure of object instances can be described through graphs. A parametric modelling system is composed of nodes that represent object classes and have several parameters attributed that can be modified. An object instance is defined by its connection with these nodes and the editable relationship with others. These internal structures are different among BIM software titles, causing information loss when models are transferred. This is what motivates the need for **interoperability**, which will be discussed later on.

The complexity of parametric systems is determined by the variety of parametric rules that objects can be attributed with. General attributes include geometric features such as distances, angles and rules like '*parallel*' or '*perpendicular to*'. Other general attributes are the '*if then*' attributes, which automatically replace an object's parameter with another based on a test result or some condition. This allows for automatic corrections when an object is placed in a model, or when changes to the model affect its parametric rules. As an example, when a structural steelwork beam is placed, its connection details may be automatically adapted depending on whether the ends of supporting elements have been defined as 'fixed or 'simply supported'.

The set of parametric capabilities that parametric systems can use when defining objects are as follows:

- General parametric relations supporting full algebraic and trigonometric capabilities.
- '*if then*' attributes that support object instance definition and modification based on conditions. Different features can be associated to a same object depending on its environment.
- Extensibility of parametric object classes. New customised objects with new behaviours and attributes can be generated.

Once objects are inserted in a model, parametric systems offer capabilities for defining their behaviour, such as:

- Constrain object's attributes to other object parameters in the model. This is basic for change management in a model. For instance, a column's face can be constrained to align to a wall's face. If the wall is moved, so will the column do in order to keep their respective faces aligned.

- Usage of global parameters to select or control the layout of objects in a model. For instance, a column placed in the intersection of two grid-lines and constrained between two floor levels can be modified in position and length through those grid-lines and levels respectively.

It is very important for designers and BIM users to acknowledge the quantity of rules found in basic object classes. Even a wall class has low-level rules that designers are not fully aware of. For example, windows or openings cannot overlap or surpass wall's boundaries; walls cannot cantilever over shaft openings; if two walls intersect, their equal layers will join; walls can accommodate different layers in different segments; and many more.

The complexity of parametric systems calls for collaboration between BIM object class modellers and BIM designers, as improved classes and behaviours can be developed and design rules be better understood. If used well, change management capabilities of parametric systems make modelling in BIM environments a remarkably effective process.

#### Parametric modelling of buildings

Building projects can be broke down into fairly basic components. Compared to infrastructure projects, buildings have a much more complex list of basic units. Even a detailed model of a medium-sized building can overwhelm an advanced personal workstation. Fortunately, industry standards and construction codes make these basic building components easy to categorize and group.

Every BIM software title has a predetermined set of object families and classes of building components, each with their own behaviours. In *ANNEX D, Tables 3 and 4* compile predefined object families that are found for both BIM design and BIM fabrication software. Although some BIM software titles have tried to embrace as many family components as possible, others have stayed within the necessary families found in their specific industry sector.

There are also **online object libraries** such as Autodesk Seek [6] or the UK's National BIM Library [33], from where BIM users can download object families and classes that are not found in BIM software titles by default. If users were not able to find their desired object families, BIM tools allow for family extensibility and customisation, as afore mentioned.

#### Parametric modelling for construction and fabrication

There are BIM software titles specifically oriented to component fabrication. Predominantly, these programs are destined to steel fabrication, precast concrete and mechanical and electrical design. As mentioned before, families and component classes will vary from general BIM applications in order to accommodate specific fabrication needs.

Connections in steel fabrication tools are a good example of these object classes destined to specific uses. Steel connections can automatically adjust their nature parametrically depending on loads, connection conditions and the size of elements being connected. Rebar of concrete components can also update to accommodate connections with other concrete elements.

As these objects are a very detailed representation of components, they are suited for fabrication and even automated manufacturing. Nevertheless, default object classes provided by BIM software titles sometimes require a further customisation by users in order to reflect their firm's engineering practices. Customisation may also allow detailers to reduce the number of different pieces in a component and the labour required for manufacturing.

#### Object customisation

Every BIM software title will provide **predefined object classes** which capture standard conventions and codes of practice relevant to their targeted application. These standards may vary from country to country and for each use inside an industry sector, and therefore, BIM tools usually include several libraries to accommodate this diversity.

Codes of practice and standards rule the design of building components and their construction. These conventions are based on the reliability of current practices, safety measures, structural performance, material properties and the functionality of components. Although design of building object components is clearly standardised, their **behaviour** is not. This is why parametric rules of predefined object classes are open to the interpretation of BIM software vendors. As there are various approaches to component behaviour, BIM users may feel the need for addressing their own customised objects for various reasons. Perhaps some of the component classes or their associated functions may not be available in the provided predefined set. Other object classes found in BIM software firms may have to be modified to reflect the user firm's practices in construction. Customisation is also commonly necessary when basic parts of an object are not fit to a given use or they are not in a desired position or order. For example, a wall that does not adjust to a sloped floor or a wall whose layers need to be spaced-out in order to fit structural columns inside it.

In the creation of customised object classes it is important that the user defines the parametric attributes that rule the behaviour and interaction with the other predefined classes. Additionally, these object classes need to be attributed information relevant for analyses, quantity take-offs, cost estimates and other assessments. These tasks require considerable effort from users, but the benefits obtained justify it when certain custom components are to be used frequently.

### **2.3.3. Parametric modelling beyond design**

#### Generation of documentation

By definition, objects have a non-redundant definition of their geometry, and thus, all drawings and documents generated from a model are consistent with each other. Although their geometry is unique, objects are represented in different ways in every view accordingly to traditional representation conventions. For instance, beams are represented as thick lines in structural plans with their type name, hidden elements are represented through discontinuous lines, electrical circuits are represented through symbols and so forth. All this information regarding line styles, line weights, annotation and symbols are representation attributes of

objects. These formatting attributes do not only affect drawing extraction from a model, but can also affect the model representation in BIM software's interfaces as well.

For drawing generation, BIM software allows the definition of the desired detail level, the visibility graphics, the scale and the necessary annotations in each view. It also allows for the creation of drafting views, which can be edited for detailing. For instance, a wall connection detail may have not been modelled, as it is considered to require much effort. Instead, a drafting view can be generated so the connection can be drawn and defined in 2D.

Drawings are generated by bringing one or several views of the model into sheets with normalised titles. View templates that define the visibility graphics in a sheet can be applied, reducing considerably the time spent on drawing formatting. These templates cover the major conventional views such as structural plans, floor plans, elevations, sections and detail callouts.

When placing a view in a sheet, all changes made to the building model **propagate** to all its views and therefore are reflected in all of the existing sheets. Only 2D drawings defined in drafting views have to be manually updated. Additionally, change propagation can be bidirectional in most of BIM software titles. This means that changes made to a view on a sheet propagate to the model and back to all its views in order to keep the consistency of documentation.

Schedules including quantity take-offs and cost estimates can also be seen as views. In terms of change propagation, most of BIM software offer bi-directional editing. Selected items from a schedule can be modified, affecting the central model. Reverse editing may be useful to edit elements whose properties are directly shown, but need careful proceeding as no model visualization is given.

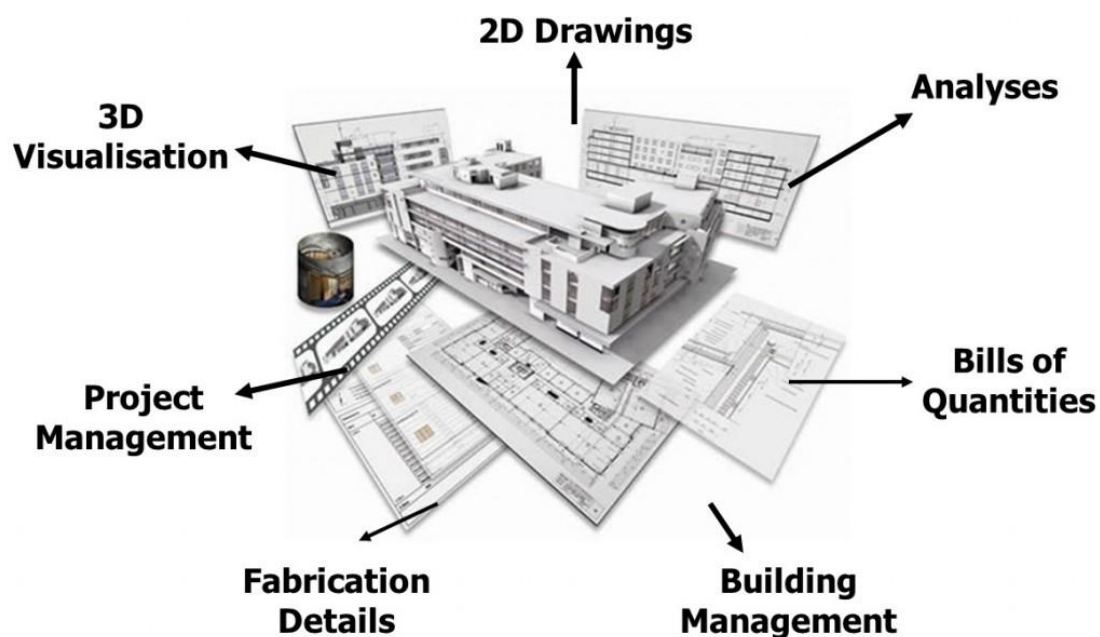


Figure 20: BIM models and their deliverables [16]

### Model size management

**Building Information models** of simple facilities can contain an enormous amount of components. This can be somehow quantified by the physical size of the project, its detail level and project typology, being building projects more complex in component types.

The memory space required for these models can possibly slow down workstation and computer performance, making simple tasks very tedious. Memory is consumed by both the object definitions and the operations carried out on them. Thus, parametric relationships are resource-consuming. Local relationships such as an embedded door on a wall are easier to manage than global or hierarchical relationships. For example, many objects in the model are aligned to a certain gridline, which if modified, would propagate a change to many objects and their respective relationships with others.

There are various ways of handling model size. Memory based models hold all of the model's updated objects and manage change directly. This can be effective in small projects, but soon encounters limitations as size grows and virtual memory reaches its limits. A more effective alternative is found in holding the model in various files and propagating changes made to objects to the rest of the files. This is done by opening, processing and closing other files automatically during edit operations, without the need of holding the whole model in memory.

**Work-sharing** in a project is a memory-effective practice. What it enables is the definition of **worksets**, or segmentation of a model. This is done by determining a central file of a master model and partitioning it through the generation of local files or associated worksets. Users have rights to edit their assigned sets, but cannot directly edit other sets without their owner's permission. This eliminates the need of holding in memory all the relationships going beyond a model segment. Nevertheless, changes that affect the rest of the model still have to be propagated. BIM software tools enable users to synchronize their work with a defined central model every now and then. When synchronized, pending changes are propagated and objects are updated in the master model. Changes made by other users affecting a user's workset are updated in the local files as well during synchronization.

Some BIM software titles offer workflow management tools over these changes during synchronization. As the updates are frequently synchronized, their size is small and can be handled easily. Additionally, changes can be registered by their time of creation, its author (based on user's ID), the objects it affects, and relevant observations made by users.

### **2.3.4. Building Information Models**

Building information models are intelligent and information-rich representations of buildings and facilities, supported in a digital format. BIM models can be described either by the information they represent (what they contain) or by their capabilities (what can be done with their information). Either way, they are characterized by:

- **Building components** that are represented by digital representations (objects) which incorporate both graphical and data information. These attributes can be read by software tools and modified in an intelligent way following parametric rules.
- Components incorporating information describing their **behaviour**. These allows the whole model to be susceptible to analyses such as quantity take-offs, energetic analyses, etc.
- **Coordinated, consistent and non-redundant** information such that a component is seen with the same attributes in all its views and representations. Changes to a component's attributes must be managed and propagated to all its views and representations to ensure model consistency.

### 2.3.5. BIM software platforms

There are many BIM software titles as well as applications for various specific purposes. Major BIM software platforms have been listed and briefly described In *ANNEX D*. In an attempt to ease their comparison, their intended field of use and description is provided, pointing out their main strengths and weaknesses.

### 2.3.6. Enabled key aspects

The presented BIM technology fundamentals are essential to understand the means which make the BIM process possible. In the following sections, the purposes that BIM technology serves beyond mere parametric modelling will be explored.

In summary, and to introduce the following sections, the key aspects which BIM technology supports within the BIM process are as follows:

- Creation and operation of digital databases for **collaboration**.
- **Change management** through these databases in order to propagate modifications and ensure model **consistence**.
- Capture and preservation of information for **re-use by industry specific applications**.

## 2.4. INTEROPERABILITY

### 2.4.1. Introduction

Information related or created during the course of a building project is used by a wide range of team players from various fields and disciplines in diverse applications suited for specific purposes. It is vital that this data-sharing and information flow can take place in an efficient and coordinated way.

Usually information flow (or interaction) should allow the importing of data for whichever use it may be necessary and its export in various formats so it enables its use by other players in other specific workflows. As described previously in the **BIM framework**, this information flow is referred to as **data interchange**, and refers to data transference in a structured and computable format without relevant information loss.

There are two basic paths for data interchange when using BIM in a project. The first one is to share information within players using software platforms of a same software vendor. This option usually makes data-interchange easier and offers advanced data-sharing features, but can be problematic when collaborating with other project stakeholders using different software platforms.

The second one is to use open-source formats which are publicly available and supported standards. Their use allows interoperability between software platforms with differing internal formats that support these open standards. Unfortunately, this option often bears with reduced data-sharing capabilities.

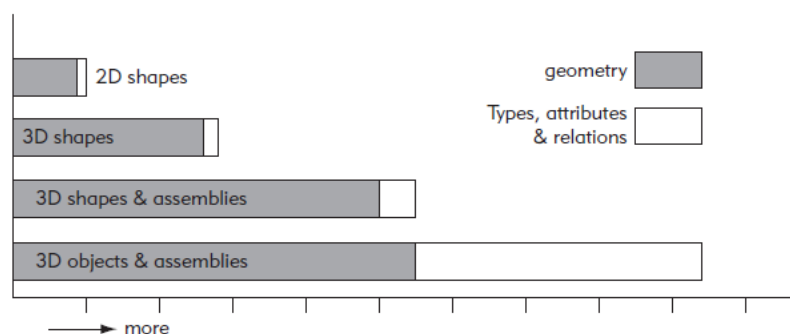
Interoperability is then understood as data interchange between BIM software applications, and allows for workflow effectiveness and refined automation of certain processes. This section will address all relevant matters of what is one of the top-rated factors for increasing BIM benefits according to McGraw Hill's Smart Market report (2012) [31].

### 2.4.2. Interoperability fundamentals

Data interchange is not a BIM-exclusive action. With the use of CAD drawing formats such as Drawing Exchange Format (DXF) or Initial Graphic Exchange Specification (IGES) [19] drawings could be shared between CAD software titles. What is new and exclusive to BIM interoperability is an added complexity that goes beyond the classic CAD geometric data interchange. It is parametric modelling that represents the main challenge for interoperability, as information attributes and object behaviours have to be handled.

**FIGURE 3-3**

The increasing complexity of data for different types of exchange. Horizontal axis is the approximate number of object classes within the schema.



*Figure 21: Amount of data attributed to information interchanges [19]*



The need for interoperability is inherent to all tasks that involve team-working. Building projects gather specialized players, all with applications that support their needs. Their activities will mostly require project information for its processing and later sharing to contribute to the project. For instance, structural engineers may extract the structural design from a BIM model to analyse it with their own application and update the resulting changes of beam or column profiles to the model. This information may later be used by a quantity surveyor to extract its own schedules. In this basic workflow, interoperability plays a basic role allowing each player to import, process, and export project data without information loss and in an easy and potentially automated way.

These workflows can happen in various different ways. Data flow may bridge different BIM **tools, platforms** and **environments**. The most important and common workflows take place between platforms and their supported applications. As each application needs a specific set of information from a platform (ex. Structural analysis tools require relevant information of structural objects only), the data set is translated from the platform's internal data structure and exported to the selected tool. Usually, the processed data and results of an application have to be manually updated to the model due to the incapability of some BIM tools to translate their data to the platform's internal structure. In some cases, applications have the capability to automatically update their results to the original model. This is the case of Autodesk Revit and Autodesk Robot structural analysis, for example.

Workflows between **applications** are not so complex. Their selected information from a BIM model is usually very specific and relevant to both tools. Exporting quantity take-off data to a cost-estimating tool is a straightforward example.

More difficulties are encountered in **platform to platform** interoperability. Both design and fabrication platforms manage a vast spectrum of information. Nevertheless, the main challenge comes with parametric objects. Although their geometry and some information attributes are manageable, their behaviour does not always have translation from one BIM platform to another. As discussed previously, this is due to the different set of parametric rules available in each platform and the different interpretation by BIM software firms on how a certain object class should behave. This issue could be addressed by creating a common vocabulary of parametric rules for each platform.

Interoperability then can be engaged as a common language that all BIM software titles can speak. If so, all players in a project team will be able to effectively undertake and share their work. This common language can be understood as a **data organizational schema**; an exchange file format. Sharing a schema destined to interoperability relieves BIM software developers of translating their internal platform schema to those of other platforms. Instead, only two translators are apparently necessary when using a shared schema: one for exporting and another one for importing. The bases for translation and for the creation of common schema are the computer languages developed in close collaboration between the **policy** and **technology** fields.

Bodies from the **policy field** are the ones which define the diverse standards in the AEC industry practices. Traditional standards cover all fields and processes within the industry,

from component fabrication to graphic representation. BIM has seen an effort in its standardisation through the development of computer languages such as EXPRESS, BPMN or XML by research bodies from the **technology field** [19]. Even so, experts from the **process field** have also contributed in defining the set of information that will be shared through these languages. The information gathered in a set will depend on the workflow it will be used in, and will have a specific use, meaning and terminology. For example, a same information attribute can have different meanings depending on the tool used. A quantity take-off tool will understand the internal surface parameter of a wall as dimension to calculate the wall's volume, while an energy analysis tool will understand it as a boundary of a room.

### 2.4.3. Exchange formats and schema languages distinction

The way data is organised for its transference is denominated **exchange file format**. The computer language used to manage information transference and structure exchange file formats is known as **schema language**. Several exchange formats are particular for their use in specific applications; nevertheless many of them can be associated to a same schema language.

### 2.4.4. Ways to interoperability

As defined, interoperability can be achieved in two ways: Staying within a software vendor's products or using open exchange formats. Therefore, there are various ways of transferring data.

**Direct links** are those which allow a BIM platform or application to interchange the necessary information for a specific use. Based on a platform's Application Programming Interface (API), a segment of a BIM model is exported and imported to an end application through the receiver's API. These data interchange usually takes place within a software vendor's products, but can also take place between vendors that have reached a commercial agreement.

These agreements allow for higher interoperability features. A certain application can be embedded in a platform's interface and facilitate certain workflows. This would be the case of an agreement between an independent structural analysis application that is to be included in a BIM platform's interface. Nevertheless, a lot of care has to be taken defining the purpose of a direct link, as the information transferred will be very specific. This can lead to errors when users use the link with different expectations.

Else than direct links, general interfacing between a same software vendor's products is done through a **proprietary exchange format**. Usually, vendors that develop their own schemas keep its specification confidential. A good example of these formats is Autodesk's Data Exchange Format (DXF) [19].

On the other hand, **open exchange formats** are publicly available. Also known as public product data model exchange formats, they are based on schema languages such as EXPRESS, XML or text. IFC, CIS/2 and ISO 151296 are the most relevant open formats.

### 2.4.5. Open product data model exchange formats

The International Standards Organization (ISO) created the Standard for the Exchange of Product Model Data (STEP) in an urge to address upcoming interoperability issues related to object-oriented design. The ISO-STEP committee developed the EXPRESS language, which supported the modelling of products and their interchange in many industries.

In the AEC industry several product data models have been developed based on the ISO-STEP standard and supported through EXPRESS language. This is the case of the IFC created by the International Alliance for Interoperability (IAI).

#### Industry foundation classes (IFC)

The IAI has its origin back in late 1994 starting off as a consortium for assisting Autodesk in developing interoperability for its applications [56]. It was later redefined as an international industry-based non-profit organisation for the development of an open product data model that covered all of an AEC's project lifecycle. **Industry Foundation Classes (IFC)** would be the designed schema, based on ISO-STEP standards, but independent from the ISO management. The IAI was later re-named as buildingSMART, and now supports IFC world-wide through its various chapters.

The IFC are intended to give a general and extensible data representation of building information so it can be shared amongst required software titles. As it covers the entire lifecycle of a project and all its processes, it defines a vast range of object and project data in a general way. Its extensibility relies in the possibility of defining a data set with further detailed and selective information for its use and interchange in specific applications (or interchanges). A basic categorization of IFC contents would include **object definitions** (ex: doors, pipes, etc.), **property sets** (ex: for structural analysis, rendering, etc.) and **data types or resources**, which are a categorization of information attributes (ex: dimensions, textures, resistance, etc.).

The system architecture of the IFC schema used to define all its content can be very complex. Based on the latest IFC version's (IFC4) specification files [12], a brief overview of its schema has been included in *ANNEX D*.

### 2.4.6. Beyond data interchange

As information interchange is addressed and mastered, other achievements and goals appear down the interoperability road. Beyond data interchange (basic export and import), interoperability can be enhanced to improve workflows and refine their processes. The new focus of attention is now on the information requirements of clearly defined tasks to guarantee the interchange's success. To perform these tasks, predefined information sets such as '*room boundaries export for preliminary energy analysis*', for example, would be necessary. Each and every one of these information sets are known as **model views**.

Model views should be clearly defined to highlight what information is necessary for an effective interchange. Usually the players exporting and receiving information for a specific workflow are identified, and play an important role on determining the content of these predefined interchanges. If the content of a model view is known, exporters are aware of the information that has to be delivered and importers have solid expectations on what to receive. **Model View Definitions (MVD)** also eliminate possible errors due to data redundancy, remove intermediate steps in data interchange and open the door to automation of workflows.

Current efforts by various industry-based policy bodies in close collaboration with process players are on establishing standards for MVD. Once all workflows are covered with their respective model views, more important goals can be achieved. These include the **definition of model views for the handover** of a project's BIM model in important phase changes of its lifecycle. These could define the detail level of design models necessary for construction modelling, or the model information requirements for project commissioning. These specifications would have important contractual implications as well, indicating **milestone handovers** as the project is developed. These advanced efforts are actually being addressed on the Construction Operation Building information exchange (COBie). In the meantime, industry-based bodies such as BuildingSMART International, publish official model view definitions, exchange requirements and related specifications<sup>8</sup>. The standards for these MVD's are issued by North America's National BIM Standard (NBIMS), created by buildingSMART.

Apart from the specification of data handovers between construction teams and owners addressed by COBie, there are other efforts aimed towards enhanced interoperability. The International Framework for Dictionaries is working in the inclusion of the many IFC object names and attributes in different languages. By its side, the OmniClass is re-defining AEC industry-related classification systems so they fit properly with BIM practices. And last but not least are XML-based schemas. Alternative to the EXPRESS schemas, they are usually used between collaborating firms or implemented in web-based information sharing environments.

#### 2.4.7. Information management and server repositories

The technology developed to manage project information is known as **building model repository**. Inspired in traditional project data management systems, BIM model repositories are databases or server solutions that gather all of the project information for its coordination and management.

BIM model repositories have been explored in depth in *ANNEX D*. The basic functionality requirements for repositories have been summarised and metadata management capabilities of major BIM platforms have been exposed. Additionally, commercial BIM server solutions have been reviewed.

---

<sup>8</sup> The official website for publication of this specification, related model view definitions, exchange requirements, and supporting materials such as implementer agreements, example data sets, references to development tools, discussion forum and issue database, and certification programs is <http://www.buildingSMART-tech.org>

## 2.5. INTEGRATED PROJECT DELIVERY (IPD)

### 2.5.1. Introduction

The implementation of Building Information Modelling has deep impact on technological and process aspects of the AEC industry. As these changes affect the traditional ways of working and the tools and means used in project development, it is to expect that traditional **policy** arrangements require updating.

Traditional AEC project contracts gradually become obsolete as higher BIM engagement levels are achieved by project players. New concerns and legal issues arise with the use of BIM, and the need for new contractual arrangements becomes evident<sup>9</sup>.

The **BIM framework** sets out BIM implementation as a process with an ultimate goal: **Integrated Project Delivery** (IPD). IPD is an ideal working methodology based on close collaboration amongst all players involved in a project. Even so, Integrated Project Delivery carries heavy legal and contractual implications. It is the goal of policy bodies to define and standardize these requirements, but not without understanding the needs and concerns of process players. For the scope of this work, IPD will be defined not only as a project development method, but as a **contractual agreement** with all its parts.

A brief mention on the Construction Operations Building information exchange (COBie) standardised handovers will be made.

### 2.5.2. Integrated Project Delivery

The AEC industry has seen a decline in productivity since the 1960's [41] [21] due to stagnant industry practices and slow adoption of new technologies that derive in over-budget and behind-schedule project delivery [57]. In an attempt to address these fundamental inefficiencies, the American Institute of Architects (AIA) California Council provided the definition for what is known as Integrated Project Delivery (IPD). In May 2007 the AIA California Council Task Force published "Integrated Project Delivery: A Guide" [4], where IPD was defined, guidelines and recommendations for its development exposed and contractual agreements between project players established.

Integrated Project Delivery aims to generate the highest value for the owner through intense collaboration of all project players along the entire project's lifecycle. This is achieved by aligning the interests, practices and objectives of all parties involved and establishing proper contractual agreements so that they all work as a unified firm.

---

<sup>9</sup> These issues are seen in further detail in the '*BIM IMPLEMENTATION*' chapter.

The AIA defines IPD as follows:

*“Integrated Project Delivery (IPD) is a project delivery approach that integrates people, systems, business structures and practices into a process that collaboratively harnesses the talents and insights of all participants to optimize project results, increase value to the owner, reduce waste, and maximize efficiency through all phases of design, fabrication, and construction.*

*IPD principles can be applied to a variety of contractual arrangements and IPD teams can include members well beyond the basic triad of owner, architect, and contractor. In all cases, integrated projects are uniquely distinguished by highly effective collaboration among the owner, the prime designer, and the prime constructor, commencing at early design and continuing through to project handover.” [4] [2]*

Usually, IPD contracts gather all project stakeholders: **Major designers:** architect, structural and system engineers; **contractors:** major contractor and subcontractors; and the **owner**, or a consultant representing the owner. These players collaborate closely from early design stages to project handover, and even to operation initial stages. High engagement levels and experience in BIM use are required for players involved in IPD endeavours, as they will have to use BIM technology resources for barely all processes related to the project. It is in their hands to deliver projects faster and at lower costs.

The implication of the owner in the project development is crucial for the team to meet its expectations and keep the project within scope. If involved in early design stages, the owner can clearly communicate and defend his design intent, the desired functionalities and his expectations. Usually, poor communication leads to misunderstandings and out-of-scope deliveries. *Figure 22* illustrates this concept.

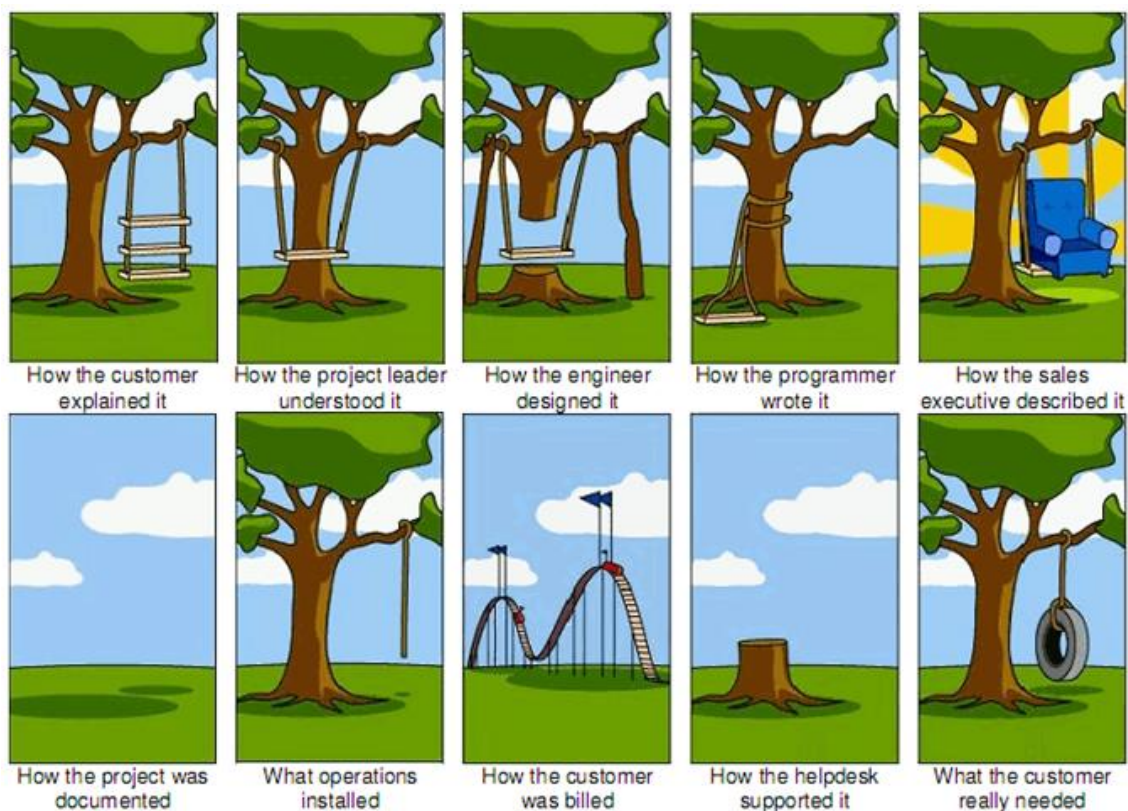


Figure 22: Cartoon of poor communication in project development [37]



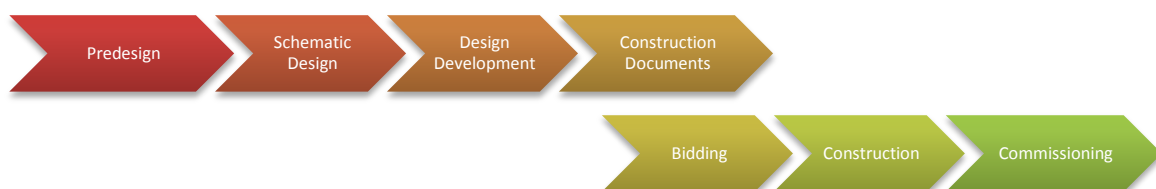
BIM is very useful at initial project stages, as it allows the exploration of major design alternatives for this purpose. The disposal of a virtual building representation is a solid base for taking **better informed decisions** in a point of the project's lifecycle where changes can be easily made without major cost implications.

Once the conceptualization of a project is achieved, design can move on to the various disciplines involved. As seen further in the '*BIM IMPLEMENTATION*' chapter, BIM technology allows collaboration of interdisciplinary designers on a master model of the project. By contrasting the disciplinary models linked to a master file, conflicts can be resolved to the benefit of the design intent. The implication of contractors in the design stage is also crucial, as constructability issues can be identified and solutions based on the contractor's experience can be implemented in the BIM model to the benefit of the project's time and cost. Once the construction phase is taking place, system engineers, contractors and subcontractors can collaborate with the owner or operator for the effective handover and understanding of as-built information issued for commissioning.

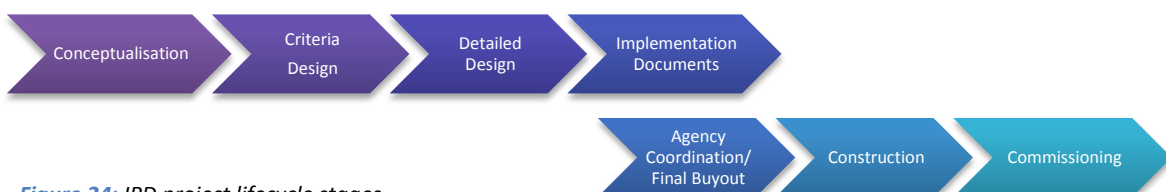
As exposed, IPD seeks the *"harnessing of talents and insights of all participants to optimize project results, increase value to the owner, reduce waste, and maximize efficiency through all phases of design, fabrication, and construction"* [57]. This reduction of resource waste and productivity increase is better known as **lean construction practices** in the AEC industry [58] [29].

### 2.5.3. Redefined project lifecycle phases

As IPD is implemented, the way players work and interact with each other change, and workflows that traditionally took place in a single lifecycle phase progressively migrate to other phases. Therefore, a renewed definition of project lifecycle phases becomes necessary. In the AIA's guide to IPD, all stages of the IPD methodology are explained. The main changes affect the design phase as traditionally understood, incorporating the collaboration of contractors. *Figure 23* and *Figure 24* compile both traditional and re-defined stages respectively.



*Figure 23: Traditional project lifecycle stages*



*Figure 24: IPD project lifecycle stages*

Redefined phases are briefly described below:

- **Conceptualisation (expanded programming):** This design stage addresses WHAT is to be built, WHO will build it and HOW it will be built.
- **Criteria design (expanded schematic design):** During this design stage, the project is preliminarily designed through exploration of major design alternatives.
- **Detailed Design (expanded design development):** At the beginning of this design stage functional requirements and features of WHAT is to be built are already determined. During this stage all important design decisions are taken. Detail level of models and documentation are issued for construction.
- **Implementation Documents (construction documents):** In this stage, effort focuses in HOW the project will be built. The aim is not to develop or change detailed design, but to complete it for constructive implementation. Fabrication level models and documentation for constructive procurement are generated. As Detailed Design information is consistent with constructability, the Implementation Documents stage requires far less effort than the traditional Construction Documents stage.
- **Agency Coordination:** In this part of the stage policy bodies, or agencies, review the model's information for compliance of building codes and regulatory criteria. Analysis software can be used to check a BIM project model's performance and code compliance.
- **Final Buyout:** Detailed definition of project design allows early buyout of certain packages offered by contractors and subcontractors, concluding in this stage. Procurement commitment can start earlier, especially with the use of precast components in design. Since more work has been contracted for, this stage is shorter than traditional buyout stages.
- **Construction:** In this lifecycle phase the project is built. Mostly construction, quality control and monitoring tasks take place. Compared to traditional construction phase, design does no longer take place on-the-go unless unexpected events occur. All of the effort put on the design phase makes construction more effective.
- **Commissioning:** In this phase, project's BIM model containing all of the as-built conditions and relevant information are handed to the owner. As the owner has been involved in the project development and has considerable BIM knowledge, handover information is understood faster. Contractual and legal issues such as warrant obligations are addressed as well.



### 2.5.4. The Mc Leamy curve

As mentioned previously, workflows migrate across project phases with IPD. The design process gathers all relevant players in early stages. *Figure 25* Shows the Mc Leamy curve, which illustrates the design effort during the stages of the IPD method (curve 4) compared to traditional approaches (curve 3). As design reaches more mature stages, flexibility to accommodate changes is reduced. Therefore, design becomes gradually stiff and modifications require greater resources and effort. Both curves 1 and 2 respond to this concept.

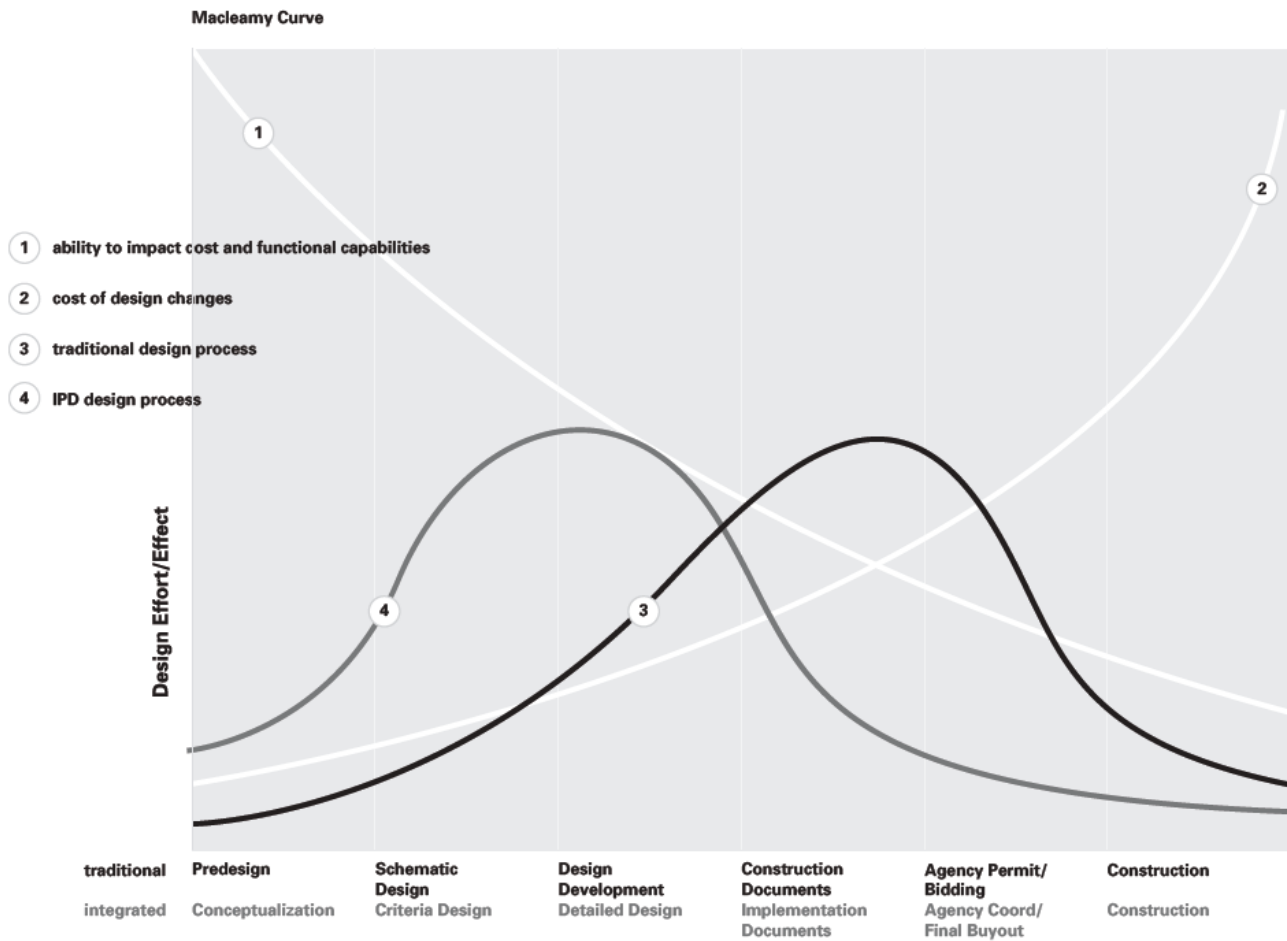


Figure 25: The Mc Leamy curve [4]

### 2.5.5. Contractual implications of Integrated Project Delivery

As exposed, IPD needs the technology supporting interoperability<sup>10</sup> for collaboration, and the experience on BIM use from project stakeholders. Nevertheless, in order for IPD to take place, contractual arrangements are necessary. In the AIA's guide to IPD, Multi Party Agreements<sup>11</sup> (MPA) are defined.

<sup>10</sup> For further information refer to the 'Interoperability' section.

<sup>11</sup> Most common Multi Party Agreements have been briefly reviewed in ANNEX D.

MPAs are a single contract specifying the roles, liabilities, obligations and rights of all players. These contracts require the will of all players to collaborate as a team and are based on trust, as benefits depend on the overall success of the project and individual achievements are tied to the other players' performances. In the development of a project approached through IPD, liability, information ownership and many other concerns arise. As every project is unique, agreements have to be tailored to each and every one. Before a project is commenced, considerable effort has to be put on MPA planning, negotiation between parts and team designation.

The implication of MPAs is seen in further detail in the AIA's Guide to IPD [4]. Despite existing diversity, most MPAs share some common attributes: Agreements are unified in a single contract; Temporary organizations are created; Decisions are consensually made to the project's benefit; Earnings are partially based on overall project success; Teams are assigned based on the best capabilities of players.

Through experienced project stakeholders, IPD can be implemented as a contractual bond to its associated methodology and legal and litigation disputes can be clearly reduced [19]. This plays in favour to all parts involved and reduces additional costs and delay overruns of project scope.

#### 2.5.6. Construction Operation Building information exchange (COBie)

The Construction Operation Building information exchange (COBie) was developed by the U.S. Army Corps of Engineers in 2007 as a format to address the information handover between the project team and the owner [52]. It is the scope of COBie to provide easy **real-time interchange** of information, provide a framework for its **storage and later reuse** and allow its direct **implementation in owner's management systems** [19]. It also establishes a standard for the collection of information during design and construction to form a set of deliverables issued for commissioning. Various deliverables have to be handed in each of the following project phases:

- 'Architectural Programming Phase'
- 'Architectural Design Phase'
- 'Coordinated Design Phase'
- 'Construction Documents Phase'
- 'Construction Mobilization Phase'
- 'Construction 60 Percent Complete Phase'
- 'Beneficial Occupancy Phase'
- 'Fiscal Completion'
- 'Corrective Maintenance'

As COBie standards are gradually implemented in AEC projects, owners may start to require these sets of deliverables in contractual agreements to their own benefit.

## CHAPTER 3 - BIM IMPLEMENTATION

### 3.1. INTRODUCTION

This chapter offers a view on the main changes BIM adoption presents to the current AEC industry. A brief review of current industry practices is given in order to fix a starting point scenario where BIM adoption transformations can be contrasted against. BIM solutions and new industry practices that it enables will be treated through the advantages and drawbacks found in its implementation.

Based on the **BIM framework** provided previously, the main changes, advantages and drawbacks in the industry's practices attributed to the use of BIM can be identified in an organised way. These changes are usually applied to **workflows** (or push – pull interaction between fields) and **deliverables** between AEC industry players. When describing these workflows and deliverables, they will be associated to the **players** (and their respective fields) that they involve, the **project lifecycle phase** that they cover and, when necessary, the **BIM Implementation level** required for them to take place.

### 3.2. CURRENT STATE OF THE AEC INDUSTRY

#### 3.2.1. Current practices

Current industry practices would fit in the description of the **pre-BIM** implementation stage that has been given in the **BIM framework**. According to the description, current facility delivery processes are discontinuous and fragmented. Project contracts encourage risk avoidance between players and therefore few collaborative processes. Asynchronous and disjointed communication between players is document based and drawings are in general 2-Dimensional.

The main difference with BIM practices lies in document-based communication. Documents often contain errors and omissions which can lead to delays, unexpected field costs and, in some cases, lawsuits between project stakeholders. Major inconveniences of 2D drawing communication are found in the design stage, where it usually takes a lot of time and financial expense to obtain field-specific assessment of the proposed design. This need of information in the design stage includes structural analyses, quantity estimates, energetic evaluation of design and so forth. Ideally, with all the requested information at hand, the design process should be iterative. Unfortunately, these assessments are done last in the design phase, leaving no time for re-design and generating a need for later corrections that undermine certain initial project objectives.

Contract methods are numerous, and are chosen to better fit each situation. Amongst dominant methods are **Design-Bid-Build**, **Design-Build** and **Project Management at Risk**:

- **Design-Bid-Build (DBB):**

Most popular amongst public projects, in DBB contracts the owner hires a designer by choice. Project requirements and design objectives are defined, and a final set of drawings and specifications are produced with enough detail to tender construction. Designers often do not reach high detail levels to avoid liability issues in construction. This often results in dispute with contractors when errors and omissions provoke unexpected construction costs. Once the project is tendered for construction, constructors perform cost estimates from the quantity surveys realised by subcontractors and themselves. The cost of bidding for contractors can reach up to 10% of a project's cost, accounting for overheads [19]. Once the contractor is awarded the project, additional work is done to arrange drawings for construction phasing and sequencing. Detailed shop drawings of construction units are requested to subcontractors to be included in the contractor's general arrangement drawings. The need for accuracy of these drawings is essential to avoid substantial costs derived from errors or inconsistencies. In general, the uncertainty in design does not allow off-site fabrication of units, as building conditions and details are unknown until its designed time for construction. This is unfortunate, as off-site production allows lower fabrication costs and better quality control.

The need for design changes during the construction phase is reasonably common and can be caused for many reasons. To manage these changes it is necessary to determine their cause, assign responsibilities and estimate time and cost implications. Requests for information are made to the designer, who often amends changes in design. These changes usually carry legal disputes, costs and delays. Unfortunately, it is a common practice for constructors to bid low-cost to win the contract and later request modification of the project's design to increase their profits.

Once the project construction is over, the facility is commissioned and the operational phase begins. Contractors hand the as built set of drawings and operational manuals to the owner. The owner's facility management and operation team has to develop a tedious, time and cost consuming process to assimilate and adapt the 2D drawing documentation for their functions.

Overall, the DBB contract methodology is not cost-efficient and often surpasses initial budget and program.

- **Design-Build (DB):**

This contract awards project design and construction all-together. At an initial stage the owner works alongside the DB contractor to set a defined project program and design objectives. Then, the DB contractor estimates cost and time needed to design and deliver the project and is open to changes requested by the owner before it is

approved. This ability to incorporate early changes in design is less resource-consuming. Once the construction phase begins, design changes, errors and omissions are DB contractor's responsibility. As construction can begin before all design drawings are completely detailed (apart from necessary initial drawings), design and construction phases slightly overlap, resulting in a project delivery time reduction. Therefore, DB contracts reduce overall time, cost and legal issues. The only drawback is the owner's few control over the project once construction has begun.

- **Construction Management at Risk (CMaR):**

In this contract method, the owner hires a designer and a contractor to offer their design and project management services respectively during the whole project duration. The owner is responsible of a start-off design, from which the contractor has to set and guarantee a maximum price for project delivery. Value of this method is found in the early involvement of the contractor in the design process and the reduced legal implications of the owner for cost overrun.

Taking a look back to the **BIM framework** previously exposed, these contracts present several limitations with regard to the BIM implementation stages. If BIM was applied to DBB contracts, only **BIM stage 1** could be achieved. On the other hand, in DB and CMaR contracts where collaboration between designers and contractors takes place, **BIM stage 2** could be reached. In the latter contract methodologies, **BIM stage 3** could be achieved depending on the owner's engagement degree and depending on the amendment of contractual issues.

### 3.2.2. Inefficiencies of current AEC Industry practices

A study developed by the Stanford University Centre for Integrated Facility Engineering (CIFE) revealed that productivity of the AEC industry in the U.S. has remained stagnant compared to other industries over the past fifty years [41]. Although a precise explanation of these trends is difficult to determine, there are several major impediments to productivity increase that could be extrapolated to the world-wide AEC practices.

The AEC Industry is characterised by its reluctance to change. Slow and fragmented adoption of new industry practices and technology retains designers and constructors from efficiency upgrade updates. Fragmentation occurs when only large firms are able to afford new industry practices, compared to smaller firms which face bigger adoption efforts and challenges.

Current upcoming contracts like joint-ventures usually bring several firms together on a project, but for a limited duration. This short-term relation does not allow experienced collaborative practices for productivity increase. Instead, it encourages protective procedures to avoid legal disputes, which compromise performance.

Field construction still does not fully benefit from upgrades technology can offer. The use of affordable construction worker labour has not pushed constructors to improve the efficiency

of field practices to reduce their use. Still, there is an emerging trend towards off-site production, or prefabrication, which can improve performance in the field if executed well.

Apart from new construction tasks, the industry is also composed of maintenance and operation contracts. The latter are more labour-intensive and are still productivity-scarce if managed through traditional approaches.

A last but not least impediment of importance is the lack of interoperability between project stakeholder's systems when exchanging and managing information. A study by the National Institute of Standards and Statistics [22] revealed the major costs of interoperability. Although it compares current interoperability issues to a fictional and utopic fluid and interoperable workflow scenario, the results of the report are worth considering.

### 3.3. BIM IMPLEMENTATION ADVANTAGES

#### 3.3.1. Introduction

Changes in the AEC Industry practices often come as new processes that fulfil major deficiencies of traditional approaches. As BIM implementation takes place, new practices are adopted and obsolete workflows and means are slowly left behind. As in all transformations, challenges and achievements are encountered in different stages. When presenting the following advantages and drawbacks, the 'process' nature of BIM implementation has to be considered. Therefore, some of them may take place straight away, as others may be encountered further down the road when higher BIM engagement levels are achieved.

Building Information Modelling has been a trending term, and there is a vast amount of information on the advantages it may represent. When it comes to analysing the potential of BIM it is crucial to remain objective and take prudent distance from the information delivered by BIM software vendors. In general, BIM software vendors claim that its use improves building professionals' capabilities to deliver projects in time, in budget and quality-compliant: *"The application of building information modelling solutions results in higher quality work, greater speed and productivity, and lower costs for building industry professionals in the design, construction, and operation of buildings."* [7].

Although in general terms these benefits are also being reported by independent industry surveys, such as McGraw Hill's Smart market reports [30] [31] and the UK's NBS National BIM Reports [34], it is very important to consider that certain challenges in BIM implementation have to be addressed before seeing many of these benefits. This is well described in The BIM Handbook, by Eastman et. al.: *"...When adopted well, BIM facilitates a more integrated design and construction process that results in better quality buildings at lower cost and reduced project duration."* [19]

As the AEC industry gains experience with the use of BIM, more reliable information on BIM implementation will be available to form a clearer image on the benefits it represents.

### 3.3.2. Advantages for the project

The major known advantages of BIM use are higher quality projects, delivered faster and with reduced cost. But there is much more to acknowledge in order to understanding where these benefits come from.

Consistent with the **BIM Framework**, the following advantages encountered in BIM implementation are presented throughout the **project's lifecycle phases** and affect players predominantly from the process field. These are the ones which are more closely related to the AEC Industry.

#### Advantages in pre-construction

These advantages benefit the **owner** predominantly.

- **Feasibility of project's scope**

All projects are defined by their time, cost and quality scope. When an owner has a defined project in mind, it is crucial to know if it can be built within a desired budget and program. Traditionally, a time-consuming preliminary design has to be carried out to answer this question, sometimes revealing the unfeasibility of the conceptual project. Using BIM, a preliminary model can be easily developed and connected to a cost database to contrast its feasibility. This results in a solid assistance tool for the **owner** when conceptualizing its project.

- **Increased building performance and quality**

Generating preliminary models of the project allow for their testing against performance and sustainability parameters. Solid analysis and simulation tools enable an early evaluation of various design alternatives. This way, projects start off with higher quality design intents, avoiding expensive and time-consuming unexpected changes in later design stages.

- **Increased compliance of project's scope**

When **Integrated Project Delivery** takes place, the design intent is best transmitted to the whole collaboration team and its requirements are better understood from initial design stages. Through the use of BIM, a better understanding and tracking of construction programming and cost can be achieved. This way, the **owner** can count on a reliable project scope.

#### Advantages in design

- **Earlier and consistent visualizations of design**

Design starts off directly on a 3D model. Although the design can be carried out in 2D views of the model, these changes are propagated to the model and all its representations. This mechanism provides accurate and consistent 3D visualization of

the model in any stage of the design phase. 3D model views also permit to verify the consistency with the design intent and improve communication between project stakeholders.

- **Automatic parametric corrections in design**

When working with objects that have parametric rules associated, changes to the model are easier to manage. Parametric rules ensure no alignment, geometric and spatial coordination errors. They automatically correct the object's attributes so parametric restrictions are complied.

- **Consistent generation of 2D drawings at any stage of design**

As drawings are extracted from the same model, consistency is ensured. Time and effort are saved in generating these drawings automatically at any stage of the design phase. If changes were made to the model, generated new drawings would be updated automatically.

- **Earlier collaboration in the design phase**

BIM technology allows simultaneous work of multidisciplinary design players on the same model. By sharing a set of models that are linked to a master model, design players can collaborate effectively. Designers work on a same master model and can modify the elements relevant to their discipline. Work-sharing tools allow the managing of privileges over the model based on the user's identification, and facilitate in great measure change management and control. Collaboration in design reduces errors and time expense. It also improves the project design, as design conflicts between disciplines can be identified earlier. Usually such inconveniences are encountered when main design decisions are made, forcing the appliance of value engineering to overcome them.

- **Generation of cost estimates in the design phase**

BIM can generate quantity take-offs, space and materials recount and therefore cost estimates when linked to a cost data-base at any stage of design. At initial stages, rough cost estimates can be delivered by introducing formulas that involve basic project quantities. For instance, cost can be assigned to a square meter of area destined for residential use, or to square meter of facade. As design grows in detail, more accurate cost estimates can be delivered. The ability to easily generate these estimates in the design phase allows all stakeholders to be aware of the design's cost implications in order to take better informed decisions on whether to proceed into a further detailed design or not. This helps the project to stay within scope. As the model approaches the end of its design phase, an accurate final cost estimate can be generated for construction. If **contractors** take part on the design team, they can bring in their knowledge and experience to both elaborate detailed cost data-bases and verify model constructability to avoid unexpected costs. As mentioned before, **BIM**



**Stage 2** of implementation must be achieved for the contractor to participate in design stages. In under-engaged stages, such as **BIM Stage 1**, contractors may also develop their own authoring models for construction from the design documentation and elaborate solid cost estimates for construction bids.

- **Simulation of building performance and behaviour**

BIM models can be analysed and tested in performance to better understand their behaviour. Better informed design decisions can be made through analysis of alternatives. Some simulation tools like energetic analyses and flow simulation for piping systems are available in the same BIM platform. Other simulations such as structural analysis may not be available to run on the same platform, but analytical structural BIM models can be exported to specific structural software, and later be reimported to visualize the analysis results.

- **Green design**

BIM models can be linked to energy analysis tools and simulate their energy consumption and sustainable performance. Traditionally these analyses are time consuming, as all the necessary information has to be put together from 2D drawings. Therefore, simulations for energetic analyses are made at the end of the design phase, a mere check for regulation requirements that leaves no room for valuable corrections. Fortunately, with BIM these analyses can be made at any point in design, allowing the evaluation of various alternatives.

#### Advantages in construction and fabrication

These advantages benefit both the **contractor** and **sub-contractors** predominantly.

- **Use of the design for model-driven fabrication**

When the design model is used for construction, it can be further edited by BIM software fabrication tools to achieve the grade of detail necessary for construction and fabrication. As components are modelled in 3D, building models can be passed forward to manufacturers, so that building components such as steel framing can be produced through numeric control machinery. Anyhow, the main benefit of detailed models is that they facilitate off-site fabrication of building components, which traditionally is considered to be cost and time effective. The accuracy of BIM also allows larger and more complex components to be built off-site, as it reduces the risk of changes on-site and dimensional errors of adjacent building components. The ability to evaluate installation procedures of off-site built components in the building model facilitates the use of smaller installation crews, faster installation and less on-site storage space. This efficiency responds to what is known as lean construction.

- **Improved change management**

Changes made in design will be automatically propagated throughout a BIM model. Objects affected by these changes will update accordingly to their parametric attributes. Interferences with other associated models, such as those from other disciplines, may be checked with clash detection tools. Compared to 2D-based documentation, BIM is extremely time-effective as it automatically updates changes made to the model in all its views and deliverables, leaving no room for errors or inconsistency.

- **Constructability evaluation before construction**

Unexpected delays and costs in the construction phase are often caused by errors and omissions in 2D design drawings. With the use of BIM no inconsistent 2D drawings are found, as they are generated from a same 3D model. By bringing multidisciplinary models together for automatic clash detection between them, and for visual evaluation, coordination errors can be easily tackled before construction. For this to happen, designers of various disciplines have to collaborate closely with main contractors in order to issue constructability problems in the design phase. Therefore, at least **BIM stage 2** has to be achieved. These practices result in early detection of design errors and omissions, faster construction process, less delays, lower costs and minimised probability of legal disputes between project stakeholders.

- **Incorporation of construction planning in design**

The BIM model can be linked to a construction plan, becoming what is known as a '4D BIM model'. Objects can be assigned a certain time of placement in the construction phase, and the model can be visualized accordingly at any point in time. This unlocks the ability to analyse the planning of on-site activities, as the model reflects what the site would look like. Furthermore, temporary elements such as scaffolding and machinery can be added to the model for planning purposes. Most important, the need for safety measures can be detected and implemented into the model when planning construction tasks on a day-to-day basis. Quantity take-offs and other deliverables associated to the program can also be generated, and construction progress can be monitored for comparison to the initial program.

- **Better implementation of lean construction techniques**

Lean construction techniques are based on a close collaboration between contractor and subcontractors, so that when field tasks have to be carried out, all necessary components, staff and machinery are on-site. As a BIM model offers an accurate description of the design and the materials needed for each building component, contractors and subcontractors can better organise and plan both fabrication and field tasks, so the crew, machinery and materials are available when required. This reduces the need of on-site storage areas and promotes more off-site fabrication, all of this

resulting in lower costs and better field task coordination. BIM platforms also offer tools for field task management that can be run on portable devices. They allow material tracking, check for installation progress and quality control and automatic positioning of components for geometric surveillance.

- **Incorporation of procurement in the BIM model**

As previously indicated, a BIM model issued for construction provides accurate detail and material quantities of building components. This information can be used to carry out procurement, as specification, quantity and component properties are available in the model. But procurement can be taken to a next level by incorporating object representations of manufacturer's products. These objects can be found in online catalogues, such as Autodesk Seek [6] or the UK's National BIM Library [33] for instance. Designers and contractors are able to download these objects and explore their attributes and behaviour by inserting them in their BIM model. This new way of procurement has vast potential, but specification and regulatory issues have to be overcome for it to become a reality.

#### Advantages in operation and management

- **Project information handover and commissioning**

When commissioning a project, a large amount of time and effort is put by the operations and management team to pick up on the vast amount of information handed over by the contractor's team. This process is often asynchronous in time and represents a considerable expense to the owner. During the construction phase of a project, the contractor and the mechanical, electrical and plumbing (MEP) technicians gather information on facility maintenance and systems operations that can be incorporated in the BIM model. This represents a huge benefit to the operator/owner, not only because this information can be easily exported to their facility management systems, but also because they can count on an intuitive and reliable as-built model of their facilities. In addition, the model can be used to test that all systems works before accepting the project hand-over. Time and cost saving benefits shift when Integrated Project Delivery takes place, and thus the operator/owner is already familiar with the project's model and its behaviour before the project is delivered.

- **Better management and operation of facilities**

The BIM model of a project is an accurate source of information to plan and carry out management and operation tasks. The model can be used to check that all systems work correctly through MEP simulation tools. Maintenance and reparation tasks can be carefully planned by visualizing the model and by generating reliable cost estimates. The building model can be a very useful tool to keep record of these maintenance operations and estimating future interventions.

- **Facility and operation management through BIM models**

As hand-over BIM models are a reliable representation of as-built conditions, they become a natural interface for management and operation systems integration. Systems could be monitored through sensors linked to the model and could even be remotely operated. Although this has not yet been developed, it remains a feasible field for development.

### 3.3.3. Advantages for BIM user firms

The advantages mentioned above are those which directly or indirectly benefit the project, either providing better quality, reduced cost or faster delivery. But it is also interesting to briefly mention those benefits to BIM user firms in the AEC industry. The use of BIM has helped industry firms to market new businesses to clients, either because it was a requirement or simply because of persuasive BIM features such as 3D visualization. Users also have reported productivity benefits like higher Return on Investment (ROI) among highly engaged users and most of them have found fewer errors in their procedures. In the *'Implementation in the AEC industry'* section, benefits to BIM user firms have been explored in further detail.

## 3.4. BIM IMPLEMENTATION CHALLENGES

### 3.4.1. Introduction

The AEC industry has long been characterised by its reluctance to change. Nevertheless, as in all transformations, the adoption of new processes and methodologies bring benefits that compensate for the effort of going through these changes. The use and implementation of BIM represents the need of transforming barely the whole of traditional approaches and thought processes related to the AEC industry.

It may be the impression of many industry players that BIM can co-exist with traditional practices, without the need of making major changes in their way of proceeding. In fact, this can be carried out and has been described as intermediate BIM implementation stages. But ultimately, this school of thought would imply undermining all of BIM's potential and forgetting its 'process' nature.

When describing major changes, drawbacks and challenges expected in BIM adoption, it has to be acknowledged that they may appear in different stages of the BIM implementation process and that they may affect certain processes, workflows or players. In fact, a proper use of BIM carries along several major changes. Amongst them are renewed relationships between players or project stakeholders, which eventually will derive in new contractual agreements. Early collaboration between interdisciplinary designers and contractors will allow taking full advantage of their field-specific knowledge in the design phase, where it has more value.

Eventually, all of the effort put in a correct use of BIM will lead to Integrated Project Delivery and all its benefits.

### 3.4.2. Efforts towards interoperability and collaboration

In practical terms, collaboration in a BIM environment translates to model information sharing. How this information is shared amongst project team members is an important matter. Initial implementation stages carry along several drawbacks that can be overcome with collaborative workflows. Still, as collaboration grows interoperability is required to support the way information is interchanged.

In early implementation stages like **BIM Stage 1** for instance, only one member develops an authoring model. If the architect develops its own model, at the end of design it may not have enough building component detail to use it for construction or fabrication. Although the contractor may implement program and cost attributes, the lack of accurate material and component building definitions does not unlock all the advantages associated with BIM use in construction. On the other side, if the architect works with 2D drawings and paper-based information, the contractor can develop its own model for construction planning, cost estimating and procurement. Unfortunately, the process of model generation from 2D drawings is prone to errors and omissions.

Further implementation stages involve the sharing of information and model interchange. As issued in the '*Interoperability*' section, when collaborating project team members use different BIM software platforms, interoperability management tools are needed. The management of information interchange can add cost, complexity and delays to the project. Usually model format management software licences have to be purchased and a BIM manager has to be named. Hardware support for model sharing has to be set up for model servers that establish communication between BIM platforms through IFC Standards. Apart from added complexity, the use of IFC standards for interoperability may cause information loss and reduced collaboration capabilities. Derived errors and omissions from information loss can cause delays and therefore indirect costs to the project.

### 3.4.3. Contractual arrays for integrated BIM use

Traditional contract terms are tailored to paper-based practices. Therefore, BIM implementation calls for new contractual arrays. As BIM users gain experience in collaboration processes, surveys indicate that important legal concerns arise amongst them [30] [31]. These issues include **legal ownership** of design models and documentation, **liability over design** and **insurance arrays**.

When the designer and the contractor collaborate in the design phase, constructability decisions are made. At the end of design, the model can be used for construction, but if any design errors or omissions arise during construction which player shall be made liable for them? In traditional contracts the designer should be made responsible, and therefore many designers see no point in spending additional time and effort in collaborating with contractors.

Even if liability issues should be covered, new insurance conditions would have to be arranged for each project player regarding these liability changes. For instance, if contractors are made liable for their contribution in design, insurance policies should cover this new array.

Furthermore, as collaboration in the design phase brings together multidisciplinary players, ownership of every part of a project's master model has to be defined for each designer. At the time, collaboration management tools in BIM platforms have temporarily solved these issues by managing privileges over the project's master model, but without legal consequences. Intellectual property of models is also a conflictive topic, especially amongst architects.

All these concerns have to be treated and overcome by creating new contractual terms specially designed for the use of BIM in construction projects. Bodies from the **Policy Field** are the ones in charge of setting the basis for these contract arrangements, but need the experience and opinions of players from the **Process Field** to aboard them. To set an example, these bodies are represented by the American Institute of Architects and the Associated General Contractors in North America, and by the buildingSMART chapters all over the world.

#### 3.4.4. Adaptation to new practices

Perhaps the most challenging achievement for AEC industry firms is for their project teams to **change its mentality and traditional way of working**. With BIM, the use given to information changes, based predominantly on collaboration. In order to ultimately achieve IPD, project teams will have to adapt to working heavily on a same model during design and on various model sets during construction and fabrication. This of course, requires qualified personnel training on BIM use, but most important, it requires experience in several projects for adaptation.

#### 3.4.5. Investment for implementation

Implementing BIM requires considerable initial investment in software licences, hardware upgrade and personnel training. Although this investment is necessary, much more has to be done to implement BIM as a process. Correct BIM implementation can be very complex, as it will affect almost every aspect of a firm's processes. In this line, it is recommended to develop and monitor **adoption plans** with the assistance of experienced BIM consultants. Although every type of firm has specific needs and ways of working, there are general guidelines to carry out this process. These guidelines recommend developing implementation plans with their own scope, starting by using BIM in small projects with traditional approaches, and later move on to bigger projects in order to explore collaborative practices with outsider firms [19]. It is generally recommended to monitor and keep track of the adoption process and the benefits it brings. As an example, in the UK's BIM Task Group website [9], in the NBIMS website [32] and in Bilal Succar's paper *BIM Maturity Matrix* [40], an organised classification of achievements is offered to contrast a firm's level of BIM implementation.

In order to evaluate BIM implementation costs, the author has developed a Return on Investment analysis (ROI), which has been included in *ANNEX E*.

## CHAPTER 4 - BIM PRACTICAL EXAMPLE

### 4.1. DEVELOPMENT OF A BUILDING PROJECT WITH BIM

#### 4.1.1. Introduction

Building Information Modelling is surrounded by a thick entourage of both theoretical and technical concepts. Once this knowledge basis has been put into background, it is time to bring it somehow to practice. In order to do so, the author has developed and reviewed a series of BIM models destined to represent the **development of a project within the process of Building Information Modelling.**

The practical example developed in this work aims to simulate a feasible real-life scenario where an edification project design is developed within Building Information Modelling processes and workflows. In accordance with this objective, an initial description of the building's functional requirements and features will be offered, as if it was delivered by owner stakeholder parties. Based on this initial description, the work of several disciplinary designers will be thoroughly explored in the development of various BIM models. With the assistance of these disciplinary models, each design player's point of view can be easily represented in terms of their competence over project design, interaction with other project players and deliverables expected as outcome of their work.

The capabilities offered by the use of BIM technology have been revised and explained through the practical realisation of comprehensive examples. As the functionalities of BIM technology are oriented to a wide range of AEC project players, specific tools have been described for each disciplinary model.

Furthermore, as the realisation of the building's design takes place, interaction between project players will be simulated in order to exemplify how Building Information Modelling enables new processes and workflows with respect to traditional AEC industry practices.

In summary, the author has decided to develop a practical example in response to the following purposes:

- Put into practice some of the most important concepts regarding BIM use.
- Familiarise with the use of BIM software platforms in order to learn and explore their capabilities.
- Develop a basic, but technically consistent, model of a building project.

The practical realisation of these examples is not to be taken lightly. Considerable amount of time and effort have been put in learning and familiarising with the use of BIM software and their conceptual fundamentals. The author has completed several tutorials from diverse

sources and developed complex examples which have not been included in this work in order to master BIM software use so that all relevant BIM capabilities exposed herein can be accurately described. It is important to highlight that the author has intended to go beyond the particularities of BIM software use. The main focus of attention has been put on offering a holistic vision of how the enabled new processes and workflows would possibly fit a real-life edification project. Therefore, the following content is not a mere Revit tutorial, but an exploration of Building Information Modelling as a process.

#### 4.1.2. Tools and methodology

The practical examples developed in this work have been generated in the 'Autodesk Revit 2014' BIM platform. This software title has been chosen by the author for the following reasons:

- Availability of student licences.
- Availability of intermediate to advanced tutorials.
- Existence of a direct link with 'Autodesk Robot Structural Analysis' structural analysis software.
- Wide downloadable content suitable for Revit in on-line BIM object libraries.
- Integrated multi-disciplinary coverage and tools in the same platform.
- Wide range of tools common to most BIM platforms.

Note that it is not the author's intention to promote or publicise any particular BIM software platform title in any way. As far as possible, the author has developed practical examples using tools which are common to most BIM software titles, and stating where necessary if a particular tool is exclusive of Autodesk Revit. Therefore, in the development of this work generality has been kept for most part of exposed BIM technology capabilities.

#### 4.1.3. Building description

All of AEC industry projects are developed in an attempt to cover the necessities of owner stakeholder parties. Project definition at initial phases of the project lifecycle is essential to carry out designs that comply with desired cost, program, quality and functional requirements. The owner parties involved in the project have developed a preliminary functional plan for the building to be constructed. The requirements and preliminary data to be considered are as follows:

##### Location

The project will be located in the surroundings of Barcelona, Spain. Note that for the purpose of this work no specific location has been defined in order to keep examples as general and comprehensive as possible. Barcelona will only be used as an approximate location for the



design of building's closing elements with regard to the use of weather and height environmental conditions.

#### Site

The project will be allocated within a 1760 m<sup>2</sup> building plot. An area of 270 m<sup>2</sup> pertaining to the owner's property is available and qualified for edification according to urbanism regulations.

#### Basic functionality

The designed building must serve both as an office facility and as a storage space. This combined functionality may correspond to various purposes. For instance, the building may be a logistics intermediate asset within a distribution chain, where products are temporarily stored and their delivery managed and controlled in the same office facilities. The building could also correspond to an infrastructure's maintenance operation centre as well, with offices to coordinate and manage maintenance efforts and available storage space for necessary equipment. As several realistic uses can be found to justify the project's requirements no specific purpose will be determined from now on in order to keep the work's generality.

#### Building geometry and structural typology

Building's plan geometry must be based on straight perpendicular lines and enclosed by four main facades. The building must have a unique story with no particular height limitations. No perimeter bounding limitations are found in terms of foundation design.

Building must have a two door main access to the office facilities and two main accesses to the storage area. Windows must represent at least 15% of total façade surface.

The building's roof is to be flat and must be supported by structural steelwork. A suspended floor with precast concrete elements will be designed.

#### Building space distribution requirements

Internal building space must contain all of the following areas and comply with the specified requirements as follows:

- Office area: Must have at least a 70 m<sup>2</sup> surface and hold a minimum quantity of 7 desk spaces.
- Reception area: Must give access to the building and have at least a 15 m<sup>2</sup> surface.
- Meeting room: Must have at least a 20 m<sup>2</sup> surface.
- Restroom: Must have at least a 12 m<sup>2</sup> surface and be sufficiently equipped for building occupancy.
- Social area: Must have at least a 20 m<sup>2</sup> surface.
- Storage area: Must have at least a 70 m<sup>2</sup> surface and have a minimum of two main exterior accesses.

### Building urbanisation requirements

Building's surrounding urbanisation must include a parking area adjacent to the storage area and must be connected to the closest road or highroad. Both the building and the parking area must be enclosed by appropriate pedestrian sidewalks which lead to office facility's access. The remaining unused surface of the building's property plot will be destined to gardening and landscaping.

The requirements for the building's parking lot are as follows:

- Parking must have at least a 600 m<sup>2</sup> surface and hold a minimum of 7 parking spaces and 2 parking spaces for the disabled.

### Special requirements

- All designed facilities are to be accessible to the disabled. Building access must be suited for wheelchairs and restroom facilities must provide adequate equipment.

#### **4.1.4. Model development: Design process simulation**

Based on the project's preliminary prescriptions and requirements, several Building Information Models will be developed for its design. In an attempt to simulate the design process, the different parts and disciplines that compose a project's definition will be treated in a logical sequence.

To begin with, it is important to state which aspects of design will and will not be developed, as edification projects involve a very wide range of disciplines, building components and processes. *Table 1* shows the aspects of design categorised by discipline. Those that appear highlighted have been considered to be most representative of each discipline and therefore will be treated in the developed models.

The main designers involved in an edification project are structural engineers, architects and MEP engineers. Therefore, structural design and architectural design will be explored through their own disciplinary models in this work. Beyond project design, contractors may find a powerful tool in BIM as well. Therefore, a model issued for construction will be developed. Although contractors are not traditionally involved in project design, BIM processes potentiate more interactions in early design stages.

The author has considered not developing a systems model design as it does not contribute by itself to substantial BIM capability explanatory purposes. Nevertheless, system elements have been included occasionally to explore coordination capabilities amongst disciplinary models.

Structure	Architecture	Systems	Urbanisation
Structural foundations	Space distribution (Internal wall layout, furniture layout, etc.)	Electrical systems (Power supply, lighting, telecoms, etc.)	Pavement, ramps & sidewalks
Suspended floor	Door, window placement	Duct systems (HVAC)	Urbanisation equipment layout
Structural steelwork structure	Architectural finishes (Furniture, equipment, lighting & plumbing fixtures, etc.)	Piping systems (Water supply, drainage, sewage, fire protection)	Landscaping & planting layout
External walls	Building accesses		
Structural roof & finishing layers			
Closing connections			

**Table 1:** Building design aspects categorised by field: Treated aspects are highlighted in green

In summary, the content of this practical example is organised under various BIM models as follows:

- Structural model
- Architectural model
- Construction model
- Coordination model

Apart from exploring BIM tools and capabilities, each model subsection has been organised in a way such that it follows a logical design sequence. All models are related to each other in order to reflect the possible interactions and collaborations amongst project players.

All complementary **drawings, renders, schedules** and **examples** developed with regard to the practical example have been compiled in *ANNEX B* of this work.

#### 4.1.5. Summarised model reviews

In the following sections, the focus of attention has been put on the practical application of BIM capabilities through various examples and on the simulation of collaborative interactions between players. For each model, the main examples and interactions have been **listed and briefly described**.

In an attempt to **remain within a limited extension**, the model reviews offered herein **summarise** the most important information relevant to this work. Nevertheless, it has been difficult to capture the full complexity of the developed models in a brief and simple way due to the intricacies of design processes. Therefore, with the aim of complementing this chapter, the **extended reviews** of this practical exercise have been included in *ANNEX A*. In these reviews all technical and conceptual considerations have been thoroughly exposed, allowing for a complete understanding of the developed examples. All the work and effort put in the generation of the BIM practical example has been clearly reflected in these descriptions.

## 4.2. STRUCTURAL MODEL

### 4.2.1. Introduction

Structural engineers may find it very helpful to use BIM in design stages. Whenever project conceptualisation is developed, structural analysis is essential to back up the design intent. Once project features and requirements are clearly defined, structural analysis is the next logic step towards delivering detailed BIM models for construction.

In the development of the structural model for this section, the role of structural engineers has been represented. A preliminary design of the project developed by architectural designers and based on owner's requirements has been used to conceptualise and develop the structural system of the building. This workflow represents the possible concurrent collaboration in early design stages between architects and structural engineers. The influence of contractors in the development of the current model has been also represented through some decisions regarding building component selection.

While structural elements are conceptualised, modelled and verified, the structural model will be linked to an architectural model. This intends to represent real-time **collaboration** amongst both players. Important changes regarding structural design may affect architectural solutions. When both structural and architectural design are detailed enough and coordinated amongst each other, a joint model will be then linked to a contractor's model issued for construction.

### 4.2.2. Structural design methodology

The structural model has been developed through the design of four fairly basic structural systems:

- Roof deck
- Structural steelwork
- Suspended floor
- Foundations

Both the roof deck and the suspended floor have been selected and dimensioned based on commercial manufacturer catalogues. The rest of structural elements have been dimensioned conventionally.

The technical codes and standards used for the design, dimensioning and structural analysis are specified in *ANNEX A*.

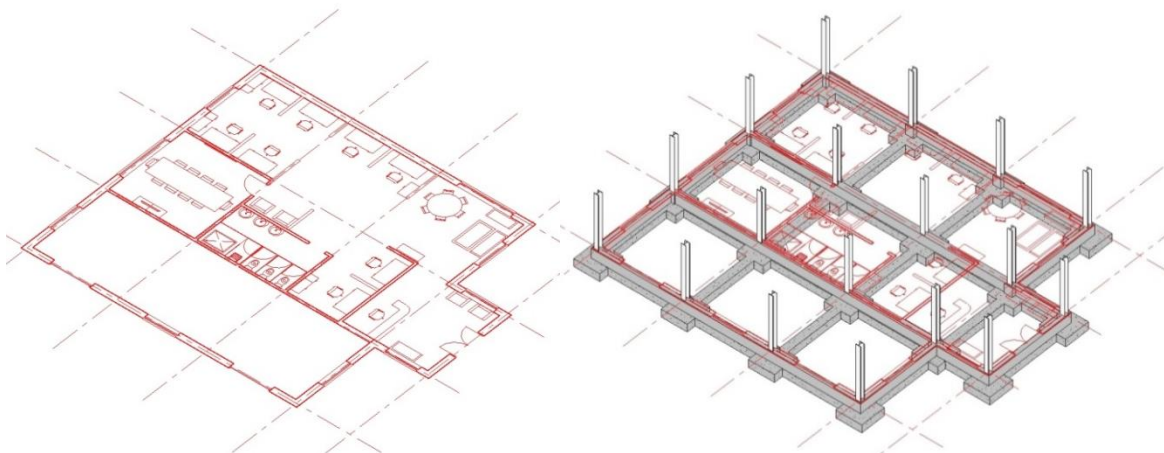
### 4.2.3. Practical examples

The developed examples illustrating the use of BIM capabilities have been performed whilst designing the structural systems listed above. Two main concepts have been explored for this model. These are **parametric object modelling** and **interoperability enabled workflows**.

#### Preliminary structural design based on a linked CAD file

CAD files can be linked to BIM models in order to assist in their 3-Dimensional development. For this example, the CAD files describing a preliminary design have been linked to the structural model. Links allow synchronisation of files, so if any change is made to the CAD drawing, it will be propagated to the BIM model.

The CAD file contains fairly basic architectural information, and it has been assigned to structural engineers to dimension the supporting building structure and its lay-out in order to evaluate structural feasibility. This would represent a scenario where the owner's team is not still familiar with BIM use and still works with CAD based information.



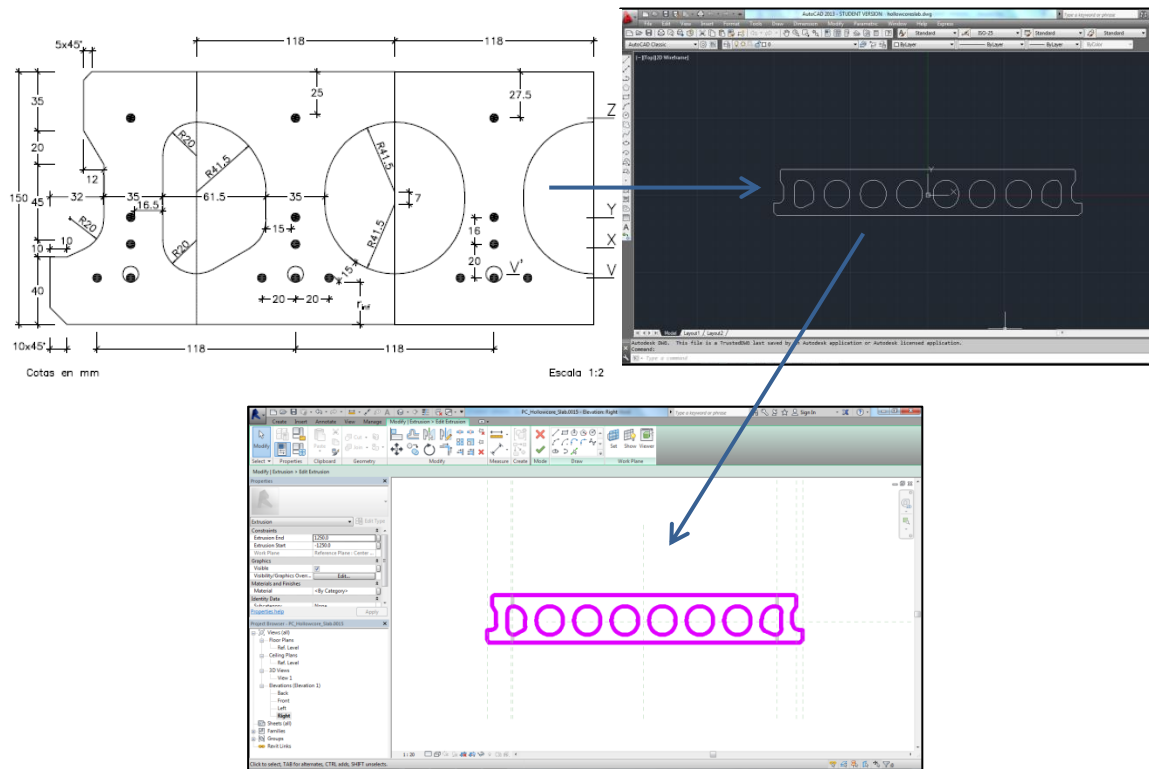
**Figure 26:** From left to right: Updated linked CAD file; Approach to foundation and column design

#### Creation of a precast concrete slab parametric family

Hollow core section slabs have been selected from a supplier's catalogue to form the building's suspended floor. In order to model and incorporate them to the model, a parametric family has been created.

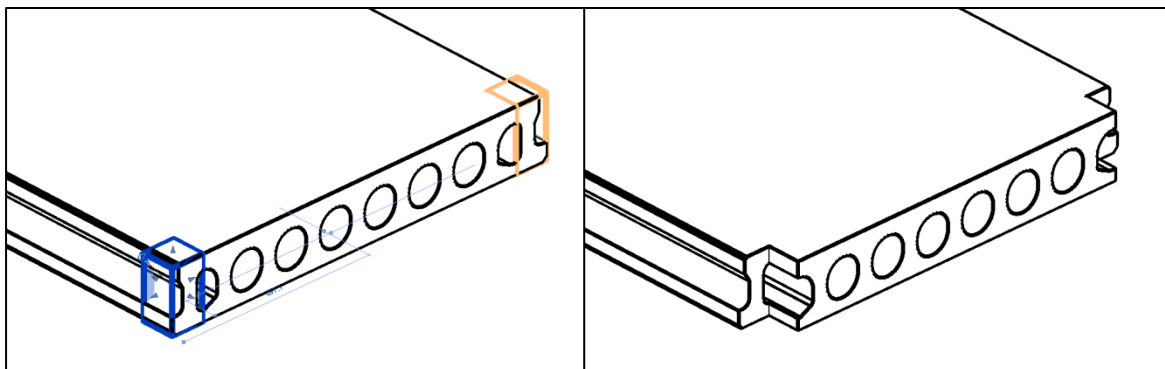
Based on the foreseen uses of the slabs, key information from the element has been incorporated to the model. Precise geometry of the slab is necessary for physical representation. This allows for constructability verification and drawing generation amongst other uses. Other basic physical properties such as material type and its appearance are necessary for both quantity take-offs and rendering respectively. Further detailed information such as material and execution cost attributes may be necessary for generating cost estimates. Other information such as fire resistance and thermal conductivity for energy analysis can be included as well.

In order to reproduce slab geometry, a 2D representation of the profile has been developed in CAD software. By importing this drawing through a direct link, the 3D geometry of the slab can be generated through extrusion. This workflow can be encountered frequently in early BIM implementation stages, as manufacturers do not yet provide their modelled products, and offer 2D CAD drawings instead.



**Figure 27:** Hollow core section slab geometric data implementation process: Paper based; CAD; BIM

In addition, parametric void forms have been added to the slab family. Parametrically controlled, these trims will cut slab corners so that columns can be fit with ease at their base connections with the foundation system.



**Figure 28:** From left to right: Parametric definition of void forms; Resulting slab edge trims

Creation of a composite metal deck parametric class

The structural roof will support roofing finishing layers and will be supported on the steelwork structural system. For constructability purposes, a composite slab with metal deck has been used for its casting simplicity according to contractor’s experience. This kind of design decisions may take place as early as **BIM stage 2** of implementation, where contractors start to collaborate in design.

In BIM models, elements such as slabs and walls are usually composed of several layers. Objects can be defined at several levels of aggregation, and in this case two basic layers can be distinguished in the roof deck: Reinforced concrete and the metal profile. Similar to precast hollow core section slabs, a parametric composite metal deck has been modelled based on a commercial supplier’s technical catalogue.

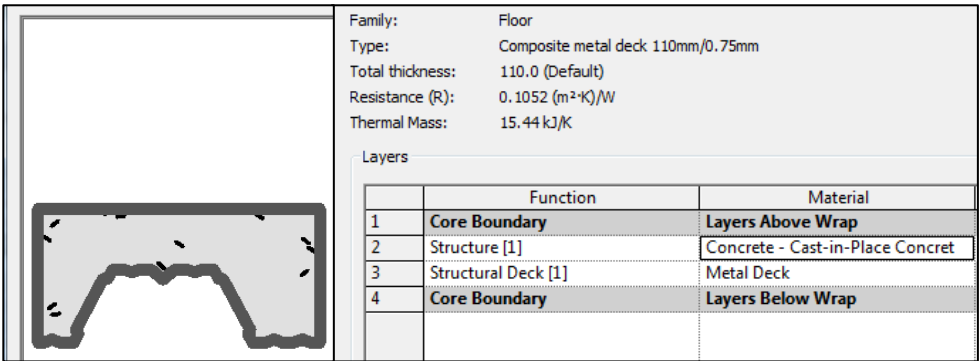


Figure 29: Composite metal deck family class’ structural layers

Steelwork structure design and dimensioning

Structural analysis has been performed through an **interoperability direct link** between Autodesk Revit and Autodesk Robot Structural analysis (RSA). A preliminary design of the steelwork structure has been developed in Revit and exported to RSA with all relevant information for structural analysis. These sets of information for specific purposes have been defined as **model views**, and for this case in particular, all relevant information has been found in the model’s analytical representation.

BIM structural models can either represent their elements physically or analytically. The analytical model of a structure represents its element in a simple and ideal manner, pointing out applied loads and boundary conditions. For the developed example, the features of analytical models have been described in depth.

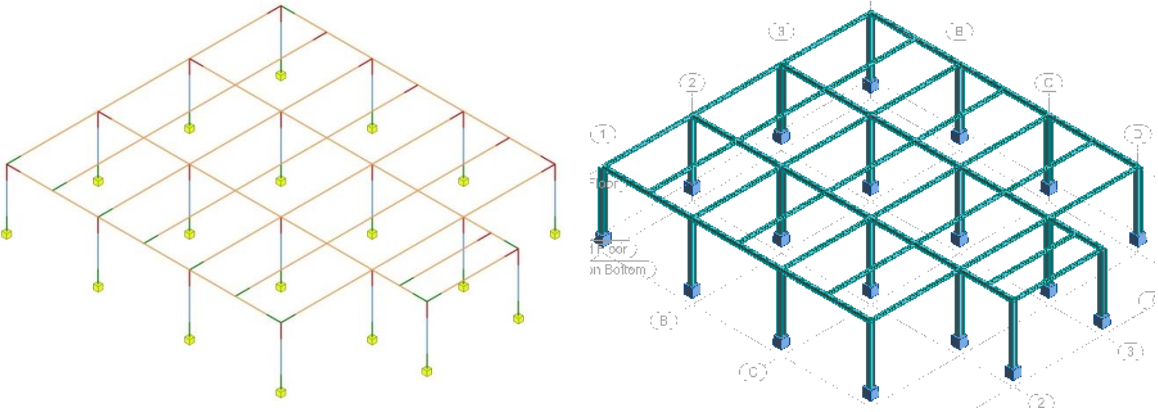
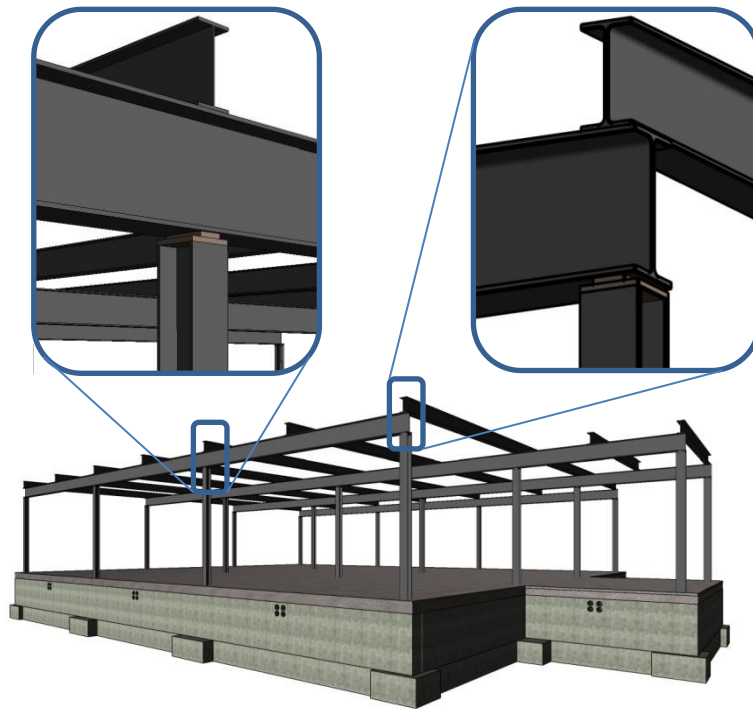


Figure 30: From left to right: Analytical model defined in Revit; Analytical model exported to RSA



Through optimised dimensioning capabilities of RSA, the steelwork structure's design has been verified and imported back to the Revit structural model. Once updated, the steelwork design has been completed with the precise modelling of steelwork connections.

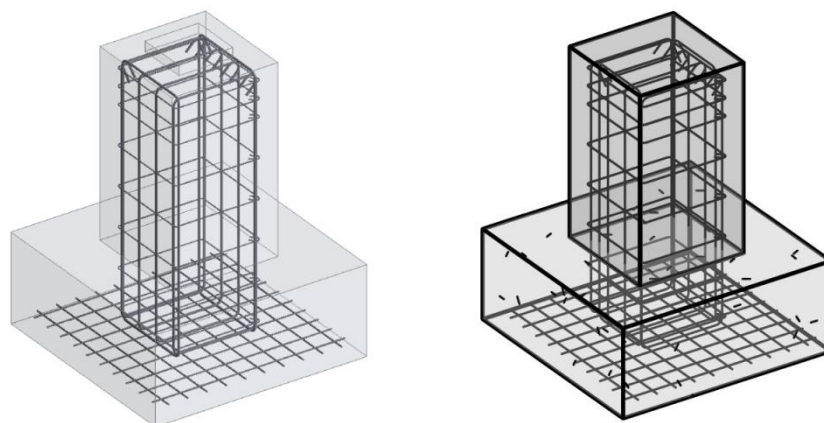


**Figure 31:** Steelwork framing system: connection details

#### Foundation system design and dimensioning

The foundation system has been the first to be predesigned and the last to be verified. This has implied its adaptation the multiple variations of the other structural systems throughout their design process. For instance, its geometry has been adapted to both the suspended floor slabs and the connections of columns at their base restraints. All of these adjustments have been easily managed with the use **parametric behaviour rules**.

Similar to the steelwork structure, foundations have been dimensioned in RSA and imported back to Revit. The existence of a **direct interoperability link** between them has allowed the import of highly detailed object instances, as shown in *Figure 32*.



**Figure 32:** Import of steel reinforcement from RSA to the Revit structural model

External closings design

Closing elements such as roof finishing layers and external walls have been designed based on several guidelines provided by architect designers. These elements have been consistently dimensioned so that they comply with health and energetic technical requirements.

For these elements, **parametric modelling** capabilities have been further explored. As both roof finishes and external walls are composed of several layers, their properties have been precisely implemented.

To illustrate the features of parametric objects with several levels of aggregation, thermal resistance properties have been assigned to each of the layer’s materials. These layers form both external walls or the roof as a unit and therefore, BIM software is capable of determining the overall thermal resistance for the closing elements. With this information, the model can be submitted to accurate energetic analyses.

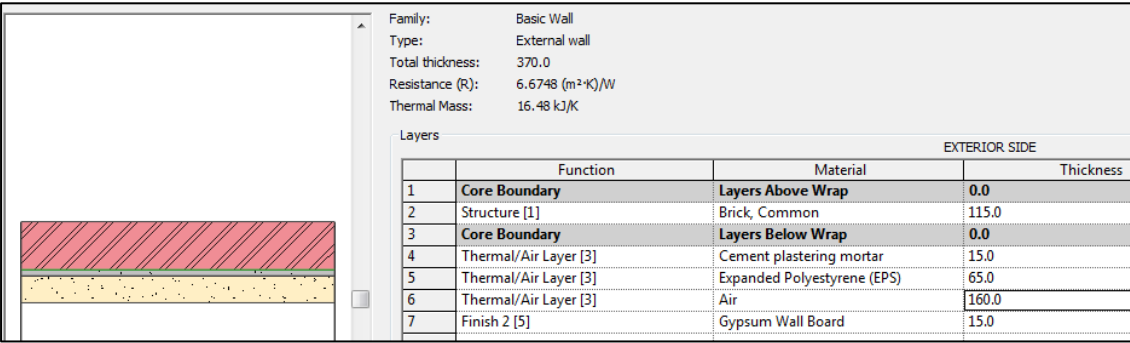


Figure 33: External wall class properties dialogue

There are other material attributes which serve different purposes. For instance, material rendering textures have been applied to the roof’s gravel layer for realistic visualisation.

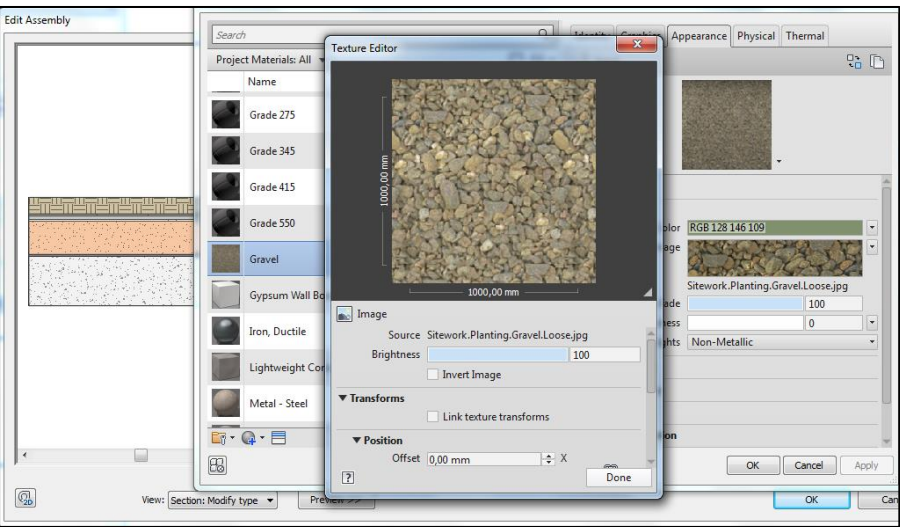


Figure 34: Definition of material appearance dialogue

### 4.3. ARCHITECTURAL MODEL

#### 4.3.1. Introduction

Architects are essential designers in the development of project definition for building facilities. Their criterion influences both conceptualisation and detailed design, providing the project with very singular design features and characteristics. It is important, therefore, that architects are aware of all changes regarding the project and that their design intent can be satisfactorily represented. In the development of the architectural model, their role will be addressed.

Architects may find BIM very useful to visually represent a building starting off from scratch and ending up painting a detailed and representative full 3D view of what they had in mind. BIM allows architects to easily explore **design alternatives**, backing up their comparison with informed model features and representations. The ultimate design can only be reached through rich study of alternatives. In addition, **visual representation** capabilities of major BIM platforms prove to be persuasive when communicating the intended design scheme to other project players. Although all BIM users can take advantage of these visual representations, it is architects that mostly benefit from them.

Beyond the capability of offering deep customisation to design, BIM does also back up its feasibility structure-wise and construction-wise. Solid **link capabilities** allow models from diverse disciplines to be contrasted and checked upon. These features also allow for evaluation of design modifications, permitting to check if a given change affects other models and consistently accommodate them if necessary.

In order to develop a realistic architectural design, the architectural model has been based on the structural model so that it backs up its constructive and resistant feasibility. This represents a workflow where designers collaborate in model development. This kind of dynamic known as ‘model based collaboration’ may take place from **BIM Stage 2** and on. Architects will base their work in the structural model to achieve consistency with accorded building dimensions and avoid unnecessary interferences amongst disciplines. If any relevant changes were to affect the structural model, they could be easily evaluated and propagated. Once this particular model is finished, it will be moved on to contractors for their particular use, as detail level will be accordingly appropriate.

#### 4.3.2. Architectural design methodology

The architectural model has been developed based on the structural design. Once linked to the provided structural model, architectural model definition has started by defining space distribution. Based on the space functional layout defined in the preliminary design, several architectural solutions have been explored.

As the design process has taken place, the model has seen itself submitted to further changes. All documentation for the final architectural design has been included *ANNEX B*.

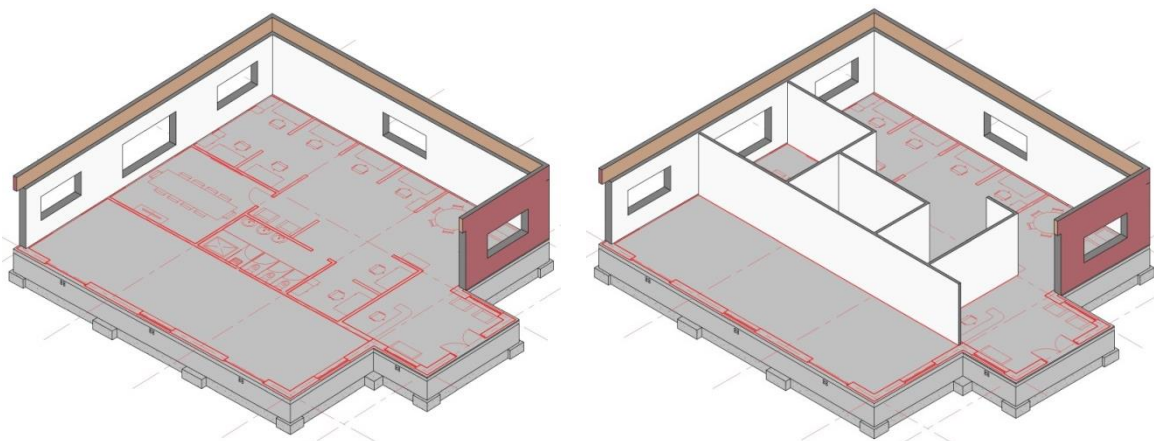
### 4.3.3. Practical examples

The developed examples illustrate how design processes can be assisted and backed up by several BIM capabilities and analysis tools. Taking informed decisions can be of great value for designers when exploring several **design alternatives**. Furthermore, it has been intended to represent the high level of detail that can be reached in BIM models with the use of **predefined and commercial object instances** for architectural components.

#### Linking of the structural model

Most BIM platforms allow models to be linked within other models. Similar to linked CAD files, any change made to a model which has been linked to another one will propagate accordingly. For this particular example, the structural model has been linked to the architectural model.

Similar to the structural model, a CAD file of the preliminary design's functional layout has been linked as well to assist in the definition of internal space partition and distribution.



**Figure 35:** Modelling of interior walls based on a linked CAD file

#### Interior architectural design

In order to illustrate the richness of component resources, interior design will include as many furniture elements are necessary to satisfactorily reflect the use it will be given. As the building has been defined by functionality areas, both **predefined** and **commercial** product object instances will be used to fit these definitions.

BIM platforms usually count with an extensive predefined object component library for interior design purposes. However, BIM users have the capability to download precise representations of commercial building components from **on-line BIM object libraries**, where manufacturer information is supplied. This allows designers to compare within products and choose the one which best fits their needs. Once selected, these object building components

include all necessary information and appearance attributes for high model accuracy. This information can be later used for procurement and cost estimating needs by treating them with Revit specific tools.

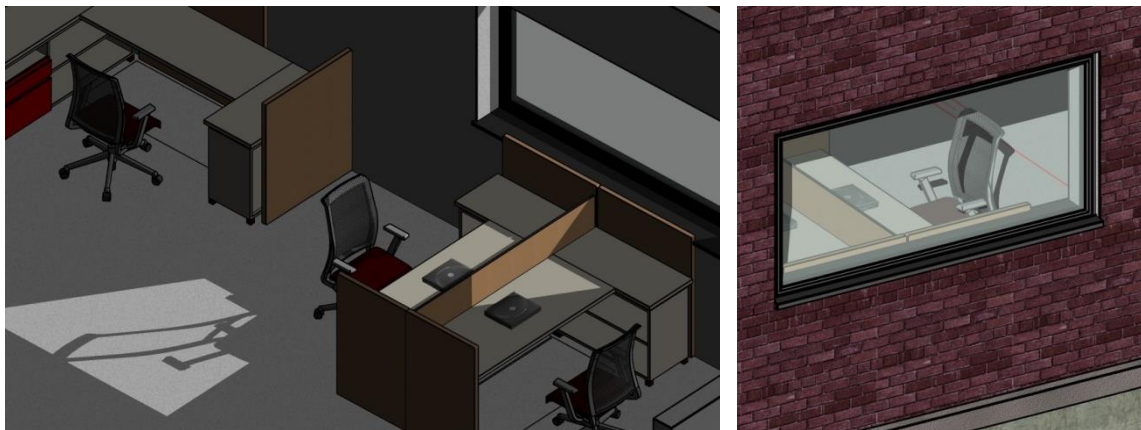


**Figure 36:** From left to right: Model view of commercial reception desk; Rendered view of commercial reception desk

#### Window disposition: study of alternatives

Window layout for the architectural model has been studied for **several alternatives**. In order to illustrate how BIM models allow designers to take informed decisions, analysis tools have been used to select the adopted alternative. In this particular case, Revit's 'sun path' analysis tool<sup>12</sup> has been used to simulate day light conditions for the model.

Based upon considerations such as internal space use and general building aesthetics a final window layout has been adopted. The results of daylight simulation have influenced the design decision as well.



**Figure 37:** Day light simulation for Eastern façade window: Interior and exterior views

#### Interior space distribution

The preliminary definition and requirements of the building describe an approximate space distribution and usage schema. There are, however, specific locations inside the building that can be distributed in different ways.

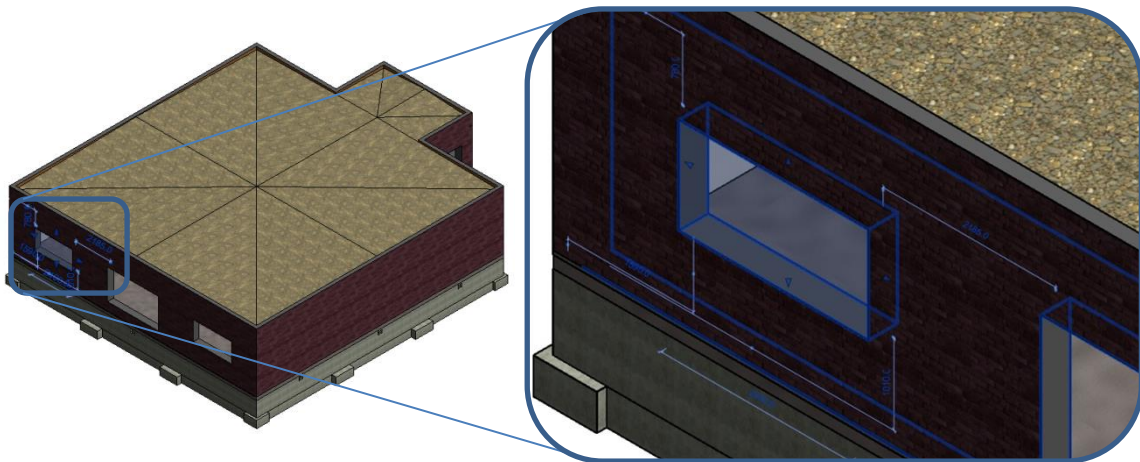
<sup>12</sup> The features of Revit's 'sun path' analysis and other tools have been further detailed in ANNEX A.



Similar to window disposition design, alternatives have been explored for internal space distribution. In this case, the focus of attention has been put on reflecting how designers can easily review several design possibilities. Through the use of **parametric behaviour rules**, object instances in a model can be modified, adjusted and relocated in an efficient and consistent manner.

#### Coordination with structural model

Parametric **coordination** capabilities have been represented for this example. As expected, the ultimate window openings have been modified with respect to the preliminary design. This calls for the updating of the structural model, to which provisional structural openings had been implemented. In order to do so, window openings have been re-dimensioned and re-located through parametric rules. In order to do so, parametric distances referred to wall's relative coordinates will be modified as desired. These dimensions appear highlighted in blue in *Figure 38*.



*Figure 38: Parametric definition of wall openings*

#### Generation of visualisations for interior design

Throughout the architectural design process, visualisation attributes have been assigned to most object instances in order to generate realistic renders that accurately represent the design intent. **Visualisation tools** and their features have been reviewed as well.

All generated model renders have been included in *ANNEX B*.



*Figure 39: From left to right: Interior 'camera' model view; rendered interior model view*

## 4.4. CONSTRUCTION MODEL

### 4.4.1. Introduction

Construction practices are fundamentally based on careful management and planning of procurement tasks and execution sequences. Ideally, contractors and subcontractors thoroughly extract specific information of the project that is to be built from the provided design documentation, so that they can efficiently carry out its construction. The extraction of material quantities and other execution characteristic parameters is necessary to develop **cost estimates** and perform **procurement** of material and building components. All these parameters are usually associated a determined time location inside a **construction program**. In the generation of a project execution program, contractors are in charge of evaluating design constructability and breaking down the whole development into feasible construction sequences based on their criterion and experience.

Contractors that model the project to be built have at their disposal many tools that will assist them in the automation of most common tasks and will also back up their decisions. BIM allows users to automatically generate a wide range of **schedules** regarding the modelled project. Amongst these schedules are quantity take-offs, which lead to cost estimation of materials and execution tasks. In fact, these schedules will be very accurate, as they are in consistency with the model's database, and will automatically update if any change is made to the model. Although these features reduce the chances of errors and omissions for these tasks, they are no more than an automation of traditional manual workflows. Perhaps the inclusion of **time attributes** to the model is one of the exclusive features that BIM has to offer. Construction sequences of a project can be assigned to each object component in the model, so that BIM users can simulate the building process for each of its stages. These time attributes can be reflected in the generation of schedules, when needed, for programing purposes. Most interesting, though, is the capability of contrasting and verifying the **feasibility of construction methods** for every development stage. With an accurate representation of the construction site at a given time phase, contractors are be able to take informed decisions regarding execution techniques, space availability, resource logistics, safety measures and so forth.

Depending on the level of BIM implementation amongst the players involved in a project, contractors may have to either develop their own model from the tendered documentation and drawings, or adapt the BIM models provided by project designers for their own use. For the development of the building example treated in this work, it has been acknowledged that contractors are provided with the models of the different disciplinary designers. It has been considered that contractors have collaborated in early design stages as well. As mentioned for the '*Structural model*', some construction aspects have been determined based on contractor criteria. For instance, the structural roof had been designed as a composite metal deck following contractor's preferences. With this kind of interaction it can be assumed that contractors are familiar with the provided structural model and therefore their construction model can be based on it. In other words, the model issued for construction has been developed starting off from the structural model, which has been directly linked to it.



The construction model has been used as a simplistic example to expose some of the most basic tasks that can be carried out with BIM use. Although the following tasks are far more complex in reality, the provided examples are representative enough of the most relevant BIM capabilities for contractors. Revit has been used to model construction **site conditions** such as topography and surrounding urbanisation spaces to the building once finished. With defined site conditions, the structural model can be linked and processed to include phasing of execution tasks. Eventually, constructability of a given sequence can be evaluated. After assigning time attributes to building components, very basic examples of most commonly used schedules can be developed as well.

Last but not least, surrounding urbanisation to the building has been modelled in order to highlight the integration of the building with its surroundings and terrain conditions. The development of urbanisation design may happen concurrently with the modelling issued for construction if contractors are involved early in design stages.

#### 4.4.2. Practical examples

The developed examples illustrate how BIM models issued for design can be adapted and used for construction purposes. Amongst these uses, special focus of attention has been put in the simulation of **construction site conditions**. In line with this purpose, time attributes have been assigned to the project's model in an attempt to reproduce each of its execution **phases**. Object instances regarding construction equipment, machinery and auxiliary means have been included for the **evaluation** of certain construction tasks.

**Procurement** and **construction management** capabilities have been also addressed in the generation of schedules regarding quantity take offs and cost estimates.

##### Construction site conditions

In order to explore BIM capabilities for contractors, construction site conditions have been necessarily modelled. In regard with project's environment, the construction model has been assigned a geographic location, which can be used by BIM analysis tools. For instance, project's location gives away associated weather and temperature data that can be used for energetic analyses.

Topography has been also defined for the construction site, allowing for the definition of excavation or landfill volumes and their quantification for earthwork task planning. Digital terrain modelling capabilities of BIM platforms have been briefly reviewed.

Object instances related to construction tasks has been also included in the model in an attempt to recreate realistic site conditions. Amongst these object instances are those destined to **health and safety** in construction. The ability to plan and evaluate safety measures has been explored as well.



**Figure 40:** Modelled site conditions: Inclusion of construction-related object instances

#### Linking models to site

The project's environment has been modelled for the construction model. Still, the main building has not been included. In order to do so, the building model that has been developed as a result of both structural and architectural design has been **directly linked** to the construction model. The tools and capabilities regarding precise location of the building model within site conditions have been briefly described.

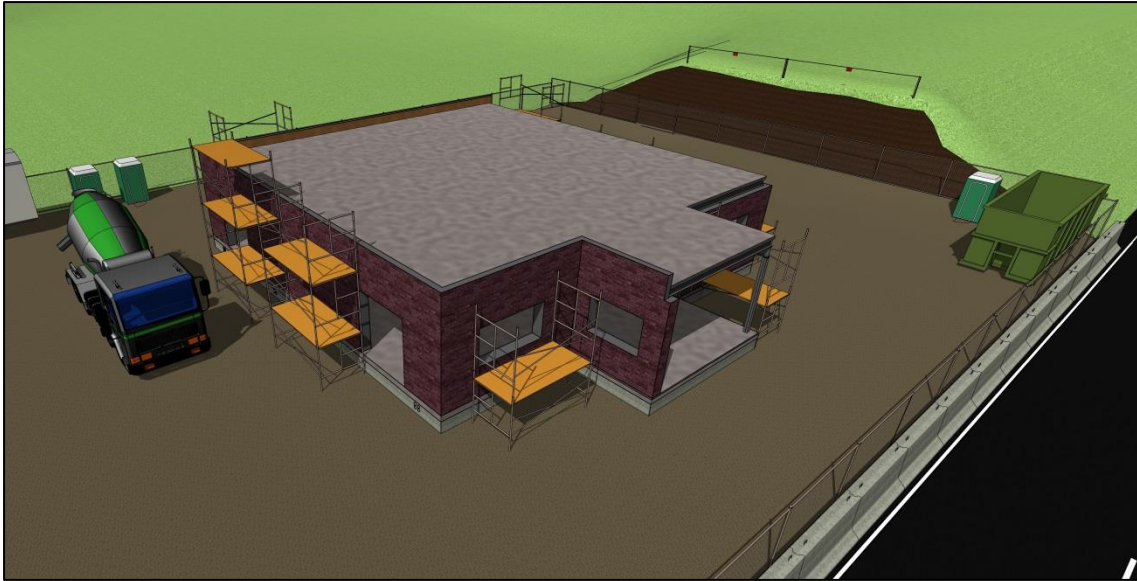
#### Implementation of construction phases

The construction process of the project treated in this work has been broken down into basic execution sequences, known as project **phases**.

Project phases can be introduced in most BIM platforms as parameters, allowing users to work in what are known as **4-Dimensional models**. These time attributes can be assigned to each object instance, identifying their phase of creation and their phase of demolition if necessary. When requested, 3-Dimensional and other views of the model can be filtered by project phase, showing what the construction site and facilities would look like at a given point in time.

#### Evaluation of construction tasks

The realisation of certain execution sequences requires in some cases the evaluation of constructive **feasibility**. Visualisations of in-situ conditions allow contractors to plan and organise all of the labours related to their work. As building's surroundings have been already modelled for the adaptation of the construction site, the model has been further used to simulate the execution of certain tasks. In line with this purpose, machinery and auxiliary means object instances have been included to the model.



*Figure 41: Evaluation of scaffolding layout in the construction model*

#### Generation of schedules

BIM software platforms allow the generation of schedules based on the information contained in a BIM model's database. The very fundamental aspects of schedule generation and their most common uses have been reviewed.

Contractors are amongst many, the players that will most likely generate and use this documentation typology in order to present relevant project aspects other than design. These aspects relate to quantities and other qualitative information, mostly focused on **procurement** of materials, **time management** and **cost estimation**. The most effective way of representing them is through the use of organised schedules.

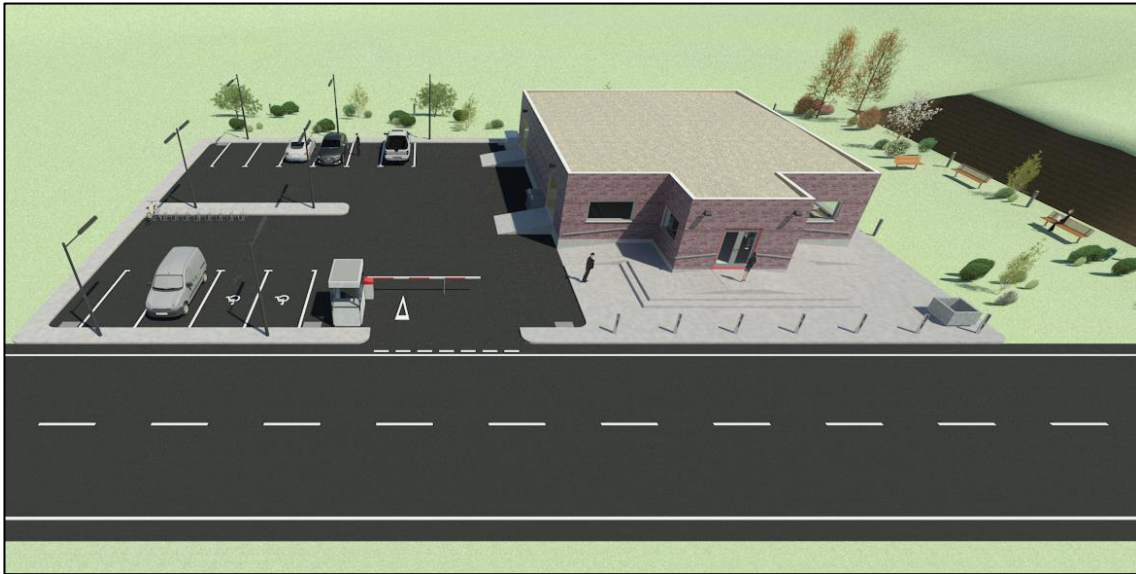
#### Urbanisation design

Project's urbanisation has been designed and modelled in order to highlight the integration of the building with its surroundings and terrain conditions. Parking, equipment and vegetation object instances have been included to outfit the final design with realism and technical consistency.

Similar to the architectural model, **rendered** views of the finished project<sup>13</sup> have been generated. These representations may be very useful to communicate the design intent to both owners and the general public, as they portrait comprehensively how it will be perceived. They have been generated in response to a simulated owner's request for marketing and communication purposes.

---

<sup>13</sup> Urbanisation design intent is represented in various drawings and rendered views found in *ANNEX B*.



*Figure 42: Rendered view of building's surrounding urbanisation*

## 4.5. COORDINATION MODEL

### 4.5.1. Introduction

Project definition is the result of the design efforts from diverse disciplines. Nevertheless, if these designs are not properly coordinated, they may compromise the project's feasibility. Design coordination issues are usually solved in design team meetings, where information is exchanged through paper-based documentation. Often, possible interferences between disciplinary designs are difficult to detect based on 2-Dimensional drawing representations, which can lead to errors and omissions. The use of BIM models can facilitate these synchronisation tasks in several aspects. To begin with, models can be viewed superposed in a fully 3-Dimensional environment, representing their interaction and possible interferences in a more comprehensive way to BIM users. This allows designers and other users to visually understand other disciplinary design intents, which are usually alien to their specialty field. Additionally, BIM platforms offer clash detection tools that detect interferences or 'clashes' between different disciplinary models. These tools can be very useful to avoid relevant omissions when coordinating various models. Although BIM platform tools for clash detection do not give design solutions yet, coordinated models offer BIM users a solid and consistent environment in which they can quickly revise design alternatives. Furthermore, when solutions to interferences are implemented in a coordinated model, all modifications with respect to initial design can be automatically updated back to the databases of each disciplinary model. This results in great savings of time and effort in comparison to manual updating of project drawings and documentation.

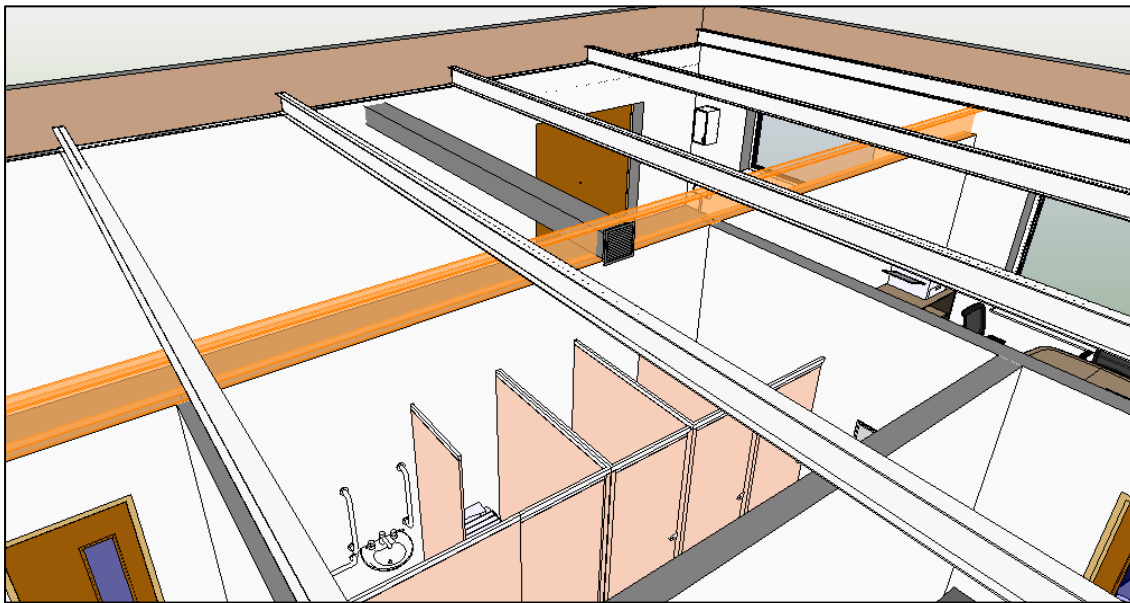
### 4.5.2. Practical examples

The developed examples illustrate BIM capabilities for managing **collaborative workflows**. Whenever BIM models have to be coordinated as a result of collaborative design processes, several tools are at user disposal to smooth out these synchronisation tasks. The focus of attention has been put on **clash detection** tools and their limitations.

#### Assisted coordination: Clash detection

Possible interferences which may occur in common edification projects have been simulated in a fairly simplistic way. In order to demonstrate how clash detection tools function, a systems model has been coordinated with the structural model.

In this systems model, a ventilation duct has been intentionally misplaced so that it collides with the steelwork framing system of the structural design. Automatic clash detection tools have been briefly reviewed and used to detect the intentional interference amongst models. Once detected, the clashes of both designs have been solved by exploring an appropriate solution.



**Figure 43:** Clash detection for ventilation duct: Colliding elements are highlighted in orange

#### Manual coordination

Automation of interference checks can be used to detect obvious interferences between model elements. Still, there are many coordination issues that cannot be addressed with these tools alone, and require the evaluation and criteria of qualified designers. The limitations of automatic clash detection for this particular case have been exposed.

The coordination of the structural model with the design of the building's access ramps has been developed manually. In particular, the layout of ventilation openings for the suspended floor has been relocated, as they have found themselves blocked by the ramps in front. The final position of ventilation openings has been defined based on qualified user's criterion.



## CONCLUSIONS

This work successfully provides a clear and useful insight into Building Information Modelling and therefore accomplishes the main objective that had been proposed. Throughout its development, the main theoretical and technical concepts that compose Building Information Modelling have been treated. The provided **BIM framework** has allowed the author to present a wide and diverse set of information in an organised and comprehensive way.

The very fundamentals of this new approach have been addressed putting special attention in explaining the origins and the technological shifts that support BIM. The development of practical examples has been crucial to contrast and evaluate the capabilities of BIM technology. Putting concepts into practice has allowed the author to extrapolate their application to realistic scenarios within a generic building project.

The relationships between the **technology**, the **process** and the **policy** field within the AEC industry have been pointed out, as to give a holistic understanding of the main efforts which make BIM possible. The path towards **interoperability** has been visited, highlighting the necessity to overcome current limitations in order to achieve **Integrated Project Delivery (IPD)** workflows.

Integrated Project Delivery is the ultimate goal of BIM implementation; it is the theoretical pinnacle of efficient project delivery. Apart from interoperability requirements, there are further legal and contractual arrangements that have to be established to make it possible. This requires deep commitment from policy and process bodies, as these legal modifications have to be tailored to each particular project. As AEC industry firms start gaining experience and confidence with collaborative projects, new and upgraded contractual typologies will surge.

Special care has been put in picturing BIM not only a set of tools and technologies, but as a whole **process** itself. Its implementation involves a deep change and renewed understanding of traditional workflows. It has been intended to give out a global image of the role that BIM can play in the AEC industry. Setting a background of current practices has awakened the awareness of the potential changes and efficiency improvements that can be implemented. As inherent to all changes, both risks and opportunities arise. Therefore, the **advantages** of implementing BIM have been laid out, pointing out the main **challenges** that have to be overcome for its ultimate adoption.

BIM is in fact a major change in how building projects are focused. Its capabilities clearly benefit society, as they will lead to a new breed of projects: Better managed, designed, executed and operated. The future lies ahead, and many possibilities are yet to be explored and discovered. Based on the gained experience and the reviewed current practices, the author has pointed out several lines of development for future works at the end of this document.

### Conclusions based on the realisation of the BIM practical example

In the development of the practical examples provided in this work, the major features of BIM platforms have been reviewed. The generated models have successfully covered a great length of a project's lifecycle, from its conception onwards to its construction and commissioning. The most relevant interactions amongst project players involved in the project have been used to justify several design decisions and introduce some applications which improve the modelling process in great measure.

The simulation of these interactions has led the author to explore **collaborative workflows beyond traditional practices**. In essence, collaborative BIM projects gather the efforts of all its players in early design stages. This is due in part for the initial need of intensive customisation of basic components. Nonetheless, the ultimate purpose of early collaboration lies in benefiting the project overall.

Figure 44 shows how Integrated Project Delivery workflows focus their effort in early design stages, where the ability of accommodating changes is bigger. As the design process involves all relevant players from the start, **coordination tasks are truly effective**. Compared to traditional practices, IPD projects are initially built as BIM models, and not until every aspect of design is revised and validated does real construction begin. This translates to improved designs which require less unexpected modifications and therefore imply less cost.

Through the use of linked models in the practical example, the author has contrasted how fluently changes can be coordinated amongst various disciplines. This fluency combined with parametric behaviour rules of object instances has allowed for the **quick evaluation of various alternatives during design**.

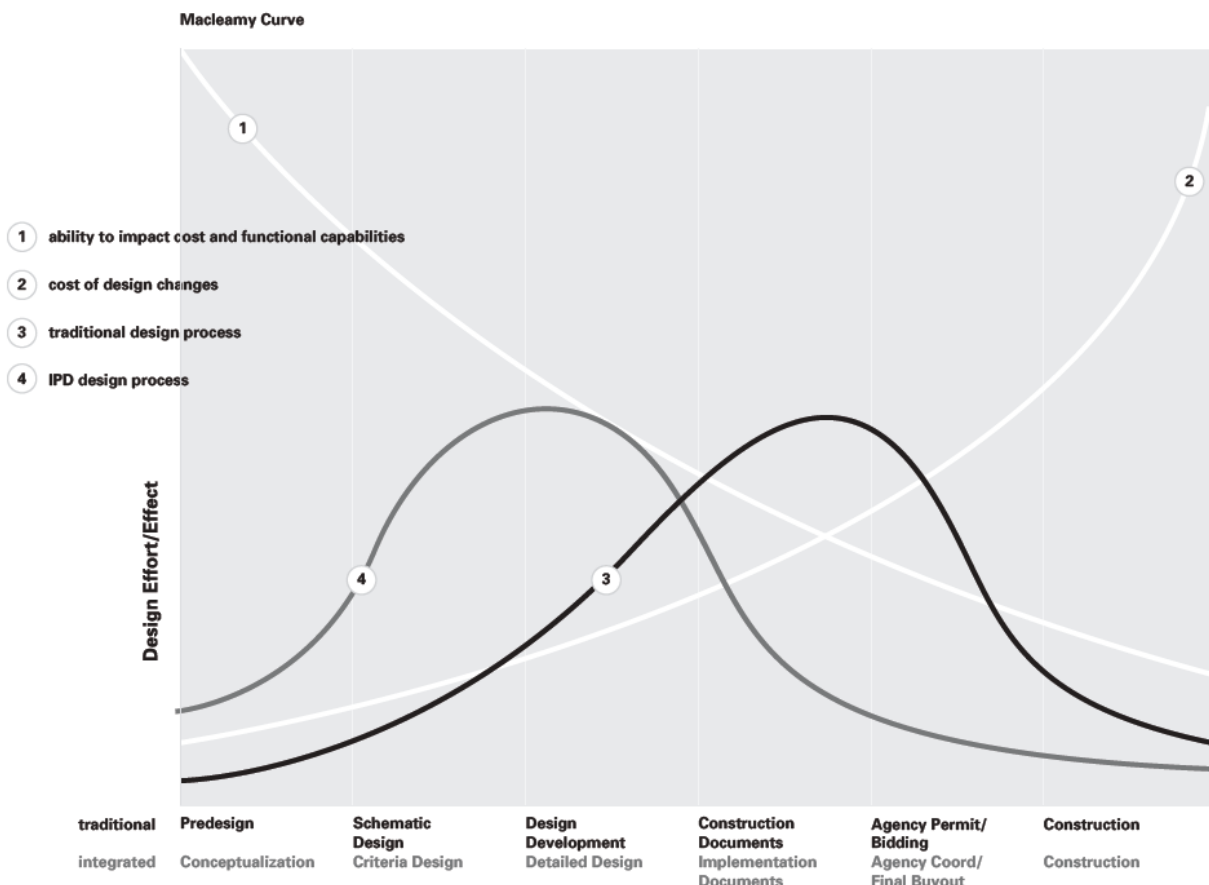


Figure 44: The Mc Leamy curve [4]

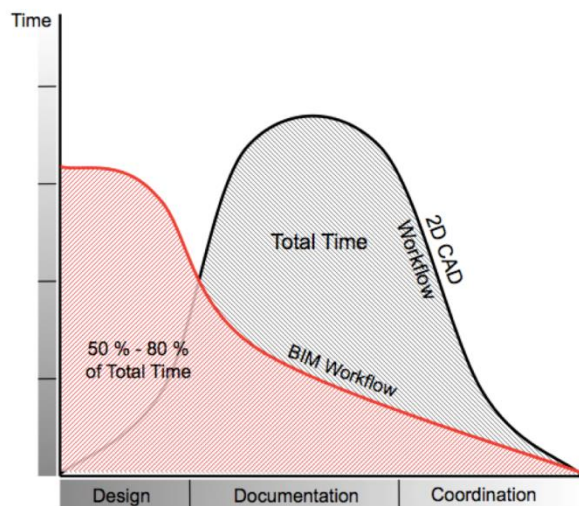


Although the advantages and possibilities of developing projects with BIM are many, some limitations have been encountered as well.

To begin with, **the learning curve of BIM software is very steep**. Considerable effort is required to model with BIM software at a very basic level for inexperienced users. This initial productivity loss has been reflected in the curve presented in the ROI analysis of BIM implementation provided in *ANNEX E*.

In addition to the setbacks of formation, there is another aspect which adds difficulty to the modelling process. Using BIM technology to model a building project requires a **considerable amount of time for the customisation of its basic components**. This is due to the wide range of information that object instances hold for various BIM-related purposes. For instance, the author has had to define many geometric and material property data attributes for basic components before modelling any part of the treated building. These attributes have been later necessary for the use of BIM applications such as structural analysis, rendering and so forth.

Although the initial effort during design might be overwhelming, it is paid off by an **efficiency increase in post-design stages**. As appreciated in *Figure 45*, BIM workflows provide fluency in the generation of documentation and the development of coordination tasks. The author has verified these phenomena when generating 2D drawings and schedules for the developed model. Furthermore, all modifications resulting of coordinating various disciplinary models have been easily managed and automatically updated to the model's documentation.



*Figure 45: BIM workflow curve [23]*

In the development of BIM software tutorials, **interoperability issues have been encountered** as well. The author has found it difficult to export its models in between different platforms. Loss of information and limited interchanges seem to be common limitations for collaborative workflows. The path to interoperability is a tough one, and although bodies from the technology, process and policy fields such as the Associated General Contractors and buildingSMART have overcome many of its intricacies, there is still a long way to go.

### Conclusions regarding BIM implementation in civil engineering

BIM implementation in civil engineering depends in great measure on the awareness of owner stakeholder parties. Not until owners and clients realise the benefits they can obtain from BIM and start to request it for their projects, will contractors and designers implement it. This is somewhat the case of the UK's plan for BIM implementation, which has had to be driven from governmental bodies.

The most benefited project players from BIM implementation would be **owners**, as a lot of added value is found in having an information-rich BIM model of a facility for its management and operation. **Designers**, on the contrary, would be the least favoured. At first, they might be reluctant to implementing BIM, as a lot of effort has to be put in early design stages. Additionally, designers may be troubled with concerns regarding legal ownership of their intellectual property when working in collaborative projects. These concerns may be accentuated when working in joint ventures.

Collaborative workflows may also put off **contractors** when implementing BIM. The involvement of contractors implies legal concerns as well. In civil engineering projects, insurance policies are to be taken very seriously, as the risks that are covered imply considerable liabilities. The participation of contractors in design decisions should be legally defined with regard to risk allocation. In this manner, designers shall not bear with unnecessary responsibilities which correspond to contractors.

Therefore, it can be concluded that there is an urgent need for flexible contractual arrangements which address the legal concerns specific to civil engineering projects.

On a technical basis, BIM technology still lacks engagement with civil engineering practices. Although many BIM platforms are destined to gather tools for many disciplines in their interfaces, only architectural design is covered in depth. Following, the author has pointed out the main aspects which could be improved in BIM platforms with regard to civil engineering:

- Need for more engineering-specific object families.
- Inclusion of commercial precast elements in on-line object libraries.
- Enhanced simulation capabilities regarding execution of construction tasks.
- Implementation of automated checks for structural codes and specifications.
- Enhanced interoperability with structural analysis and construction management software.

From an investment point of view, BIM turns out to be a **healthy and profitable investment**. Based on the ROI analysis developed, and on the reports cited in this work it can be concluded that if BIM practices are adopted and engaged as a **process**, appreciable return on investment can be assured. On the contrary, if BIM is implemented as a simple software tool no satisfactory results will be perceived. Implementing BIM is not only about changing the way players work, but changing the way players think.

BIM is most likely to be the future, and it may be a promising one. Nevertheless, certain distance has to be taken from revolutionary statements. As afore mentioned, many interoperability, legal and technical issues have to be overcome before BIM can be taken advantage of at its full potential. In the meantime, firms from the AEC industry which voluntarily engage with BIM will gain valuable endurance and advantage over their competitors. In this line, the experience of construction projects developed with BIM will be essential to back up the established theoretical understanding of BIM and dismiss any assumed misconceptions. Firms pioneering in BIM use that **document and develop case studies** of their projects will provide a sound knowledge base to guide the evolution of BIM practices in the future.

Certainly, the greatest benefits of BIM implementation are those of society at large. Projects will eventually enjoy **higher performances** and will be operated at **lower costs**, as a result of improved design. The use given to models issued for construction may as well favour efficient and sustainable practices, leading to **carbon emission reduction** [44]. **Fewer resources** will be necessary, and **risk will be reduced** at the construction site as well. Finally, all the information held by models issued for operation will clearly **facilitate the planning and execution of maintenance and other related tasks**. These models will act as as-built information archives that can be constantly updated, proving to be especially useful in busy and concurred environments such as urban areas.

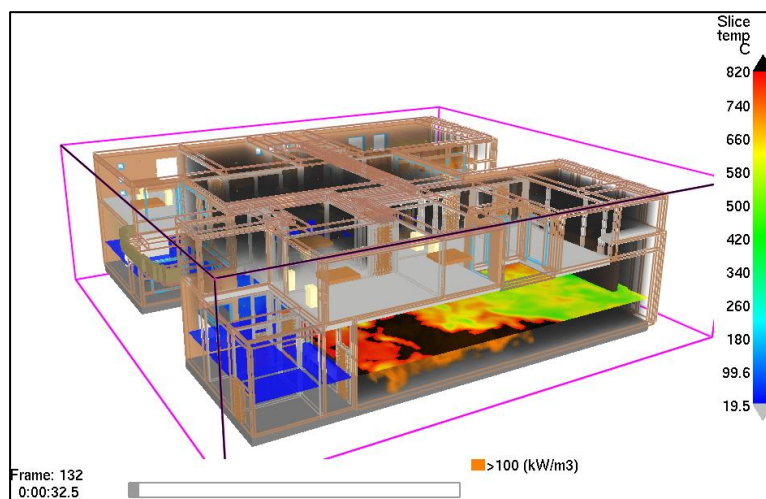
## FUTURE WORKS

Nearly every field within the AEC industry is sensitive to the potential improvements of BIM. There are both necessities to cover and new possibilities to explore and discover. Based on the gained experience and the reviewed current practices, the author has pointed out several lines of development for future works. Note that these proposals have been mostly focused in the development of BIM applications.

### Fire resistance analysis

Fire resistance simulation could be implemented in BIM models to improve the safety measures of a project. The inclusion of fire resistant data attributes to structural objects could allow the determination of collapse time within a facility. If all necessary information is included in a model, it can be exported as a **model view** to Computational Fluid Dynamics (CFD) software for fire simulation and analysis. The outcome of these analyses would be time-dependent temperature values for each point in space within the model. Through combining this output with structural analysis, the collapse time of structural elements could be determined.

If the collapse times of various sectors within a building were to be known with accuracy, improved evacuation plans could be planned and developed.



*Figure 46: Dynamic Fire Simulation with CFD software [14]*

### Inclusion of project demolition in sustainable design

Sustainable design tools are in strong development by BIM software platform vendors. Nevertheless, the main focus of attention has been put in simulating the energetic efficiency of a given project. It would be interesting to include tools for the planning and simulation of demolition tasks, which is a relevant project phase to sustainability.

The inclusion of recyclable material properties to object instances would allow material take offs from the model's database. Furthermore, efficient demolition plans could be implemented in early design stages, when major conceptual decisions are taken. This could be done by assigning time attributes to objects. In this manner, owners would have an accurate as-built model of their facilities with a well-documented demolition plan.

#### Machinery automation at the construction site

The use of BIM technology in the field is currently under great development. Models of the building site developed by contractors can reach high levels of fidelity. Laser scanning techniques and topographic reference points allow the accurate representation of site locations in the model.

This technology could be used to automate the operation of building construction cranes for instance. By defining the desired placement of the crane jib in the BIM model, precise crane control could be achieved remotely.



*Figure 47: BIM model of building site and machinery [28]*

#### Enhanced modelling of health and safety measures

The inclusion of time attributes to BIM models enables users to represent the project at various points in time during its construction. This can be of assistance in planning works and determining any necessary health and safety measures. Up to date, few object families regarding these measures are found in these platforms. In addition, no parametric tools have been developed to associate objects and activities with certain risks. Their development would surely benefit most of current construction practices.

Augmented reality can be of great use to signal and determine health and safety measures. With the assistance of portable devices such as tablets and smartphones, the BIM model issued for construction can be accessed remotely in the field. Construction personnel can orient their portable devices in various directions within the site and visualise the procured safety measures issued for a certain building phase. It would be interesting to explore the potential of these capabilities in terms of making construction as safer as possible.

## REFERENCES

The presented references comply with ISO 360: 1987 (UNE 50-104-94); Citing of electronic documents is in accordance with ISO 690-2 1997.

- [1]. **A. Edgar.** *Overview of Building Information Models presentation.* [Online] s.l. : NBIMS, 2007. [Consulted: 14 December 2013] Available at:  
<[http://www.google.es/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0CDcQFjAA&url=http%3A%2F%2Fprojects.buildingsmartalliance.org%2Ffiles%2F%3Fartifact\\_id%3D1348&ei=DeCtUteWNuS50QWH\\_4DICA&usg=AFQjCNG8aBacjKYmTc](http://www.google.es/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0CDcQFjAA&url=http%3A%2F%2Fprojects.buildingsmartalliance.org%2Ffiles%2F%3Fartifact_id%3D1348&ei=DeCtUteWNuS50QWH_4DICA&usg=AFQjCNG8aBacjKYmTc)>.
- [2]. **AIA California Council.** *Integrated Project Delivery: A Working Definition.* [Online] [ed.] McGraw Hill Construction. s.l. : AIA California Council, 13 de June de 2007. [Consulted: 27 January 2014] Available at: <<http://aiacc.org/wp-content/uploads/2010/07/A-Working-Definition-V2-final.pdf>>.
- [3]. **Alexander, Cristopher.** *Notes on the Synthesis of Form.* Berkeley : President and Fellows of Harvard College, 1964.
- [4]. **American Institute of Architects California Council.** *Integrated Project Delivery.* [Online] 2007. A Guide. [Consulted: 14 December 2013] Available at:  
<<http://www.aia.org/aiaucmp/groups/aia/documents/document/aia085539.pdf>>.
- [5]. **Architecture Research Lab.** *Trends in Generative Design.* [Online] s.l. : Architecture Research Lab. [Consulted: 21 November 2013] Available at:  
<<http://www.architectureresearchlab.com/arl/2012/01/04/trends/>>.
- [6]. **Autodesk.** *Autodesk Seek.* [Online] s.l. : Autodesk. [Consulted: 06 February 2014] Available at: <<http://seek.autodesk.com/>>.
- [7]. —. *Building Information Modelling.* [Online] s.l. : Autodesk Building Industry Solutions, 2003. Whitepaper. [Consulted: 25 November 2013] Available at:  
<[http://images.autodesk.com/apac\\_sapac\\_main/files/4525081\\_BIM\\_WP\\_Rev5.pdf](http://images.autodesk.com/apac_sapac_main/files/4525081_BIM_WP_Rev5.pdf)>.
- [8]. **Bergin, Michael S.** *A Brief History of BIM.* [Online] Berkeley, California : Architecture Research Lab, August 21, 2011. [Consulted: 27 October 2013] Available at:  
<<http://www.architectureresearchlab.com/arl/2011/08/21/bim-history/>>.
- [9]. **Bew, Mark.** *BIM Task Group Presentation.* [Online] s.l., U.K. : U.K. Government. [Consulted: 02 January 2014] Available at:  
<<http://www.thinkbim.org/presentations/UK%20Gov%20Perspective%20Leeds%2014-9.pdf>>.
- [10]. **BIM Task Group.** BIM Task Group website. *About.* [Online] [Consulted: 1 December 2013] Available at: <<http://www.bimtaskgroup.org/>>.



- [11]. **Buildig Design +Construction**. *'Augmented reality' comes to the job site*. [Online] s.l. : BDCnetwork. [Consulted: 14 November 2013] Available at: <<http://www.bdcnetwork.com/%E2%80%98augmented-reality%E2%80%99-comes-job-site>>.
- [12]. **BuildingSMART**. *IFC 4 Schema*. [Online] s.l. : BuildingSMART. [Consulted: 1 December 2013] Available at: <<http://www.buildingsmart-tech.org/ifc/IFC4/final/html/index.htm>>.
- [13]. —. *OPEN BIM ExCom Agreed Description*. [Online] 2012. The BIM Evolution Continues with Open BIM. [Consulted: 11 December 2013] Available at: <<http://www.buildingsmart.org/organization/OPEN%20BIM%20ExCom%20Agreed%20Description%2020120131.pdf>>.
- [14]. **CYPE**. *Dynamic Fire Simulation (DFS)*. [Online] s.l. : CYPE. [Consulted: 01 May 2014] Available at: <[http://fds.cype.es/ampliadas/fds\\_02\\_simulacion\\_dinamica\\_incendio.htm](http://fds.cype.es/ampliadas/fds_02_simulacion_dinamica_incendio.htm)>.
- [15]. **Department of Business, Innovation and Skills**. *A report for the government construction client group*. [Online] March de 2011. Building Information Modelling (BIM) Working Party Strategy Paper. [Consulted: 1 December 2013] Available at: <<http://www.bimtaskgroup.org/wp-content/uploads/2012/03/BIS-BIM-strategy-Report.pdf>>.
- [16]. **Dispenza, Kirstin**. *The Daily Life of Building Information Modeling (BIM)*. [Online] s.l. : Buildipedia, 29 de June de 2010. [Consulted: 27 October 2013] Available at: <<http://buildipedia.com/aec-pros/design-news/the-daily-life-of-building-information-modeling-bim?print=1&tmpl=component>>.
- [17]. **Eastman, Charles and Henrion, Max**. *GLIDE: A Language for Design Information Systems*. [Online] s.l. : Institute of Physical Planning, School of Urban and Public Affairs and Department of Architecture; Carnegie-Mellon University. [Consulted: 28 October 2013] Available at: <<http://design.osu.edu/carlson/history/PDFs/eastmanGLIDE.pdf>>.
- [18]. **Eastman, Charles, et. al**. *An Outline of the Building Description System*. [Online] Pittsburg, U.S.A. : Carnegie-Mellon Univ., Pittsburgh, Pa. Inst. of Physical Planning, September de 1974. Research Report no.50. [Consulted: 28 October 2013] Available at: <<http://files.eric.ed.gov/fulltext/ED113833.pdf>>.
- [19]. **Eastman, Chuck, et. al**. *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers, and Contractors*. Second Edition. Hoboken : Wiley: John Wiley & Sons, Inc., 2011. 978-0-470-95134-7.
- [20]. **Engelbart, Doug C**. *Augmenting Human Intellect*. [Online] Menlo Park, California, U.S.A. : Stanford Research Institute, October 1962. A Conceptual Framework. [Consulted: 28 October 2013] Pg. 4-6. Available at: <[http://www.dougenelbart.org/pubs/papers/scanned/Doug\\_Engelbart-AugmentingHumanIntellect.pdf](http://www.dougenelbart.org/pubs/papers/scanned/Doug_Engelbart-AugmentingHumanIntellect.pdf)>.



- [21]. **G. Allen, Steven.** *Why Construction Industry Productivity is Declining*. [Online] Cambridge, U.S.A. : National Bureau of Economic Research, February de 1985. NBER Working Paper Series. [Consulted: 21 December 2013] Available at: <<http://www.nber.org/papers/w1555.pdf>>. Working Paper nº 1555.
- [22]. **Gallaher, Michael P, et. al.** *Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry*. [Online] Maryland : National Institute of Standards and Statistics, 2004. [Consulted: 21 December 2013] Available at: <[http://www.bentleyuser.dk/sites/default/files/nist\\_report.pdf](http://www.bentleyuser.dk/sites/default/files/nist_report.pdf)>.
- [23]. **Graphisoft.** *Why should I switch from CAD to BIM?* [Online] s.l. : ArchiCAD. [Consulted: 01 May 2014] Available at: <[http://www.graphisoft.com/archicad/open\\_bim/about\\_bim/](http://www.graphisoft.com/archicad/open_bim/about_bim/)>.
- [24]. **GSA.** *BIM Guide Overview*. [Online] 2007. GSA BIM Guide Series 01. [Consulted: 11 December 2013] Pg.12 Available at: <[http://www.gsa.gov/graphics/pbs/GSA\\_BIM\\_Guide\\_v0\\_60\\_Series01\\_Overview\\_05\\_14\\_07.pdf](http://www.gsa.gov/graphics/pbs/GSA_BIM_Guide_v0_60_Series01_Overview_05_14_07.pdf)>.
- [25]. **Infraestructures.cat.** *Separata técnica anunci Institut Lluís de Requesens*. [Online] [Consulted: 10 December 2013] Available at: <<https://licitacions.infraestructures.cat/download.php?NTI4Nzg%3D>>. PE+DB INA-12903.
- [26]. **Laiserin, Jerry.** *Comparing Pommès and Naranjas*. [Online] s.l. : The Laiserin Letter, 16 de December de 2002. [Consulted: 25 November 2013] Available at: <<http://www.laiserin.com/features/issue15/feature01.php>>.
- [27]. **Lee, Angela, et. al.** *Developing a vision of nD-enabled construction*. [Online] Salford : University of Salford, 2003. [Consulted: 14 December 2013] Available at: <<http://www.construct-it.org.uk/pages/publications/members/research%20reports/Developing%20a%20Vision%20of%20nD-Enabled%20Construction.pdf>>.
- [28]. **Magazine of the Chartered Institute of Building.** *Adventures in time and space*. [Online] s.l. : Chartered Institute of Building. [Consulted: 01 May 2014] Available at: <<http://www.construction-manager.co.uk/features/adventures-time-and-space/>>.
- [29]. **Mathews, Owen and A. Howell, Gregory.** *Integrated Project Delivery: An Example of Relational Contracting*. [Online] s.l. : Lean Construction Journal Organization, April de 2005. Lean construction Journal, Vol. 2. [Consulted: 27 January 2014] Available at: <[http://www.leanconstruction.org/media/docs/lcj/LCJ\\_05\\_003.pdf](http://www.leanconstruction.org/media/docs/lcj/LCJ_05_003.pdf)>. ISSN: 1555-1369.
- [30]. **Mc Graw Hill Construction.** *The Business Value of BIM in Europe*. [Online] s.l. : SmartMarket Report, 2010. Getting Building Information Modeling to the Bottom Line in the United Kingdom, France and Germany. [Consulted: 3 December 2013] Available at: <[http://bim.construction.com/research/FreeReport/BIM\\_Europe/Business\\_Value\\_of\\_BIM\\_in\\_Europe\\_SMR\\_2010.pdf](http://bim.construction.com/research/FreeReport/BIM_Europe/Business_Value_of_BIM_in_Europe_SMR_2010.pdf)>.

- [31]. —. *The Business Value of BIM in North America*. [Online] s.l. : SmartMarket Report, 2012. Multi-Year Trend Analysis and User Ratings (2007-2012). [Consulted: 3 December 2013] Available at: <[http://download.autodesk.com/us/offercenter/smartmarket2012/SmartMarket\\_2012\\_Prelim.pdf](http://download.autodesk.com/us/offercenter/smartmarket2012/SmartMarket_2012_Prelim.pdf)>.
- [32]. **National BIM Standards**. *Practice document - Minimum BIM*. [Online] s.l., U.S.A. : NBIMS, May de 2012. National BIM Standards - United States Version 2. [Consulted: 2 January 2014] Available at: <[http://www.nationalbimstandard.org/nbims-us-v2/pdf/NBIMS-US2\\_c5.2.pdf](http://www.nationalbimstandard.org/nbims-us-v2/pdf/NBIMS-US2_c5.2.pdf)>; <[www.nationalbimstandard.org/nbims-us-v2/doc/Interactive\\_BIM\\_Capability\\_Maturity\\_Model\\_v\\_2\\_0\\_NBIMS.xls](http://www.nationalbimstandard.org/nbims-us-v2/doc/Interactive_BIM_Capability_Maturity_Model_v_2_0_NBIMS.xls)>.
- [33]. **NBS**. National BIM Library. *National BIM Library webpage*. [Online] [Consulted: 15 November 2013] Available at: <<http://www.nationalbimlibrary.com/>>.
- [34]. —. *National BIM Report 2013*. [Online] s.l., UK : RIBA Enterprises Ltd., 2013. [Consulted: 3 December 2013] Available at: <<http://www.thenbs.com/pdfs/NBS-NationalBIMReport2013-single.pdf>>.
- [35]. **Nemetschek AG**. Nemetschek History. *Nemetschek webpage*. [Online] [Consulted: 12 November 2013] Available at: <[http://www.nemetschek.com/en/home/the\\_company/history/nemetschek\\_ag.html](http://www.nemetschek.com/en/home/the_company/history/nemetschek_ag.html)>.
- [36]. **Nemetschek Allplan Deutschland GmbH**. Allplan History. *Nemetschek Allplan webpage*. [Online] [Consulted: 12 November 2013] Available at: <<http://www.nemetschek-allplan.eu/more/company/history.html>>.
- [37]. **Project cartoon**. *Project management*. [Online] [Consulted: 1 December 2013] Available at: <<http://www.projectcartoon.com/cartoon/2>>.
- [38]. **Silva, Victor**. *Evolution, Methodologies & Concepts of CAD & BIM Software tools in the AEC Industry*. [Online] s.l. : ArchiMAG, December de 2012. [Consulted: 21 November 2013] Available at: <<http://www.slideshare.net/v5ilva/archimagbimevolutionbyvictorsilva>>.
- [39]. **Succar, Bilal**. *Building information modelling framework: A research and delivery foundation for industry stakeholders*. [Online] Newcastle, Australia : Elsevier B.V., Automation in Construction num. 18 pg.357-375, 2008. [Consulted: 14 December 2013] Available at: <<http://www.sciencedirect.com/science/article/pii/S0926580508001568>>.
- [40]. —. *Building Information Modelling Maturity Matrix*. [Online] s.l., Australia : Change Agents AEC, November de 2009. Handbook of Research on Building Information Modeling and Construction Informatics: Concepts and Technologies. [Consulted: 02 January 2014] Available at: <[http://www.academia.edu/186259/Building\\_Information\\_Modelling\\_Maturity\\_Matrix](http://www.academia.edu/186259/Building_Information_Modelling_Maturity_Matrix)>.
- [41]. **Teicholz, Paul, Goodrum, Paul M. y Haas, Carl T**. *U.S. Construction Labor Productivity Trends, 1970-1998*. [Online] Berkeley : Stanford University, 2001. [Consulted: 21 December 2013] Available at: <<http://ascelibrary.org/doi/abs/10.1061/%28ASCE%290733-9364%282001%29127%3A5%28427%29>>.

- [42]. **Tekla.** History. *Tekla webpage*. [Online] [Consulted: 12 November 2013] Available at: <<http://www.tekla.com/company/about>>.
- [43]. —. Tekla Structures BIM Software. *Tekla webpage*. [Online] [Consulted: 12 November 2013] Available at: <<http://www.tekla.com/products/tekla-structures>>.
- [44]. **UK HM Government.** *Building Information Modelling*. [Online] 2012. Industrial strategy: government and industry partnership. [Consulted: 1 December 2013] Pg. 2. Available at: <[https://www.gov.uk/government/uploads/system/uploads/attachment\\_data/file/34710/12-1327-building-information-modelling.pdf](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/34710/12-1327-building-information-modelling.pdf)>.
- [45]. **Wikipedia.** *AutoCAD*. [Online] [Consulted: 28 October 2013] Available at: <[http://en.wikipedia.org/wiki/Auto\\_CAD](http://en.wikipedia.org/wiki/Auto_CAD)>.
- [46]. —. *Autodesk Revit*. [Online] [Consulted: 12 November 2013] Available at: <<http://en.wikipedia.org/wiki/Revit>>.
- [47]. —. *Autodesk*. [Online] [Consulted: 14 November 2013] Available at: <<http://en.wikipedia.org/wiki/Autodesk>>.
- [48]. —. *Boolean data type*. [Online] [Consulted: 3 November 2013] Available at: <[http://en.wikipedia.org/wiki/Boolean\\_data\\_type](http://en.wikipedia.org/wiki/Boolean_data_type)>.
- [49]. —. *Boundary representation*. [Online] [Consulted: 3 November 2013] Available at: <[http://en.wikipedia.org/wiki/Boundary\\_representation](http://en.wikipedia.org/wiki/Boundary_representation)>.
- [50]. —. *Building information modeling*. [Online] [Consulted: 20 October 2013] Available at: <[http://en.wikipedia.org/wiki/Building\\_information\\_modeling](http://en.wikipedia.org/wiki/Building_information_modeling)>.
- [51]. —. *BuildingSMART*. [Online] [Consulted: 1 December 2013] Available at: <<http://en.wikipedia.org/wiki/BuildingSMART>>.
- [52]. —. *COBie*. [Online] [Consulted: 28 January 2014] Available at: <<http://en.wikipedia.org/wiki/COBie>>.
- [53]. —. *Computer-aided Design*. [Online] [Consulted: 28 October 2013] Available at: <[http://en.wikipedia.org/wiki/Computer-aided\\_design](http://en.wikipedia.org/wiki/Computer-aided_design)>.
- [54]. —. *Constructive solid geometry*. [Online] [Consulted: 3 November 2013] Available at: <[http://en.wikipedia.org/wiki/Constructive\\_solid\\_geometry](http://en.wikipedia.org/wiki/Constructive_solid_geometry)>.
- [55]. —. *Graphisoft BIM Server*. [Online] [Consulted: 15 November 2013] Available at: <[http://en.wikipedia.org/wiki/Graphisoft\\_BIM\\_Server](http://en.wikipedia.org/wiki/Graphisoft_BIM_Server)>.
- [56]. —. *Industry Foundation Classes*. [Online] [Consulted: 13 November 2013] Available at: <[http://en.wikipedia.org/wiki/Industry\\_Foundation\\_Classes](http://en.wikipedia.org/wiki/Industry_Foundation_Classes)>.
- [57]. —. *Integrated Project Delivery*. [Online] [Consulted: 13 November 2013] Available at: <[http://en.wikipedia.org/wiki/Integrated\\_Project\\_Delivery](http://en.wikipedia.org/wiki/Integrated_Project_Delivery)>.

- [58]. —. *Lean Construction*. [Online] [Consulted: 23 December 2013] Available at: <[http://en.wikipedia.org/wiki/Lean\\_construction](http://en.wikipedia.org/wiki/Lean_construction)>.
- [59]. —. *Nemetscheck*. [Online] [Consulted: 12 November 2013] Available at: <[http://en.wikipedia.org/wiki/Boolean\\_data\\_type](http://en.wikipedia.org/wiki/Boolean_data_type)>.
- [60]. —. *NLS (Computer System)*. [Online] [Consulted: 28 October 2013] Available at: <[http://en.wikipedia.org/wiki/NLS\\_%28computer\\_system%29](http://en.wikipedia.org/wiki/NLS_%28computer_system%29)>.
- [61]. —. *Sketchpad*. [Online] [Consulted: 28 October 2013] Available at: <<http://en.wikipedia.org/wiki/Sketchpad>>.
- [62]. —. *Tekla Structures*. [Online] [Consulted: 12 November 2013] Available at: <[http://es.wikipedia.org/wiki/Tekla\\_Structures](http://es.wikipedia.org/wiki/Tekla_Structures)>.
- [63]. **Withfriendship**. *Building Information Modelling Pictures*. [Online] [Consulted: 20 November 2013] Available at: <<http://withfriendship.com/user/levis/building-information-modeling.php>>.
- [64]. **Yares, Evan**. *50 years of CAD*. [Online] s.l. : Design World, 13 de February de 2013. [Consulted: 1 November 2013] Available at: <<http://www.designworldonline.com/50-years-of-cad/>>.
- [65]. **Canal, Josep Farré i**. *RE: Implementació de la tecnologia BIM en l'àmbit de l'enginyeria civil i l'edificació*. [Online] 23 de October de 2013. Message for: Xavier Echegaray. [consulted: 4 December 2013] Personal Communication.