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Understanding the context for the implementation of Building
Information Modelling in engineer-to-order prefabricated building
systems

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**UNDERSTANDING THE CONTEXT FOR THE
IMPLEMENTATION OF BUILDING INFORMATION
MODELLING IN ENGINEER-TO-ORDER PREFABRICATED
BUILDING SYSTEMS**

Dissertation presented to the Graduate Program in Civil Engineering of
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Dissertation submitted in partial fulfilment of the requirements for the degree of Master of Engineering awarded by the Graduate Program in Civil Engineering (Concentration Area: Building Construction) of the Federal University of Rio Grande do Sul

Porto Alegre, 30th March 2016

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ABSTRACT

SHIGAKI, J.S. **Understanding the context for the implementation of Building Information Modelling in engineer-to-order prefabricated building systems.** 2016. Dissertation (Master of Engineering) – Graduate Program in Civil Engineering, UFRGS, Porto Alegre.

Coordination challenges caused by the lack of integration between design, production and assembly in companies that deliver engineer-to-order (ETO) prefabricated building systems have resulted in the growing adoption of information technologies. Although Building Information Modelling (BIM) tools have been used in the construction industry for several years, many firms have not been able to fully implement them and take advantages of BIM integrated workflows. By contrast, robust technology infrastructures developed in the manufacturing sector, such as those employed in Product Lifecycle Management (PLM), represent new opportunities to establish better connections between digital tools which are necessary for the development of sophisticated engineering products, and planning and controlling production systems in complex environments, such as ETO prefabricated building systems. The aim of this investigation is to understand the context of BIM implementation in this type of firm. Design Science Research was the methodological approach adopted in this investigation. A set of empirical studies were conducted in a Steel Fabricator company from Brazil. Those studies enabled the identification of challenges at project and organizational level by showing that product information contained in BIM models could be reused downstream in the value chain for different purposes, such as engineering analysis, clash detection, simulation of logistics and assembly operations. Therefore, integrated solutions should be co-developed by team members from different functional departments. This would be the first step for the transition from the current utilization of BIM functions towards the envisioned BIM-PLM environment. A roadmap and a set of guidelines for implementation, grounded on Socio-Technical Systems and Technology Roadmapping approaches, have been proposed to support the creation of a vision for technology management. In order to do so, this investigation provides the settings to understand the implementation context and critical factors related to the adoption of integrated digital technologies.

Keywords: BIM; Implementation; Engineer-to-order; Prefabrication.

RESUMO

SHIGAKI, J.S. **Compreensão do contexto para implementação de Building Information Modelling em sistemas de edificação pré-fabricados engineer-to-order.** 2016. Dissertação de Mestrado – Programa de Pós-Graduação em Engenharia Civil, UFRGS, Porto Alegre.

Desafios em coordenação causados pela falta de integração entre projeto, produção e montagem em empresas que entregam sistemas de edificações pré-fabricados do tipo engineer-to-order (ETO) têm levado a um aumento na adoção de tecnologias de informação. Embora as ferramentas de Building Information Modelling (BIM) têm sido utilizadas há vários anos, muitas empresas ainda não puderam implementar integralmente e tampouco perceber as vantagens de fluxos de trabalho integrado por BIM. Por outro lado, infraestruturas robustas de tecnologia desenvolvidas no setor da manufatura, a exemplo das empregadas em Product Lifecycle Management (PLM), representam novas oportunidades para estabelecer melhores conexões entre as ferramentas necessárias para o desenvolvimento de produtos de engenharia sofisticada e para o planejamento e controle de sistemas de produção em ambientes complexos. O objetivo dessa pesquisa é entender o contexto de implementação de BIM nessas empresas. Design Science Research foi a abordagem metodológica adotada nesta pesquisa. Um conjunto de estudos empíricos foram conduzidos em uma empresa de estruturas metálicas do Brasil. Esses estudos permitiram identificar desafios a nível de projeto e da organização, mostrando que informações do produto contidos nos modelos BIM poderiam ser reutilizadas a jusante da cadeia de valor para diversas finalidades, tais como análise de engenharia, detecção de conflitos, e simulações de produção e de operações logísticas. Portanto, soluções integradas devem ser co-desenvolvidas por membros de equipes de diferentes departamentos funcionais. Esse poderia ser o primeiro passo para a transição da atual utilização de funções BIM para o visionado ambiente BIM-PLM. O roteiro e as diretrizes de implementação – fundamentadas nas abordagens de Sistemas Sociotécnicos e Technology Roadmapping – foram propostas para apoiar a criação de uma visão para a gestão de tecnologia. Para tanto, esta investigação fornece as configurações para entender o contexto de implementação e apresenta fatores críticos relacionados à adoção de tecnologias digitais integradas.

Palavras-chave: BIM; Implementação; Engineer-to-order; Pré-fabricação.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS	5
ABSTRACT	6
RESUMO	7
TABLE OF CONTENTS	8
LIST OF FIGURES	12
LIST OF ABBREVIATIONS	14
1 INTRODUCTION.....	17
1.1 Background	17
1.2 Motivation and practical problem.....	21
1.3 Research problem	23
1.4 Research questions.....	26
1.5 Research objectives.....	26
1.6 Limitations	27
1.7 Overview of the research method.....	28
1.8 Structure of this document	28
2 DESIGN AND PRODUCTION INTEGRATION IN ETO SYSTEMS.....	30
2.1 Engineer-to-order production systems.....	30
2.1.1 Characterization of engineer-to-order production systems.....	30
2.1.2 Engineer-to-order in prefabricated building products	31
2.1.3 Vertical integration of the engineer-to-order supply chain.....	33
2.1.4 Discussion	33
2.2 Issues in design and production process integration.....	34
2.2.1 Fragmented nature in construction and integration concepts.....	35
2.2.2 Critical stages interfacing design and production.....	36
2.2.3 Information technologies supporting collaborative initiatives.....	37
2.2.4 Discussion	38

3	BUILDING LIFECYCLE MANAGEMENT: BIM AND PLM	40
3.1	Role of BIM in design and construction	40
3.1.1	Overview of CAD and BIM evolution.....	40
3.1.2	Interoperability and standardization	42
3.1.3	BIM for prefabricated structural systems.....	44
3.1.4	Information management and BIM implementation	46
3.1.5	Discussion	48
3.2	Process streamlining and integrated delivery	48
3.2.1	Business process reform in implementation.....	48
3.2.2	Contracts, standards and specifications for BIM projects.....	50
3.2.3	Discussion	52
3.3	Trends and challenges for PLM in construction.....	52
3.3.1	General concepts of PLM in manufacturing industry.....	53
3.3.2	BIM as an enabler for lifecycle management in construction.....	54
3.3.3	Working changes in PLM-based design and production	55
3.3.4	Discussion	56
4	ENTERPRISE CONTEXT FOR VISION AND IMPLEMENTATION.....	58
4.1	Context and vision creation process	58
4.2	Socio-Technical System approach.....	60
4.3	Technology Roadmapping approach	61
4.4	Discussion	63
5	RESEARCH METHOD	65
5.1	Design Science Research	65
5.1.1	Definition and characterization	65
5.1.2	Distinction of design science research to action research.....	67
5.1.3	Mission of the design science research.....	68
5.2	Research design	68
5.3	Description of the company	70

5.4	Research process.....	72
5.4.1	Empirical studies and literature review.....	72
5.4.2	Sources of evidence	76
5.4.3	Limitations concerning the empirical studies.....	79
5.5	Outcomes of this investigation	79
6	EMPIRICAL STUDIES: DEVELOPMENT AND RESULTS.....	81
6.1	Project flow and supporting technologies.....	81
6.1.1	Departments and project phases	82
6.1.2	Use of digital technologies.....	83
6.2	Exploratory study: impact of design issues in fabrication and site work.....	85
6.3	Working process and information management.....	89
6.3.1	Product development process.....	89
6.3.2	Use of BIM before this investigation.....	92
6.3.3	Internal data exchange and interoperability	93
6.4	Implementation in empirical studies.....	96
6.4.1	Study of simulation of assembly schedules in early stages	96
6.4.2	Merge of architectural-structural models for visualization and coordination... 98	
6.4.3	Study of erection schedules and logistics planning using BIM.....	102
6.4.4	Study of product development flow enhancement through BIM.....	107
6.5	Summary of findings in empirical studies	127
7	BIM IMPLEMENTATION STRATEGY FOR ETO FABRICATORS.....	131
7.1	Roadmapping approach to devise a vision.....	131
7.2	Guidelines to shift from vision to implementation.....	136
7.2.1	Preparatory stage	138
7.2.2	Development of the viewpoints.....	141
7.2.3	Prioritization, implementation and feedback	147
7.3	Impacts of digital integration strategies	149
7.3.1	Impacts at project level	149

7.3.2	Impacts at organizational level.....	151
7.3.3	Impacts on the long-term vision.....	153
7.3.4	Discussion	155
8	CONCLUSIONS.....	160
8.1	Critical reflection about the research outcomes	161
8.2	Contributions to practice and knowledge.....	164
8.3	Suggestions for further research	167
	REFERENCES.....	169

LIST OF FIGURES

Figure 1: Research design	70
Figure 2: Prior NORIE research studies developed within this company	73
Figure 3: Types of review	74
Figure 4: List of empirical studies	75
Figure 5: Source of data in each study	77
Figure 6: Business units of the steel fabricator company	81
Figure 7: Generic process of the steel fabricator	82
Figure 8: Departments assisting multiple projects.....	82
Figure 9: Main departments involved directly in the research	83
Figure 10: Set of digital technologies currently used by the company.....	84
Figure 11: Fabrication drawing for new and highly customized ETO component	86
Figure 12: Conventional detailing drawings for standardized components.....	87
Figure 13: BIM clash detection used for clearance assurance	88
Figure 14: Integration efforts in industrial facilities vs multi-storey generic process.....	91
Figure 15: IFC export test from SDS/2.....	94
Figure 16: IFC export-import test with SDS/2 file.....	95
Figure 17: Generic set of technologies used in processes of the company.....	96
Figure 18: Screenshots of a 4D simulation of the assembly master plan	97
Figure 19: Architectural model and structural model – separate files.....	99
Figure 20: IFC optimization procedure of large files	99
Figure 21: Merged model navigation and visualization.....	100
Figure 22: Clash detection: architectural wall vs bracing and concrete wall vs steel beam .	101
Figure 23: Default model based on fabrication batches (left) vs adjusted to erection (right)	103
Figure 24: Screenshots of a 4D simulation of an erection master plan.....	105
Figure 25: Complementary model of the external inventory area.....	106
Figure 26: Simulation of skid rearrangement on the auxiliary yard using 4D BIM.....	106
Figure 27: Use of multiple applications along the project process (as proposed).....	108
Figure 28: Structural analysis in CAE tool	111
Figure 29: Conversion of structural analytical model to parametric model.....	111
Figure 30: Approval design model checking	112

Figure 31: Report sample of structural validation using default structural rule checking....	113
Figure 32: Clash detection in approval design model for tolerance checking purposes.....	114
Figure 33: Check and management of acceptable design detailing incompleteness	114
Figure 34: Level of Development (LOD) corresponding to delivery stage	115
Figure 35: Proposition of reference values for LOD in the design of multi-storey typology	115
Figure 36: Product Structure/Bill of Materials of a small batch (sub-stage) in ERP system	116
Figure 37: Input for an outline 4D: erection schedule (left) and 3D structural model (right)	118
Figure 38: Master plan 4D simulation	118
Figure 39: CNC fabrication file (left) and a 2D non-scale assembly diagram (right).....	120
Figure 40: Tracking and matching of sub-components with mobile visualization	120
Figure 41: 3D visualisation of the model in pdf format.....	122
Figure 42: Example of a pre-load skids and a load plan design (courtesy of Viana, 2015) .	123
Figure 43: 3D load plan model (left) and actual random load (right).....	124
Figure 44: Load plan design – layer display using 3D modelling (as proposed)	124
Figure 45: Mobile visualization of the detailed 3D model.....	125
Figure 46: Instantaneous comparison of as-modelled and as-built	126
Figure 47: Envisioned states for the selected viewpoints	133
Figure 48: Vision for prefabricated steel structure enterprises	134
Figure 49: Steps of the roadmap deployment process	137
Figure 50: Prioritization of the stages	148
Figure 51: Perceived BIM capability maturity level after the research intervention	150
Figure 52: Scheme for BIM-ERP link through web service	152
Figure 53: Scheme of a BIM-ERP-PLM integrated system.....	153
Figure 54: Conceptualization of a computer-integrated system for design and production .	154

LIST OF ABBREVIATIONS

AI – Artificial Intelligence
AIA – American Institute of Architects
AISC – American Institute of Steel Construction
ATO – Assembly-to-order
BCF – BIM Collaboration Format
BIM – Building Information Modelling
BOM – Bill of Materials
BPMN – Business Process Modelling Notation
BSI – British Standard Institute
CAD – Computer Aided Design
CAE – Computer Aided Engineering
CAFM – Computer Aided Facilities Management
CAM – Computer Aided Manufacturing
CAPEX – Capital Expenditure
CIC – Construction Industry Council (UK)
CIC – Computer Integrated Construction/Penn State University
CIM – Computer Integrated Manufacturing
CIOB – Chartered Institute of Building
CIS/2 – CIMSteel Integration Standard 2
CNC – Computer Numerical Control
COBIE – Construction Operations Building information exchange
CODP – Customer Order Decoupling Point
CPC – Complex Project Contract
DFX – Design for X-ability
DXF – Drawing Exchange Format
DSR – Design Science Research
EDM – Engineering Data Model/Management
EPC – Engineering, Procurement and Construction
ERP – Enterprise Resource Planning
ETO – Engineer-to-order
FTO – Fabricate-to-order

GBXML – green building XML
IAI – International Alliance for Interoperability
I-CMM – Interactive-Capability Maturity Model
IDEF0 – Icam DEFinition for Function Modelling
IDM – Information Delivery Manuals
IFC – Industry Foundation Classes
IFD – International Framework for Dictionaries
IGES – Initial Graphics Exchange Specification
IOT – Internet of Things
IPD – Integrated Project Delivery
IT – Information Technology
JCT – Joint Contracts Tribunal
LOB – Line of Balance
LOD – Level of Development
LPS – Last Planner System
MRP – Material Requirement Planning
MRPII – Manufacturing Resource Planning
MTO – Make-to-order
MTS – Make-to-stock
MVD – Model View Definition
NBIMS – National BIM Standard (US)
NC1 – Numerical Control File
NEC3 – New Engineering Contract 3
NORIE – Núcleo Orientado para Inovação da Edificação
OPEX – Operational Expenditure
PDES – Product Data Exchange Specification
PDP – Product Development Process
PDM – Product Data Management
PEP – Project Execution Plan
PLM – Product Lifecycle Management
PPC – Production Planning and Control
PSD – Production System Design
PSM – Product Structure Management
QR – Quick Response code
RIBA – Royal Institute of British Architects

RICS – Royal Institute of Chartered Surveyors
RFI – Request for Information
RFID – Radio-frequency identification
ROI – Return of Investment
SDNF – Structural steel Detailing Neutral Format
STEP – STandard of Exchange Product data
STS – Socio-technical system
TRM – Technology Roadmapping
UPC – Universal Product Code
VDC – Virtual Design and Construction
VP – Virtual Prototyping
UFRGS – Universidade Federal do Rio Grande do Sul
XML – eXtensible Markup Language
WBS – Working Breakdown Structure

1 INTRODUCTION

This chapter presents: (a) the background and fundamental aspects related to the scope of this study; (b) the motivation and practical problem that was the starting point for this investigation; (c) the research problem; (d) the research questions; (e) the research objectives; (f) an overview of the research method; and, finally, (g) a description of the structure of this document.

1.1 BACKGROUND

The construction industry has some peculiarities that represent major challenges when compared to traditional manufacturing. According to Vrijhoef and Koskela (2005), such peculiarities are influenced by the characteristics of the product, ways of production and the industry itself. At the production level, the three main peculiarities are: (a) site production; (b) one-of-a-kind production; and (c) temporary organization, and these are interlinked by causal relationships to both product and industry levels (VRIJHOEF; KOSKELA, 2005).

It is often believed that advances in construction can be related to the mitigation of these peculiarities by means, for instance, of industrialization (SEGERSTEDT; OLOFSSON, 2010). Vrijhoef and Koskela (2005) highlight solutions such as modular design, pre-engineering and off-site production to reduce the impacts of these peculiarities. In turn, prefabricated building systems are positioned at the intersection of manufacturing and construction (BALLARD; ARBULU, 2004). Therefore, building systems fabricators can take advantage of experiences from other advanced industries in terms of management and use of technologies.

Another typical characteristic of construction projects is the strong separation between design and production activities, influenced by the characteristics of the product itself and ways of transaction. The design phase has traditionally been treated as a separate activity to the construction phase, so that teams work towards individually defined objectives that are often in conflict with one another (BAIDEN; PRICE; DAINTY, 2006). Regarding the long project delivery times, a major reason for not addressing their causes earlier is because stakeholders are not aware of the delivery process as a whole; thus, they lack a systemic view of the process (ELFVING; TOMMELEIN; BALLARD, 2004). The lack of coordination between the

different disciplines involved in various stages of the construction process has been pointed as a leading contributory factor to poor project performance (FANIRAN *et al.*, 2001).

In this regard, Jørgensen and Emmitt (2009) point out four inter-related aspects to be considered in pursuing design and production integration: (a) vertical and horizontal integration in the construction supply; (b) integration of information systems for product and process, which is approached through a strong information technology (IT) orientation; (c) integration of working practices and collaborative processes in the construction project organization; and (d) constructability, which is approached from the perspective of specific practical advices for producing constructible designs.

Alternatively to the cross-organizational temporary teams, some engineering and construction firms have combined different disciplines and expertise under the configuration of vertically integrated organizations (HOOVER, 2013). In manufacturing, vertical integration has been adopted with the intent of facilitating companies to achieve control over the process by merging business in different production stages. Likewise, in construction, Akel, Tommelein and Boyers (2004) recognize that a vertically-integrated structure creates unique opportunities to improve practices in the supply chain through smooth information and material flows. Firms of the prefabrication sector have incorporated this vertical structure as companies that design, fabricate and assemble their products.

Taxonomies of production situations have been proposed with the aim of describing sets of generic operations (TOMMELEIN; BALLARD; KAMINSKY, 2009; WORTMANN, 1992). According to Vrijhoef and Koskela (2005), most of production systems in construction can be characterized as engineer-to-order (ETO) or assembly-to-order (ATO). This study focuses on ETO systems, in which “individual products are generally highly customised to meet individual customer requirements and are produced in low volume (HICKS; MCGOVERN; EARL, 2000)”. In ETO systems, the Customer Order Decoupling Point (CODP), defined as “the point in the material flow from where customer-order driven activities take place (WORTMANN, 1992)”, is located in the design phase.

Due to the unique aspects of ETO, required information for developing products are not always promptly available. Difficulties in managing information and the lack of integration between functional departments lead to a range of waste throughout the delivery process (FORSMAN

et al., 2012). Elfving, Tommelein and Ballard (2004) report problems of waste implying in increased cost due to additional design iteration, change orders and add-ons.

A decision made for one sub-system can have a major influence on the design or assembly processes of other sub-systems due to the strong interdependences between them (JØRGENSEN; EMMITT, 2009). In other words, information generated upstream is critical to planning and execution of downstream activities. Furthermore, deficient supply chain coordination and poor information exchange may cause high amounts of Request for Information (RFI), quality shortcomings (implying in rework), and delays in schedule.

Efforts to integrate sources of project data have focused on using IT to improve the information flow. Some of the intended benefits are: reducing errors; increasing data integrity; and improving communication, coordination and product quality (FANIRAN *et al.*, 2001). Lehtinen (2010) discusses the idea of digital vertical integration meaning that inter-organizational IT systems could enable separate organizations to collaborate in a similar way as internal business units do in a vertically integrated firm.

Manufacturers have adopted Material Requirement Planning (MRP) and Manufacturing Resource Planning (MRP II) for production management (BERTRAND; MUNTSLAG, 1993; WORTMANN, 1992). However, their use still struggle to respond to the characteristics of ETO situations such as the important role of the customer order, the customer-specific product specifications, and the product and production uncertainty (BERTRAND; MUNTSLAG, 1993). More recently, Enterprise Resource Planning (ERP) systems have been adopted with a wider scope and supported by a comprehensive range of functionalities. Nevertheless, their implementation in a stand-alone way remains insufficiently effective.

In the last decades, the concept of Building Information Modelling (BIM) has become a recurrent topic in construction. BIM is defined as “a set of interacting policies, processes and technologies generating a methodology to manage the essential building design and project data in digital format throughout the building's lifecycle (SUCCAR, 2009)”. Eastman *et al.* (2011) state that ETO fabricators are possibly one of the major beneficiaries of using BIM in the construction process. By nature, ETO components demand sophisticated engineering and collaboration to achieve proper interface between systems.

According to Čuš-Babič *et al.* (2014), BIM provides an adequate context for making essential information available throughout project development. The integration of design,

manufacturing and construction phases and the increased transparency across these processes can benefit the entire supply chain. Sacks, Radosavljevic and Barak (2010) suggest that BIM can provide a powerful platform for better understanding the flow of work in control systems that also enables deeper collaboration between teams on-site and off-site.

However, Faniran *et al.* (2001) report that the benefits of IT have not been forthcoming since deficient applications are a result of a deficient understanding of the specific construction problem being addressed. In addition, Hartmann *et al.* (2012) advocate the potential of aligning functionalities of BIM tools with specific and well-established management work process. Thereby, it is possible to adopt a BIM-based approach in a “technology pull” manner (aligning BIM-based tools with current work practices), as opposed to widespread “technology push” implementation of software packages, which requires radical changes in the existing process (HARTMANN *et al.*, 2012).

At the industry level, several roadmaps from the public sector, industry organizations and academic institutions display visions concerning the utilization of technologies (highly focused on BIM at present time) to support continuous improvements in project performance (e.g. BSI B/555¹; FIATECH’ Capital Projects Technology Roadmap²). Some of these visions have hypothesized an evolution towards Product Lifecycle Management (PLM), which has been more discussed in other industries, and refers to “a concept for the integrated management of product related information through the entire product lifecycle (SCHUH *et al.*, 2008)” enabled by advances in IT and resulting from the integration between several systems such as CAD/CAM, ERP and PDM to provide robust platforms. In the construction sector, PLM can hereafter contribute in managing lifecycle information of building assets, figured as an advanced BIM situation (e.g. the BLM stage, reported in the Dassault Systèmes White paper³).

In summary, there is a gap in understanding the context and the challenges related to the implementation of BIM (extensible to additional IT modules and platforms) for providing systemic improvements of product and process information management, especially for those companies developing ETO prefabricated building systems. In addition, there is a lack of guidelines for supporting enterprises to prepare the ground to promote such strategic reforms.

¹BSI B/555 Roadmap (June 2013 Update)

²FIATECH Roadmap Initiative

³Dassault Systèmes - End-to-end collaboration enabled by BIM level 3

1.2 MOTIVATION AND PRACTICAL PROBLEM

In this research study, the empirical studies were conducted within a leading Steel Fabricator company in Brazil which delivers steel structural systems for the construction sector. This company has had a partnership with the Building Innovation Research Unit (NORIE) of the Federal University of Rio Grande do Sul (UFRGS) for jointly developing research projects, predominantly related to the implementation of Lean Production. Most of the company's operations can be considered as engineer-to-order (ETO), providing customized solutions according to client's requirements. The scope of contracts typically covers phases, such as sales, cost estimation, planning, conceptual design, design detailing, bill-of-materials, manufacturing, logistics and site assembly.

At the beginning of this research study – in the first contacts with the technical staff of the company – the research scope was defined as the “use of BIM as a supporting tool for production management”, to be a continuation of another research study under development, which was concerned with capital industrial projects. However, after a few interviews, it was identified an opportunity to work in another type of business unit, involved in the delivery of steel structures for multi-storey buildings. Multi-story building project teams had already used BIM in design and engineering phases (although limited in scope and maturity), in contrast to the traditional CAD processes employed in other business units. Besides, this company was committed with the implementation of a Product Lifecycle Management (PLM) system, whose strategic goals were considered in this investigation.

A critical issue was the lack of integration among teams of different functional departments and the coordination of information flow along the project life. Previous studies carried out in the same company suggested as further topics for research: (a) ways to integrate production planning and control processes with design, fabrication and assembly processes (FABRO, 2012); and (b) mechanisms for integrated design planning and control with other product development processes (WESZ, 2013). Partial results of ongoing studies also identified issues related to logistics management and production system design, which required stronger collaboration across the whole value chain (BORTOLINI, 2015; VIANA, 2015). As a result, additional efforts have been put to align manufacturing-logistics-assembly teams with the aim of developing more integrated solutions.

In the initial exploratory studies, some problems were identified: (a) deficient information exchange; (b) poor understanding of documents and digital files; and (c) ineffective interactions and lack of collaboration between teams. These issues were critical because teams needed sets of project information produced at other departments to accomplish their tasks. For example, detailing information (drawings and specifications delivered by the design team) was forwarded to plant scheduling and site assembly teams in different file standards and timing.

Findings from these exploratory studies indicated that: (a) some mistakes in manufacturing or site assembly had their origin in the design phase caused by design errors, unclear representation, or lack of required content; (b) some requirements of the assembly process were not known by designers or planners, so that relevant information were not available on time or as-requested; (c) challenges on how people and software interact related to the levels of abstraction, and indirectly, to training and technical skills; and finally, (d) tacit knowledge was unmanaged, and levels of capabilities to address similar problems varied considerably.

The company has allocated large amounts of capital investment in IT. For almost two years, an Enterprise Resource Planning (ERP) system had been implemented. One of the business units (multi-storey) was progressing in the use of BIM for design in integration with Computer-Aided Engineering (CAE) applications, for developing scheme design (discipline system level) and detailing design of the steel structure, as well to generate technical documentation and fabrication data to Computer-Aided Manufacturing (CAM) supported machines. Attempts to explore the use of 4D BIM simulation to support site logistics were under development and carried out in partnership with NORIE (BORTOLINI, 2015). In parallel, a PLM project was underway in co-development with an external vendor. Project leaders expected to improve knowledge management capabilities and to reduce project lead time, by systematically reusing information and pre-set design configurations of PLM modules.

Due to these initiatives, human resources of the company were re-allocated to build multidisciplinary teams to develop and implement those systems. This study focuses on the context of implementation at organizational level. Although BIM plays an important role in transforming the whole industry, this investigation is set up from the perspective of firms that deliver prefabricated building systems. It highlights practical issues found in design and production processes and suggests strategic changes to prepare the ground for the implementation of upcoming technologies capable to bring benefits to the entire enterprise management system.

1.3 RESEARCH PROBLEM

The practical problem discussed above is similar and applicable to a range of organizations – not limited to steel fabricators, but also other companies that deliver ETO prefabricated building systems. Those firms could benefit from a wider industry-level of awareness to establish strategic plans aiming to improve project performance through technologies aligned with their business needs. However, despite of new technology trends, how these systems can be effectively employed to improve business process at organizational level is yet unclear.

What is the problem?

Design and construction integration issues have been reported under different perspectives including: product quality and process productivity; working practices and collaboration; supply chain integration; and IT integration (FANIRAN *et al.*, 2001; JØRGENSEN; EMMITT, 2009; KESTLE; POTANGAROA; STOREY, 2011; LI *et al.*, 2008; LING *et al.*, 2014). Prefabrication has driven innovation shifts to promote design and production integration at both horizontal and vertical integration with support of computer-aided technologies (ELFVING; TOMMELEIN; BALLARD, 2004; JØRGENSEN; EMMITT, 2009). In this regard, fabricators have used information model based technologies (such as BIM) as part of their core business strategy (EASTMAN *et al.*, 2011; PENTTILÄ, 2006).

Nevertheless, the lack of appropriate information sharing mechanisms is leading to poor decision-making (LING *et al.*, 2014). The industry is possibly hindering the ability to deliver value because of inefficiencies in cross-phase knowledge sharing, and subsequent lack of feedback loop for nurturing a culture that shares learning outcomes to mutually improve performance (HENDERSON; RUIKAR; DAINTY, 2013). This losses are potentialized as a significant amount of tacit knowledge is generated in every project and not reused across future projects or engagements.

Several authors suggest technology as a powerful enabler to address interface issues between design and construction (FANIRAN *et al.*, 2001; KARTAM, 1999; LI *et al.*, 2008). Others approach this problem from process and policy perspectives, focusing in collaboration together with contractual changes (HENDERSON; RUIKAR; DAINTY, 2013; LING *et al.*, 2014). In addition, the need to improve BIM maturity levels and to develop competencies is also mentioned (SUCCAR; SHER; WILLIAMS, 2013).

However, there are only few examples of studies dedicated to the ETO prefabrication environment (e.g. FORSMAN *et al.*, 2012; ELFVING; TOMMELEIN; BALLARD, 2004); and although they mention the role of BIM and other technologies to support the management of ETO operations, they do not directly address recommendations to the challenges of implementation and subsequent transformations within the enterprise.

Looking at the evolution of IT, managers and technology developers have figured to possible BIM-PLM connections, enabling the reach of advantages from concepts and functionalities of both (ARAM; EASTMAN, 2013; JUPP; NEPAL, 2014). Despite of gradual improvements, applying PLM functions in BIM-based enterprise systems remains complex to manage. Since it has been indicated as a trend, there is a need to develop strategies capable to guide organizations in preparing the ground for such change.

What is on the way?

The industry is gradually acknowledging the impact of collaborative strategies and IT to bridge design and production (BAIDEN; PRICE; DAINTY, 2006; MITCHELL *et al.*, 2011). Due to the inherent characteristics of ETO operations, managers have put more effort to integrate lifecycle phases, internal teams (functional departments) and external teams (temporary project teams) to streamline the flows of goods and information between off-site manufacturing and site construction.

Diversified technology platforms used across building component's planning, design, manufacturing, logistics and assembly demand ever more complex exchange mechanisms. Interoperability has been discussed to overcome bottlenecks in communicating, exchanging and sharing complex data structures by means of open standards (LAAKSO; KIVINIEMI, 2012). Integrated delivery methods have been designed to promote the alignment of business objectives and working process, so to enable the transition of mere information recovery "just-as-needed" to early contributions to knowledge and expertise (AIA, 2007).

Furthermore, researchers have now attempted to develop new system architectures capable to integrate BIM to ERP and mobile technologies (BABIČ; PODBREZNIK; REBOLJ, 2010). In view of the uniqueness of ETO products, the management of information across lifecycle has gained prominence with the proposition of PLM integrated system architectures in complement to the BIM-operated systems (HOLZER, 2014; OTTER; PELS; ILIESCU, 2011).

What is the probable way forward?

The construction industry is driving BIM implementation by means of push-pull strategies, addressing both (a) the supply side of the industry enabling players to reach improved delivery performance, and (b) the client side to use the facility information across the operations and maintenance. After the BIM Level 2⁴ mandate in some countries (i.e. the UK, 2011-2016), new efforts towards BIM Level 3⁵ are expected for the upcoming years⁶. Apart of the discussion on what is the so-called “i-BIM” or “Lifecycle Management stage” and their potential benefits; how to reach Level 3 is yet unclear. In relation to the technology foundations, reports suggest improved connections to Cloud Technologies and PLM platform integration (ARAM; EASTMAN, 2013; HOLZER, 2014; JUPP, 2013), as well as to Big Data, Artificial Intelligence (AI) and Internet of Things (IoT)⁷ (CIC, 2014).

The potential of technology to improve business performance can be expressed in future-oriented visions (MIETTINEN; PAAVOLA, 2014). Companies seeking for technology-based innovations use strategic planning tools to help them in developing their individual visions. Roadmapping is widely employed to align research and other investments with goals and strategy (PHAAL; OUGHTON, 2013). Greater clarity about trends meeting the company’s goals can be obtained through the use of techniques such as Roadmapping, facilitating the vision creation as done in industry level but fit to a specific enterprise context.

What is yet to do in research?

ETO fabricators could benefit from an approach to support them to accommodate technology trends on behalf of their business goals. However, it is necessary to first obtain a deeper understanding of the context and identify barriers and opportunities to set up an enabling environment to implementation meeting strategic objectives.

In construction, BIM has played a major role over the last years and it has been the focus of prevailing discussions. However, only a few companies have already reached the expected

⁴ “Managed 3D environment held in separate discipline ‘BIM’ tools with attached data. Commercial data managed by an ERP. Integration based on proprietary interfaces or bespoke middleware could be regarded as ‘pBIM’ (proprietary). The approach may utilise 4D program data and 5D cost elements (BSI B/555 Roadmap, 2013)”.

⁵ “Fully open process and data integration enabled by IFC / IFD. Managed by a collaborative model server. Could be regarded as iBIM or integrated BIM potentially employing concurrent engineering processes (BSI B/555 Roadmap, 2013)”.

⁶ Digital Built Britain – Level 3 Strategy and UK Government Construction Strategy: 2016-2020

⁷ Built Environment 2050: A report on our digital future (Construction Industry Council, 2014)

benefits of BIM in their processes and operations, as there are still many technical and human issues to be addressed. In manufacturing, PLM features some advanced functionalities and concepts that seems to fit to building systems fabricators. The debate on future trends in IT for construction relating PLM and BIM is yet limited to a few discussion papers (ARAM; EASTMAN, 2013; HOLZER, 2014; JUPP; NEPAL, 2014; MIN *et al.*, 2008; OTTER; PELS; ILIESCU, 2011), which suggests that firms should, as the first step, establish well operating BIM-based schemes to enable expansions accommodating further IT modules.

This investigation does not intend to provide details of the operations of an advanced computer-integrated system (which is also a gap to be better understood in future research). Rather, it focuses on a previous stage: understanding the context to setting a friendly environment towards the implementation of BIM processes and functionalities from a strategic perspective. It attempts to understand the challenges related to BIM implementation in companies that deliver ETO prefabricated building systems.

1.4 RESEARCH QUESTIONS

From the gap in knowledge, the main research question for this investigation is:

How to set an enabling environment for the gradual implementation of Building Information Modelling towards advanced computer integrated systems for companies that deliver engineer-to-order prefabricated building systems?

Further questions are:

Q1. Which are the potential impacts of BIM implementation in this type of company?

Q2. How to implement BIM and gradually introduce extensible IT modules in view of enhancing product lifecycle integration in ETO production systems?

1.5 RESEARCH OBJECTIVES

The research objectives are:

O1. Understand the challenges related to the BIM implementation in the context of companies that deliver ETO prefabricated building systems.

O2. Propose guidelines for driving the shift towards higher levels of digital integration with the support of BIM.

O3. Discuss the impacts of BIM implementation from a socio-technical perspective at project- and organizational-level aiming to prepare the ground for the required changes.

1.6 LIMITATIONS

This investigation is centred on companies delivering prefabricated building systems and is limited to engineer-to-order production systems, whilst acknowledging that some companies may concurrently operate a mix of ETO, MTO and ATO production systems (which means dealing with varying levels of customization of products or parts and inventory strategies).

Even recognizing the intent to promote whole lifecycle management, the project life span addressed in this study is limited to the section between design (from scheme design and structural analysis to shop drawings) and production (covering from off-site manufacturing to site assembly) phases. In this section of the project, there are several improvement opportunities that relies on the own company's effort (regardless of suppliers and clients). It also deals with phases that are, in some extent, more clearly understood in comparison to the fuzzy front-end and operation and maintenance, or redevelopment and demolition phases.

These phases are also strongly tied with the use of tools and technologies. There are several software packages for planning, modelling, analysis and simulation, as well as machinery and gadgets for manufacturing, control, transport and installation. The outcomes of the empirical studies provide insights for the introduction and refinement of practices supported by digital technologies, key for increasing delivery rates in such level of customization. Despite of the vision towards multi-technology systems, the actions in this study focus on the BIM platform.

This research strived to involve multiple disciplines and positions within the company: from top managers (strategic level), sectoral coordinators (tactic for implementation and management), to design and production teams (operational level). However, in practice, most of the collaboration between the researcher and the company's staff occurred with professionals of the design, assembly and IT management sectors belonging to the intermediate layer of the company's hierarchy.

1.7 OVERVIEW OF THE RESEARCH METHOD

The research strategy adopted is Design Science Research. It is a sociotechnical approach, prescriptive in nature and focused on problem-solving paradigms faced in the real-world involving the design of an artefact (KASANEN; LUKKA; SIITONEN, 1993; LUKKA, 2003; VOORDIJK, 2009). The research process is based on the steps proposed by Lukka (2003) and is here consisted of a literature review, exploratory study, empirical studies, artefact design and a reflective discussion.

The real-world feature of the investigation takes place by carrying out the empirical studies within the above-mentioned company, while the research findings generate useful knowledge to other firms facing similar challenges. Understanding the problem is the first step of a constructive research process followed by the design of an artefact and its evaluation. This investigation proposes guidelines for the gradual implementation of trending technologies and discusses the impacts of implementation from a socio-technical perspective. Theoretical contributions to BIM implementation focus ETO contexts, which is yet little discussed. Research outputs are expected to be adapted and employed by other ETO prefabricators to support them reaching their technology management objectives and to promote a wider sensitization in the industry.

Despite of the sub-division in three objectives, the major focus is centred in understanding the problem. As part of a Design Science Research approach, the contribution of this research is providing an understanding of the problem, which is the first step towards the development of more detailed and applicable solutions for solving the problem of implementation of computer integrated systems in these firms, which still need to be refined in future research. Hence, this research provides the basis to promote awareness and sensitization, and then, enables firms to develop their own visions and custom their implementation methods.

1.8 STRUCTURE OF THIS DOCUMENT

This dissertation is organised in eight chapters, which are summarized as follows.

Chapter 1 introduces the theoretical background, followed by the motivation, research problem, research questions and research objectives. Then, the research method is outlined in advance to situate the rationale and progress of this investigation.

Chapter 2 consists of a literature review dedicated to design and production integration in engineer-to-order systems. It oversees the environment in which this takes place, highlighting the main issues and alternatives to overcome the bottlenecks identified in prior researches.

Chapter 3 focuses on process and technologies related to building lifecycle management, mainly focused on BIM. The conduction of the review follows the evolution of computer-integrated systems in construction to understand major drivers and to identify trends.

Chapter 4 oversees the concepts of Socio-Technical System (STS) and Technology Roadmapping (TRM) used as a basis for the creation of the artefact of this research.

Chapter 5 describes the research method. The Design Science Research approach is presented followed by the research design. Then, research strategy frames the process of literature review and empirical studies, and finally discusses the outputs of this investigation.

Chapter 6 presents the empirical studies. An initial section encompasses an exploratory case to elucidate practical problems. Then, it provides information of the company in which the empirical studies are developed; and broadly describes work and digital information flow, as well as data exchange and interoperability issues. After that, the empirical are presented followed by a summary of findings.

Chapter 7 exhibits the proposed artefact and the research outcomes. A roadmap for BIM implementation is devised in consideration of ETO fabricator's context, followed by guidelines for the strategic implementation. Finally, the impacts are analysed to evince the challenges at project and organizational level.

Chapter 8 concludes this document with the final reflections, followed by suggestions for further research of related topics not covered in this study.

2 DESIGN AND PRODUCTION INTEGRATION IN ETO SYSTEMS

This chapter introduces key-concepts related to: (a) engineer-to-order production systems, and (b) core issues on design and production process integration, including the support of information technology.

2.1 ENGINEER-TO-ORDER PRODUCTION SYSTEMS

Production systems can be examined from the perspective of the typologies of production situations. The concept of Customer Order Decoupling Point (CODP) is key to understand the features of these typologies. In engineer-to-order (ETO) systems, “individual products are generally highly customised to meet individual customer requirements and are produced in low volume (HICKS; MCGOVERN; EARL, 2000)”. The decoupling point in ETO is at the design phase, so that complex product structures give rise to numerous components affecting the design and production interfaces along the project. In addition, an ETO supply chain has to deal with diverse customer requirements in a context that tends to face more uncertainties than in other production situations (MELLO; STRANDHAGEN; ALFNES, 2015).

2.1.1 Characterization of engineer-to-order production systems

Prior research had described typologies of production situations, including such as engineer-to-order (ETO); make-to-order (MTO); assemble-to-order (ATO); and make-to-stock (MTS) (BERTRAND; MUNTSLAG, 1993; SACKETT; MAXWELL; LOWENTHAL, 1997; WORTMANN, 1992). Afterwards, other typologies have been named (e.g. concept-to-order, ship-to-stock, etc.), as well as sub-classifications of the main categories have been proposed. For instance, Tommelein, Ballard and Kaminsky (2009) propose a division between make-to-stock (MTS) and make-to-order (MTO) streams, in which make-to-order is sub-classified into engineer-to-order (ETO), fabricate-to-order (FTO) and assemble-to-order (ATO). Therefore, it is not uncommon to find authors referring to MTO while encompassing both engineer- and fabricate-to-order typologies.

The concept of CODP is defined by Wortmann (1992) as “the point in the material flow from where customer-order driven activities take place”, meaning that “activities upstream of the CODP are driven by planning activities based on forecasts, rather than on firm customer orders”. Following this line of reasoning, Gosling and Naim (2009) state that the CODP is “a

stock holding point that separates the part of the supply chain that responds directly to the customer from the part of the supply chain that uses forecast planning”. Earlier, Sackett, Maxwell and Lowenthal (1997) explained that CODP could also be used as a basis to provide a sharper graduation than the classic “mass”, “batch” or “continuous” process terminology.

Wortmann (1992) distinguishes product-oriented companies from workflow-oriented companies. The first makes considerable investments in product development, while the second in production process, both independently of the customer order. An ETO type of business usually fits into a product-oriented approach, responding to the highly-customized nature of their products, although the challenges in production process are also relevant.

Bertrand and Muntslag (1993) highlight three key-characteristics of ETO systems: (a) the important role of the customer order; (b) the customer-specific product specifications; and (c) the product and production uncertainty. Thus, the following aspects require major attention: (a) dynamics, as firms have to cope with strong fluctuations in mix and sales volumes in the short and medium term; (b) uncertainty, related to product specification, mix and volume uncertainty of the future demand, and process variation; and (c) complexity, related to the structure of the goods flow, the multi-project character of the situation, and the composite or assembly structure of the product (BERTRAND; MUNTSLAG, 1993).

From the viewpoint of supply chain, ETO systems are composed of: (a) non-physical stage, covering tendering, engineering and planning activities; and (b) physical stage, comprised of components manufacturing, assembly and installation (JANSSON; JOHNSON; ENGSTRÖM, 2014; SACKETT; MAXWELL; LOWENTHAL, 1997). The design and engineering processes are highly information intensive (PANDIT; ZHU, 2007). The level of customisation impacts delivery times as more activities are performed after receiving an order. The high degree of uncertainty caused by the lack of information leads to a condition in which decision makers cannot accurately predict the impact of possible actions.

2.1.2 Engineer-to-order in prefabricated building products

Typical examples of ETO refer to operations in industries like shipbuilding, aircraft and spacecraft. In the construction industry, there are studies about precast concrete and structural steel systems, and a few cases related to HVAC ductworks, envelope façade, and joinery works. Most challenges associated with building products are like those found in other industries, such as uncertainty to estimate lead-times, expensive rework caused by the late realization of errors,

poor product quality and material wastage resulting from the competitive bidding process, and incompatibility between project and manufacturing schedules (PANDIT; ZHU, 2007).

The complexity of ETO operations require the mobilization of a diverse range of specialists working together to meet individual customer needs (GOSLING *et al.*, 2014). An effective management of the supply chain is subject to mechanisms that facilitate transparency and information sharing about the benefits of cooperation among stakeholders (ISATTO; AZAMBUJA; FORMOSO, 2014). Project participants can benefit from increased availability of information across integrated design and production processes whose coordination is sustained by iterative information exchanges (ČUŠ-BABIČ *et al.*, 2014).

Concerning the phases of a prefabrication process, off-site manufacturing and logistics schedules should be aligned with the site schedule (ČUŠ-BABIČ *et al.*, 2014). Hindrances in coordination are likely to occur as very little is known about what to order or manufacture until receiving the customer order and engineering specifications (BERTRAND; MUNTSLAG, 1993). The phases of procurement, competitive bidding and design are said to be time bottlenecks for the supply chain, affecting the flow of an ETO product (GOSLING *et al.*, 2014).

Flexibility has been pointed to respond to uncertainties of ETO systems since “different types of supply chains have different uncertainty profiles, and therefore strategies must be tailored to match these profiles (GOSLING; NAIM; TOWILL, 2013)”. In this sense, product structure, modularity and standardization could contribute to minimize the impacts in design customization and assembly flow (HICKS; MCGOVERN; EARL, 2000).

Many of the challenges such as dynamics, uncertainty and complexity faced in ETO supply chains relate to typical characteristics of construction projects such as: the existence of a site production to be orchestrated with the off-site production, highly-customized products influencing design decisions, and the formation of the temporary teams each with their own priorities and working methods. Hence, fabricators strive to improve: (a) product architecture – by means of modularization, standardization and Design-for-X (DfX) (GOSLING *et al.*, 2014); and (b) process synchronization – by means of collaborative information sharing among the stakeholders, and the adoption of IT to integrated design and engineering, off-site manufacturing and site assembly (BABIČ; PODBREZNIK; REBOLJ, 2010).

2.1.3 Vertical integration of the engineer-to-order supply chain

Companies working under an ETO configuration can be classified according to the level of vertical integration (HICKS; MCGOVERN; EARL, 2000). Vertical integration refers to “the degree to which a company does things with in-house employees (KRIPPAEHNE; MCCULLOUGH; VANEGAS, 1992)”, or also to “a combination of several or all functions in the value chain under a single firm (LEHTINEN, 2010)”. Accordingly, ETO fabricators may carry out activities across the whole-life of the product or limit the business scope to design and manage outsourced production contracts.

Apart of the make-or-buy-decision, functional teams in charge of design, manufacturing, logistics and site assembly need to work collaboratively and maintain high degrees of integration so that process can flow smoothly, and value is delivered to the client. A company can “develop close collaborative relationships with its suppliers to extend the boundary of the firm and exert indirect control over their resources (HICKS; MCGOVERN; EARL, 2000)”.

Over the last decades, some large engineering and construction companies have combined disciplines and expertise into single firms (LEHTINEN, 2010). This configuration has enabled to achieve tighter control over processes and position themselves closer to their end-users, as they overpass design and engineering and perform all activities until commissioning (HOOVER, 2013). Forsman *et al.*(2012) cite the case of Japanese house-building companies, which achieved strong customer orientation together with vertical integration.

2.1.4 Discussion

ETO can be particularly complex to manage due to uncertainty derived from the impact of client decisions in design, affecting downstream activities. ETO systems usually involve multiple participants in the development of complex projects. Hence, the ability to effectively coordinate cross-business activities is essential to avoid delays, cost overruns and quality problems (MELLO; STRANDHAGEN; ALFNES, 2015).

Some fabricators have set up vertically integrated structures, internalizing or closely managing activities from design to commissioning. However, it does not mean that companies always performs all these functions (AKEL *et al.*, 2001). Process integration is addressed not only between functional departments attaining different activities of product development, but also across supply partners involved in the delivery process.

Čuš-Babič *et al.* (2014) identified two main areas for improvement: (a) integration of design and industrialized production, improving the planning and organization of prefabrication processes; and (b) integration of site project management and project documentation-related activities, improving the efficiency of the physical activities including logistics, site material handling, and overall project progress tracking.

Improvements enabled by advances in IT have become a competitive factor in ETO markets (HICKS; MCGOVERN; EARL, 2000). IT systems can increase the visibility of project progress and more proactive communication between supply chain members (GOSLING *et al.*, 2014). The impact of information transparency obtained by the introduction of IT can be realized on faster response, better planning and facilitated product innovation. Virtual design and construction methods can be useful to manage specific technical solutions and to obtain pay-off from the process repetitiveness in the product offering, fostered by modularization and assembly standardization (JANSSON; JOHNSON; ENGSTRÖM, 2014).

IT for prefabricated building products offer constructability analysis opportunities for uniquely engineered elements. Over the years, CAD and ERP connections had been explored into integrated system architectures introducing new model-based workflows. Currently, BIM can potentially provide a propitious context for bridging the information gaps between product design, off-site manufacturing and site construction (ČUŠ-BABIČ *et al.*, 2014). An effective management of ETO systems stands on product information sharing, process alignment and strong collaboration. In the context of prefabricated systems, there is a special need for coordinating activities from design, off-site manufacturing and site installation, since prefabrication and construction processes run in parallel (ČUŠ-BABIČ *et al.*, 2014).

2.2 ISSUES IN DESIGN AND PRODUCTION PROCESS INTEGRATION

The integration of design and production, together with the production capability, is a critical factor influencing the coordination of an engineer-to-order supply chain (MELLO; STRANDHAGEN; ALFNES, 2015). Faniran *et al.* (2001) accredit the underwhelming performance to the lack of coordination between disciplines involved in project lifecycle. In a construction site, it is not unusual to identify inconsistencies for building components originated from design decisions. Decisions made during the design phase strongly impact other downstream phases and the whole product lifecycle (BRICOGNE *et al.*, 2010).

Jørgensen and Emmitt (2009) pointed out that process integration had initially focused on production aspects, but gradually design issues have received more attention; and the integration of design and production processes has begun to be addressed. Integration can be achieved by means, for instance, of: modular architecture in product design (ULRICH, 1995), constructability analysis (JØRGENSEN; EMMITT, 2009), and design of production system considering both off-site and site operations (BALLARD *et al.*, 2001).

Since the 90's, the introduction of information technologies have been explored with the assumption of: (a) being more effective for constructability review; (b) producing more constructible designs; (c) generating better construction schedules than those generated by conventional means; (d) as being effective for construction planning and simulation by supervisors on the site using remote graphics terminals and hard-copy devices connected to a central data base; (e) as being effective to instruct and to train construction personnel on the site; (f) leading to improved construction productivity as a consequence of the learning-curve effect; and finally, (g) for construction progress reporting in a more effective way than conventional techniques (REINSCHMIDT; GRIFFIS; BRONNER, 1991).

Independent development of activities using multiple computer applications led to difficulties in sharing data between applications and the subsequent lack of integrated project data (KARTAM, 1999). Then, new concepts for the use of computer technologies have emerged, such as the notions of virtual design and construction and digital prototyping (KHANZODE *et al.*, 2006; LI *et al.*, 2008). As will be further described in the following topics, these approaches are concerned not only with technical aspects of digital modelling and interoperability, but also with working practices agreed by the project team.

2.2.1 Fragmented nature in construction and integration concepts

In traditional schemes, responsibilities for design, fabrication, and assembly are in charge of separated parties, each with their own responsibility, objectives and agenda (MITCHELL *et al.*, 2011). Thus, projects must be defined and executed by integrating the efforts of a large number of different teams, which usually have different and conflicting priorities (FANIRAN *et al.*, 2001). The fragmented approach to project procurement and product delivery processes frequently lead to project teams being in adversarial relationships, resulting in the lack of transparency and mistrust (BAIDEN; PRICE; DAINTY, 2006).

Some organizations are reducing the scope of internal activities within the boundaries of a firm and relying them on outside suppliers (ULRICH; ELLISON, 2005). It relates to the often called “make-buy” decision, or, in other words, the definition of what to do in-house versus what to outsource. In addition, Ulrich and Ellison (2005) distinguish the concepts of internalization and integration, in which the first is “the inclusion of an activity within the organizational boundaries of the manufacturer, the entity on which our analysis focuses”, and the second is “the consolidation of two or more activities into the same organizational entity, whether this entity is the manufacturer”. In this context, integration can also be understood as “the merging of different disciplines or organizations with different goals, needs and cultures into a cohesive and mutually supporting unit (BAIDEN; PRICE; DAINTY, 2006)”.

Ling *et al.* (2014) propose a classification in: (a) functional integration: indicating the merge of functions such as design and construction into a single organization; (b) relational integration: denoting organizations in a supply chain that collaborate well through co-operative relationships built on shared goals and values; and (c) transactional integration: signifying the link of organizations for specific transactions through formal means.

Both manufacturing and construction industries are striving to bridge the disjunction between design and production. As to be continued in the following topics, alternatives to address fragmentation issues have been grounded on: product design strategies, adoption of collaborative IT, and use of collaborative procurement and delivery methods.

2.2.2 Critical stages interfacing design and production

Kartam (1999) identifies advantages in recovering detailed design information to be used in the production of construction schedules. Information shared in advance enable project teams to improve: constructability analysis, selection of construction equipment and methods, evaluation of change orders, monitoring and control of ongoing projects, safety planning, project costs and financial evaluation (KARTAM, 1999). Design detailing is an important stage that interfaces with the construction process (off-site and on-site), and therefore, should be managed together with project planning, procurement of subcontractors, production of shop drawings, off-site fabrication and pre-assembly and site installation (MITCHELL *et al.*, 2011).

Ballard (2000) recommends the practice of “work structuring”, which is defined as “the development of operation and process design in alignment with product design, the structure of supply chains, the allocation of resources, and design-for-assembly efforts”. According to

Ballard *et al.* (2001), the design of production systems “extends from global organization to the design of operations” serving to the goals of: doing the job, maximizing value, and minimizing waste. Production System Design (PSD) aims to make workflow more reliable and quicker while delivering value to both customer and producers (BALLARD *et al.*, 2001).

2.2.3 Information technologies supporting collaborative initiatives

The evolution of computer databases and 3D modelling tools had strongly changed the methods used by the construction industry through the support to manage a variety of information and knowledge sources (EASTMAN; CHASE; ASSAL, 1993; REINSCHMIDT; GRIFFIS; BRONNER, 1991). Architects and builders use different sets of knowledge, and in order to produce high performance buildings or to explore new styles, they can mix multiple technologies within a single project (EASTMAN; CHASE; ASSAL, 1993).

IT can provide improvements to the information flow which are not limited to process automation. Efforts to integrate different phases can contribute in reducing errors, improving co-ordination, increasing data integrity and improving communication between project participants (FANIRAN *et al.*, 2001). Data management systems, in which relational database contains all non-graphical information (attributes) related to objects shown in the digital design can enhance value adding by making data accessible to several users, bridging the gaps within project phases and stakeholders (REINSCHMIDT; GRIFFIS; BRONNER, 1991).

Virtual Design and Construction (VDC) is defined as “the use of multi-disciplinary performance models of design-construction projects, including the Product, Work Process, and Organization of the design-construction-operation team in order to support business objectives (KHANZODE *et al.*, 2006)”. VDC is said to be applicable to lean project delivery process and can be used as a mechanism for sharing knowledge resources related to a facility, forming a reliable basis for decisions during its lifecycle from the project’s inception and onwards (JONES, 2014; KHANZODE *et al.*, 2006).

The concept of Virtual Prototyping (VP) involves simulating construction processes with a certain degree of realism and capture design and construction knowledge which can be re-used in future projects. Developing VP is about “the use of integrated product, process and resource models of construction projects to support the construction planning in virtual environment (LI *et al.*, 2008)”, concerned with the construction of digital product models and realistic graphical

simulations that address broad issues. It enables contractors to “construct the building many times”; while many scenarios can be forecast, and potential problems identified in advance.

Some of the benefits of using VP include: (a) the creation, analysis and optimization of construction; (b) effective constructability analysis; (c) elimination of construction risks through digital mock-up of processes; (d) clearer understanding of project scope and better work instruction from main contractor to subcontractors; (e) effective communication between the client and contractors; (f) effective management of design changes and; (g) better capture and re-use of knowledge (LI *et al.*, 2008).

According to Akanmu, Anumba and Messner (2012), virtual models contain representations of building components which can be linked to physical objects on the construction site. Information embedded in the virtual building components provides an integrated database of relevant information that can be used during construction and post construction phases. Cyber-physical systems refer to a tight integration and coordination between virtual models and the physical components, supporting the communication of as-built status information to the model (AKANMU; ANUMBA; MESSNER, 2012).

Moreover, virtual models of product components can be supplemented with models of the construction site, machinery and temporary works equipment. Variables affecting the construction processes (including site layout, plant locations, rate of machinery operation, quantities of resources, etc.) can be considered in order to evaluate the feasibility of the proposed construction methods and sequences (LI *et al.*, 2008). It could also be used for (a) safety planning, (b) change orders evaluation, (c) financial evaluation, and (d) communication between project participants (KARTAM, 1999; LI *et al.*, 2008).

2.2.4 Discussion

Jørgensen and Emmitt (2009) cite three inter-related process for facilitating collaboration: (a) establish an appropriate project delivery framework for the project, including the establishment of incentives, agreements and resources as well as appropriate legal contracts; (b) identify value, specify and effectively communicate a common understanding of customer value, needs, etc. ensuring that participants have the support necessary for project continuity; (c) stimulate project stakeholders into active involvement throughout the project, encouraging team learning and exchange of knowledge at all levels of project processes and at all relevant levels of the organizations involved.

Ling *et al.* (2014) highlight the fact that many building projects are still procured as traditional design-bid-build schemes implying in reduced level of integration of the supply chain. However, even in design-build schemes, interactions might not be sufficiently strong. In this regard, major attention has been dedicated to project stages in which contractual arrangements encourage higher levels of collaboration, based on overlapping and concurrent development of activities leading to mutual benefits generation. This can be observed in “detailing design”, “planning/scheduling” and “production system design”. In addition, “concept design” is also considered a key-stage in project development due to the impact of the decisions of outline product geometry and functional systems, modularity, technology, site occupancy and so on.

The fast-growing use of product and process information in computer-based systems has raised problems (both technical- and policy-related) concerning, for instance, the access permission to information, key-user’s definition, and interoperability. As outlined by Bricogne *et al.* (2010), during the progress of every project, meetings are organized to evaluate constraints of the stakeholders and to find solutions to problems likely to occur. Nonetheless, it is still difficult to give facts based on data stored in software used by different disciplines. Therefore, Bricogne *et al.* (2010) examine the importance of a “capitalization project manager” who should be responsible for sharing knowledge sourced from experts of the different departments.

Moreover, new roles have been introduced to fit these new types of practice. For example, at an operational level, inexperienced teams employing digital modelling technologies have subcontracted modelling activities. Li *et al.* (2008) identified projects wherein design and construction teams did not have the requirements (both technological infrastructure, and mainly, technical knowledge) to perform virtual prototyping activities, so that specialist professionals served as process modellers to connect design and construction teams.

In this case, the process modeller retrieves 3D design models from designers and decompose relevant information into file formats required by the main contractor, sub-contractors and other project participants. At the same time, integrative models enable the assembly of virtual prototypes of the construction process according to the specific needs of the project. As suggested by Henderson, Ruikar and Dainty (2013), cross-phase learning has the ability to positively influence the degree to which buildability can be improved, and a process modeller can potentially facilitate teams to perform feedback loops by providing appropriate information package in a compatible digital format.

3 BUILDING LIFECYCLE MANAGEMENT: BIM AND PLM

This chapter discusses fundamental aspects of information technology in support of building lifecycle information management. Studies in design and production addresses management strategies assuming an ever-growing use of IT. The topics covered below discuss: (a) an integrative perspective for BIM enabling improvements in the interface between design and production; (b) reflections about the challenges to streamline processes balancing vertical and horizontal relationships; and (c) trends and challenges of lifecycle information management in construction based on PLM.

3.1 ROLE OF BIM IN DESIGN AND CONSTRUCTION

Computer provides information-related abilities that lead many to believe in its potential to solve some of the most persistent and critical problems faced by construction teams (LAWSON, 1998). The advent of new technologies has provided possibilities to designers and builders in managing complex design and construction projects. Thus, IT has enabled, or made it possible, to achieve wider control of both the design and construction processes (PENTTILÄ, 2006). The integration of design and manufacturing through BIM has reduced errors in data transfer from one project stage to another and has facilitated the communication efforts by designers and production planners (ČUŠ-BABIČ *et al.*, 2014).

3.1.1 Overview of CAD and BIM evolution

Penttilä (2006) noted that CAD has been in an evolutionary changing process since the advent of the concept in the 60's. The need for developing more integrated or interoperable software was recognized in the 70's by researchers developing “integrated design databases” or “integrated design systems” (MIETTINEN; PAAVOLA, 2014). The spectrum of the so-called CAD applications ranges from CAD as Computer-Aided Drafting tools to more advanced Computer-Aided Design systems; then, providing design-manufacturing integration by means of Computer-Aided Manufacturing (CAD/CAM) for the use of Computer Numerical Control (CNC); and then Computer-Integrated Manufacturing (CIM), in which CAD/CAM data is used as input to design and operation of manufacturing systems (CROTTY, 2011).

Recent developments include advanced parametric modellers, electronic document management systems, virtual and augmented reality, and efforts driving CAD to PLM. Building product modelling is believed to be “a promising method to increase the ability to manage some more vague building and design criteria, such as design richness or even overall building quality (PENTTILÄ, 2006)”. Such evolution provided more intelligent and interoperable systems approaches named as Project Modelling, Virtual Design and Construction (VDC) and nD modelling (MIETTINEN; PAAVOLA, 2014).

BIM vendors has expanded their scope and has provided specific tools to a larger set of disciplines (EASTMAN *et al.*, 2011; MIETTINEN; PAAVOLA, 2014). In this sense, BIM is pointed out as an effective approach to reduce industry's fragmentation, improve effectiveness, and lower the costs of inadequate interoperability (SUCCAR, 2009). A streamlined workflow requires the integration of functionalities authored by different professional backgrounds.

BIM provides logical access to model objects using standardized approaches such as STEP (STandard of Exchange Product data) or IFC (Industry Foundation Classes) (BABIČ; PODBREZNIK; REBOLJ, 2010). The employment of BIM tools supporting analysis, engineering and simulation is enabled by technical improvements of interoperability via CIS/2 for structural steel (CIMSteel Integration Standard 2) and gbXML (green building XML) schema for performance and sustainability related purposes. Moreover, the link between BIM data and fabrication equipment, either directly or via CAD/CAM interface applications, becomes more common in prefabrication and off-site production (HOLZER, 2014).

Large construction companies, focused on supply chain integration, prefabrication, rapid manufacture and assembly, have increasingly introduced ERP systems. ERP-BIM integration strives to increase efficiency across inter- and intra-organizational business processes (OTTER; PELS; ILIESCU, 2011). Statuses of building elements are made transparent throughout the supply chain and can be visualized on 3D building-models. However, there are remaining difficulties to connect engineering related data (developed in CAD/BIM) with manufacturing related data (managed at ERP), because these systems have different views on the construction object (BABIČ; PODBREZNIK; REBOLJ, 2010).

More recently, clients concerned with Capital Expenditure and Operational Expenditure (CAPEX/OPEX) issues have demanded integrated solutions for operations and maintenance. Thus, large efforts on the development of BIM/CAFm (Computer-Aided Facilities

Management) are underway (RICS, 2014). For this, COBie (Construction Operations Building information exchange) standard delivers building asset information necessary for the successful maintenance and management of facilities.

This evolution has been strongly based on technology leaps and innovations in computing technologies. Several companies have taken advanced model-based technologies as an essential core for their business strategy (PENTTILÄ, 2006). Technology improvements and innovations has enabled a gradual transition towards higher integration levels between project participants and higher performance in their product-service offerings.

3.1.2 Interoperability and standardization

In an ideal scenario, information is easily shared, retrieved and used for multiple purposes. Interoperability plays a major role in this context. Current applications store information in their native formats, which entail challenges for reusing data downstream in the workflow (BELSKY; SACKS; BRILAKIS, 2015). In order to avoid participants to have too many specific proprietary applications, there is a need for technical platforms that are widely accepted and preferably based on open standards (LAAKSO; KIVINIEMI, 2012). Eastman *et al.*(2011) define interoperability as the “ability to exchange data between applications, which smooth workflows and sometimes facilitate their automation”.

Since the earlies days of 2D CAD, the need to exchange data between applications was evident. In the late 70s and early 80s, Intergraph, and then, IGES (Initial Graphics Exchange Specification) were developed to address those issues (EASTMAN *et al.*, 2011). Formerly, file formats (i.e. IGES and DXF - Drawing Exchange Format) did not separate the way information was formatted from its semantic content, but newest data exchange technologies (i.e. SQL schema language - Structured Query Language) incorporate this distinction.

Laakso and Kiviniemi (2012) point out that although it should seem natural to shift to open standards (either file-based exchange or server-based data exchange), users continue to perceive vendor-specific proprietary formats as the *de-facto* standard format even though free and open alternatives have been made available for many years.

The EXPRESS data modelling language (ISO-STEP) serves as the basis for a range of product modelling technologies and schema including IFC, CIS/2 and other schema for a range of industries. Alternatively to EXPRESS, other exchanges schemes are supported by XML

(eXtensible Markup Language), which is good in exchanging small amounts of business data between two applications set up for such exchanges (EASTMAN *et al.*, 2011).

The historical evolution of IFC is reviewed by Laakso and Kiviniemi (2012) from its origins prior to the foundation of the IAI (Industry Alliance for Interoperability, further renamed to International Alliance for Interoperability) until the latest activities of BuildingSMART about to release IFC4 at that time. These authors described the history of IFC and its major shifts in the standardization process in four phases: (a) Pre-1994 “stepping out”; (b) 1994-1999 “from IFC 1.0 to IFC 2.0”; (c) 2000-2005 “ISO PAS and IFC 2x”; and (d) IFC 2x3 and IFC4.

In 2006, IAI consortium was re-branded to buildingSMART, changing the vision from merely enabling interoperability to emphasize its business importance in “improving communication, productivity, delivery time, cost, and quality throughout the whole building lifecycle”. Remarkable outcomes consist of concept definitions such as Information Delivery Manuals (IDM - ISO 29481), Model View Definition (MVD), and International Framework for Dictionaries (IFD – ISO 12006-3).

The aim of IDM is to provide integrated reference for process and data required by identifying discrete processes undertaken within building construction, the information required for their execution and the results of that activity. MVD defines a subset of IFC schema needed to satisfy one or many exchange requirements. IFD is a library with terminologies and ontologies to assist the identification of the type of information being exchanged. Apart from that, BIM Collaboration Format (BCF) is an open file XML format that supports workflow communication in BIM processes (LAAKSO; KIVINIEMI, 2012).

IFC2x3 is still one of the most used standard and was first released in 2006. However, “the process of certifying the quality of implementation proved to be too simple to ensure real-world usability, was inconsistent in its methods, and only covered IFC data export (LAAKSO; KIVINIEMI, 2012)”. In this regard, IFC Certification 2.0 brought major improvements to the issuance of certification.

IFC4 was released in 2013 as a full international standard (ISO 16739) correcting technical problems of previous versions, enhancing the capability of IFC specifications and enabling numerous new workflows. It is not only an extension of IFC2x3, but also contains modified

and enriched existing entities and lacks some obsolete and deprecated IFC2x3 entities, as explained in BuildingSMART⁸ website.

Concerning the specific field of steel structures, Eastman and Wang (2004) analysed the characteristics of two data exchange formats. In the mid-90s, the Intergraph Corporation developed the Structural steel Detailing Neutral Format (SDNF) to support the exchange of steel structure design between two applications. In the late 90s, AISC (American Institute of Steel Construction) developed the CIMSteel Integration Standard (CIS) based on a review of different available technologies for the development of both bi-directional exchange and a database repository for steel applications used by the North American structural steel industry. Thereafter, the second version – developed as a European Union project – was released as CIS/2, which offers formal specifications that allow software developers to make their applications mutually compatible (EASTMAN; WANG, 2004).

Recently, the AISC launched a new strategy⁹ on interoperability. AISC recognizes that CIS/2 has been only steel focused, whereas other disciplines demand data exchange for better integration to accomplish project objectives. In face of the industry migration towards IFC, AISC has re-evaluated its overall strategy and IFC forms a central part of the new direction.

The heterogeneous adoption of information technologies together with interoperability issues in using software in isolation rather than networked are problems that could be addressed by process with less redundancy and disconnections (LAAKSO; KIVINIEMI, 2012). It is noteworthy that construction industry has matured over the years, and interoperability has moved from merely data exchange between two BIM applications to support workflows (EASTMAN *et al.*, 2011). Benefits of interoperability are not limited to exchange automation, but it embraces the outcomes of refined workflows, elimination of steps and improved process.

3.1.3 BIM for prefabricated structural systems

According to Eastman *et al.* (2011), a structural designer working BIM produces both analytical models and design models, which can embed and retrieve large sets of information for several uses. Analytical models can take different forms like stick and node representation to characterize the structural topology for transmitting its behaviour (e.g. connection behaviours,

⁸ BuildingSMART IFC4 Release Summary (www.buildingsmart-tech.org/specifications/ifc-releases)

⁹ AISC Interoperability strategy for the structural steel (www.aisc.org/WorkArea/showcontent.aspx?id=29624)

external loads, and the code requirements to address load combinations), while some parts of a structure may be represented as a mesh in 3D finite element models (EASTMAN *et al.*, 2011).

The information content for exchanging models are prescribed by some national manuals and guides. The Finish Senate Properties BIM Requirements (2007) and the Common BIM Requirements (2012) dedicate exclusive volumes for structural design within the series of documents. The Australian National Guidelines for Digital Modelling (2009), the Norwegian Statsbygg BIM Manual (2011), and the Singapore BIM Guide (2012) provide shorter, but straightforward guidelines for structural modelling with requirements and descriptions.

Structural BIM applications can interact with other engineering tools directly importing proprietary formats, via CIS/2 or even IFC schema for a range of uses. Due to interoperability limitations, additional processing steps (in relation to the default processes) can be necessary to compute the information needed to perform specific tasks (KAMAT; LIPMAN, 2007). Although some software can modify IFC files, there are still limitations in transforming IFC structural models containing specific structural information such as connections, boundary conditions and loadings (WANG; YANG; ZHANG, 2015).

In structural steelwork, integrated digital applications can interface design information and fabrication equipment saving laborious and time-consuming activities of programming CNC machines through direct link to MRP/ERP, facilitating the generation of Bill of Materials (BOM) and production planning and control. Zhang and Hu (2011) advocate that 4D technologies can support more than the common uses of construction simulation, scheduling analysis, resource and cost management, but also contribute to the analysis and management of dynamic structural safety on site. Due to the complexity of pre-assembly and erection operations, simulation can also be used to test scenarios for site configuration and control of logistics operations, taking into account moving materials, transportation routes and storage areas and temporary facilities (LUTH; SCHORER; TURKAN, 2014; ZHANG; HU, 2011).

Tagging systems integrated to BIM models can aid decision-making over the end-of-life phases involving disposal, recycling and reuse of steel components. Radio-frequency identification (RFID) and BIM can possibly enable the reuse of steel through the creation of new platforms for lifecycle data services, resealing services and product-service systems (NESS *et al.*, 2015). Besides, Universal Product Code (UPC) and Quick Response (QR) code technologies have supported logistics operations, but yet scarcely integrated with BIM (CHIN *et al.*, 2008).

In prefabrication, BIM can support the team to: (a) quickly confirm the constructability of the designed systems, (b) refine the solutions with fabricators, and (c) store important information that would later facilitate production planning and control (TILLMANN *et al.*, 2015). Besides, with the support of BIM, installation of prefabricated assemblies tends to put construction crews at less risk (LUTH; SCHORER; TURKAN, 2014).

3.1.4 Information management and BIM implementation

Kiviniemi (2011) states that obstacles for changes towards integrated BIM rely on old work processes based on the use of documents, and low-bid business models, which do not reward for the actual added value or optimisation of the whole project. For Smith and Tardif (2009), business process reform has failed probably not due to flawed processes in implementation, but because important decisions are communicated as strong suggestions with no consequences for failure to implement them or because even though business leaders recognise the need for change, they do not know how to transform their organizations.

According to Succar and Kassem (2015), BIM implementation refers to the “set of activities undertaken by an organizational unit to prepare for, deploy or improve its BIM deliverables (products) and their related workflows (process)”. On the one hand, changes in business culture allow partners to test different practices and workflows, gain insight from their experiences, and modify their approach in a continuous cycle of innovation (SMITH; TARDIF, 2009). On the other hand, Hartmann *et al.*(2012) advocate a technology pull implementation approach, based on the deep understanding of work routines allowing the organization to customize existing BIM technologies to the needs of local projects.

Due to the varying levels of understanding, experience and confidence for implementing BIM; there is a need for guidance on where to start, what tools are available and how to work through the legal, procurement and cultural challenges (HARTMANN *et al.*, 2012). A collaborative BIM decision framework should take into consideration four interrelated elements: (a) defining scope, purpose, roles, relationships and project phase; (b) developing work process roadmaps; (c) identifying technical requirements of BIM; (d) customising the collaborative BIM decision framework (GU; LONDON, 2010).

Once BIM is established in the company, the successfulness of BIM implementation at project level relies on: (a) structure of the project organization and the type of procurement strategy; (b) implementation of agreed exchange file formats for all key applications, identifying the

types of information that might be exchanged between the different applications; and (c) implementation of agreed information exchange protocols, identifying the originator of each type of information and the status or level of detail it should contain at each interchange point throughout the duration of the project (CROTTY, 2011).

At a broader level, key-players of the construction industry have published visions of future state for BIM. Examples of Roadmaps for BIM can be found in:

(a) Public sector strategies working to remove the impediments for reaching the envisioned states, such as the BSI B/555 Roadmap (BSI, 2013a) in the UK; and the Singapore's BIM Roadmap of the Building and Construction Authority (BCA, 2014).

(b) Industry sectorial organizations, which have been influential in incentivising early adopters and supporting companies to define long-term visions, such as the Construction Industry Council Built Environment 2050: A report on our digital future (CIC, 2014); and the FIATECH's Capital Projects Technology Roadmap (FIATECH, 2007).

(c) Research and academic institutions, often in partnership with agents in the market, aiming to create a blueprint of the research and technology milestones required to achieve practical improvements, such as the ERABUILD's Strategic roadmaps and implementation actions for ICT in construction (STRAT-CON, 2007); and the University of Salford's nD Modelling Roadmap (LEE *et al.*, 2005).

(d) Technology developers aiming to provide guidance on how to benefit from their product offerings and to achieve business value, such as the Dassault Systèmes's End-to-end collaboration enabled by BIM level 3 (DASSAULT SYSTÈMES, 2014) and the Autodesk's Framework for implementing a BIM business transformation (AUTODESK, 2012).

For more practical purposes, implementation guides have assigned recommendations regarding high standards of professional competence. The RICS¹⁰'s International BIM Implementation guide (UK), the ACIF¹¹'s Framework (Australia) for the adoption of project team integration and BIM, and the CIC/Penn State¹² BIM Project Execution Guide (US) are examples of documents to support BIM implementation.

¹⁰ Royal Institute of Chartered Surveyors, UK

¹¹ Australian Construction Industry Forum

¹² Computer Integrated Construction (CIC) Research Program of The Pennsylvania State University

3.1.5 Discussion

Product characteristics and ways of production should be considered when selecting the structural BIM authoring tools to ensure that the Structural BIM meets the expected purposes (SENATE PROPERTIES, 2007). The use of BIM can potentially contribute to better integrate engineering analysis in the design development, improved interdisciplinary coordination, and faster generation of documentation for approval, fabrication and assembly processes (EASTMAN *et al.*, 2011; ZHANG; HU, 2011). However, the design of the workflow and selection of tools depends on specific production characteristics.

The success of BIM in prefabrication domain depends on the ability to capture relevant data in the model and to exchange information between participants of the Engineering Procurement Construction (EPC) chain, from fast verification of the proposed design to the storage of information for fabrication and installation activities (TILLMANN *et al.*, 2015).

According to Miettinen and Paavola (2014), BIM can be analysed from a trans-discursive perspective as it operates simultaneously in research, policy-making, and industry. Therefore, a BIM vision plays an interdisciplinary organizer role enabling multi-disciplinary groups to define shared interests and commitments and still maintain their own identity and goals.

3.2 PROCESS STREAMLINING AND INTEGRATED DELIVERY

Increased control over product information has encouraged companies to aspire for a better management of the knowledge generated throughout design and construction processes. Although technology has an important role to play, equally important is the way technology is implemented to support knowledge management and how it can generate benefits to both the client and the organization.

3.2.1 Business process reform in implementation

Many companies have spent large efforts on implementing BIM and setting project delivery methods. However, a company might realise major benefits only after most of the industry had made the transition from current technology and business practices, because construction projects are accomplished by a broad network of people and organizations who need to work together to exchange information in a coordinated way (SMITH; TARDIF, 2009). Thus, organizations need to determine to what extent integrate BIM into their operations.

The need for business process reform is a consequence of existing juridical, business, human, and technical obstacles for adopting BIM. Typical delivery schemes have led to information loss and do not support collaborative decision-making processes. Rather, it causes sub-optimisation at organizational level and decisions based on the direct investment costs only (KIVINIEMI, 2011). Cost saving pledges has driven decision of both owners and developers for adopting BIM. On the one hand, initial high costs have deterred organizations from putting BIM to practice. From the organizations side, those who measure Return of Investment (ROI) focus on areas like: (a) improved project outcomes such as reduced RFIs and field coordination problems; (b) better communication through 3D visualization; (c) productivity improvements of personnel; (d) positive impacts of winning projects; (e) lifecycle values of BIM; and (f) initial cost of staff training (GIEL; ISSA; OLBINA, 2010).

According to Kiviniemi (2011), standardized data exchange is a mandatory precondition for an efficient BIM-based workflow between participants (Integrated BIM or iBIM) and its development and implementation proved to be significantly more complex than believed in the beginning. Despite of the technical problems and limitations in data exchange, the main obstacle for the deployment of iBIM has not been technology, but the old work process, old business models and conservative attitudes in the industry (KIVINIEMI, 2011). Tribelsky and Sacks (2010) argue that waste in engineering design occurs, for instance, from wasteful management of design resources to the creation of erroneous and ineffective documents.

Business process modelling can be represented by a range of methods. Among the most common, IDEF0 (Icam DEFinition for Function Modelling) and, more recently, BPMN (Business Process Modelling Notation) have been applied by organizations, including the US NBIMS Committee and the BuildingSMART; or documents like the Penn State BIM Execution Planning Guide. The customization of Business Process Models has gained increased importance since it provides a more solid understanding of their business process.

A complementary approach for organising project process is the based on the RIBA Plan of Work¹³ 2013 (RIBA, 2013). The newest version acts across the full range of sectors and project sizes; provides straightforward mapping for all forms of procurement; integrates sustainable design process; maps BIM process; and provides flexibility in relation to town planning procedures. As clarified in its guide, it is not a contractual document, but it orientates users to

¹³ Royal Institute of British Architects – RIBA Plan of Work (First developed in 1963, the RIBA Plan of Work is the UK model for the building design and construction process)

various tools and supplementary core documents including professional services contracts, schedule of services, project protocols and various forms of building contracts.

The RIBA Plan of Work older version (2007) was supplemented by the BIM Overlay (RIBA, 2012) to position core BIM activities within the standardized project stages. The latest version, in turn, has a web template to be customised according to specific project conditions. Recent efforts have been done to align the RIBA and CIC (Construction Industry Council) framework process stages to improve cohesion within the construction industry.

It is worth noting that different approaches can be more appropriate to: (a) reforming and aligning business process at organizational level, with a more strategic view to coordinate internal operations of the business chain, aiming to reduce process waste and information loss; whereas other focus on (b) the streamlining process of assembled teams with greater emphasis on contractual arrangements and requirements for the project successfulness.

3.2.2 Contracts, standards and specifications for BIM projects

Despite of a variety of procurement methods, there is an apparent trend of moving towards multi-party agreements, which create a “temporary virtual, and in some instances formal, organization to realize a specific project (AIA, 2007)”. Integrated Project Delivery (IPD) is increasingly debated within the context of BIM projects. However, changes in the way project participants communicate and collaborate through BIM have raised additional challenges to be managed through standard forms of contracts.

Gibbs *et al.*(2007) explored the impact of BIM in contracts, with major focus to the Chartered Institute of Buildings (CIOB)’s Complex Projects Contract 2013 (CPC 2013), which is the first standard form of construction contract to include BIM clauses in its provisions and appendices. Looking at the British scenario, Gibbs *et al.*(2007) concluded that CPC 2013 goes some way to facilitate BIM adoption in attempt to overcome the perceived barriers associated with working BIM in a Level 2 environment by incorporating a BIM protocol mandatory. In turn, NEC3¹⁴ and JCT¹⁵ do not directly refer to BIM but use complementary guides to advise on how CIC BIM protocol can be incorporated to the contract forms (NEC3) and suggest steps

¹⁴ The New Engineering Contract – NEC3 suit

¹⁵ The Joint Contracts Tribunal – JCT

and modifications to be made when work and information exchange is governed by a BIM protocol (JCT).

Due to the UK Government BIM mandate, BSI (British Standards Institution) standards have been published to support the BIM Level 2 adoption, including PAS 1192-2 Specification for information management for the capital/delivery phase of construction projects using building information modelling (BSI, 2013b), PAS 1193-3 Specification for information management for the operational phase of assets using building information modelling (BSI, 2014a), BS 1192-4 Collaborative production of information – Part4: Fulfilling employer’s information exchange requirements using COBie – Code of practice (BSI, 2014b) and PAS 1192-5 A specification for security-minded building information modelling, digital built environments and smart asset management (BSI, 2015), as well as the CIC BIM protocol (CIC, 2013).

In the US, the AIA Digital Practice Documents have been employed in major projects and has led to the creation of addendum documents worldwide. From the former AIA Document E202-2008: Building Information Modeling Protocol Exhibit (AIA, 2008), the AIA has later released the AIA Document E203™–2013 Building Information Modeling and Digital Data Exhibit (AIA, 2013a); the AIA Document G201™–2013 Project Digital Data Protocol Form (AIA, 2013b); and the AIA Document G202™–2013 Project BIM Protocol (AIA, 2013c).

In New Zealand, the Standards New Zealand provides flexibility to cover BIM and Project Team Integration (PTI) through the contractual standards NZS3910:2013 Conditions of contract for building and civil engineering construction (SNZ, 2013a); NZS3916:2013 Conditions of contract for building and civil engineering – Design and construct (SNZ, 2013b); and NZS3917:2013 Conditions of contract for building and civil engineering – Fixed term (SNZ, 2013c).

Together with BIM implementation guides, contractual standards have played major role in the support of assembling teams to enable Integrated Project Delivery. The existing standards published internationally has been adapted for specific projects, even outside the borders of the referred countries. Protocol templates have been improved based on experiences of pilot projects and early adopting organizations, encouraging a wider adoption over the next years.

3.2.3 Discussion

Mäkeläinen *et al.* (2013) highlight the need to develop transactional business process models with practical strategies for exchange of meaningful information between BIM applications. Streamlined flows facilitate the generation of knowledge to be captured, organized and shared among stakeholders, serving as a learning repository for improving the performance of the involved organizations in future projects. Systematic management of knowledge encourage continuous improvement, faster response to customers, disseminating best practices, and reduction of rework (DESHPANDE; AZHAR; AMIREDDY, 2014).

In this regard, knowledge sharing among project managers and jobsite engineers can alleviate problems on site and reduce the time and cost of solving problems related to constructability (HO; TSERNG; JAN, 2013). However, created knowledge often remains stored with project participants and is not transferred across the organization for reuse (DAVE; KOSKELA, 2009).

In a traditional process (non-BIM), data is stored in a fragmented manner, so that is complicated to effectively capture, catalogue and disseminate information (DESHPANDE; AZHAR; AMIREDDY, 2014). Digital formats facilitate updating and transferring in BIM environment. Shared information associated with objects of BIM model can be referred to and reused in other projects (HO; TSERNG; JAN, 2013). Nevertheless, not enough attention has been paid to tacit knowledge which is, in turn, of utmost importance due to the fragmented nature of the construction industry and due to the fact that each construction project is unique and generates a significant amount of knowledge during its execution (DAVE; KOSKELA, 2009).

3.3 TRENDS AND CHALLENGES FOR PLM IN CONSTRUCTION

Product Lifecycle Management (PLM) has advanced over the last years, mainly in the automotive and aerospace sectors, while there are some early adopters in other industries too (GRIEVES, 2005). PLM has been said to be an essential element for coping with the challenges of global competition, shortened product and component lifecycles, and highly demanding customer needs (SAAKSVUORI; IMMONEN, 2008). However, most organizations has not reached lifecycle management concepts thoroughly yet (SCHUH *et al.*, 2008; STARK, 2011).

While a few companies using Product Data Management (PDM) migrated to PLM in the past decade, many are still in the very initial phases of PLM implementation or did not even start

the digital changes from the traditional approach (SILVENTOINEN *et al.*, 2011). Despite of software acquisition and dissemination, several integration issues for improving project and organizational performance remain unresolved. Analogous to BIM in construction – which is expected to avoid information losses among teams – practical experiences revealed that strategies and practices concerning collaborative information exchange remain flawed. In practical terms, the integration of processes, technologies and protocols across building lifecycle phases is still a big challenge (JUPP, 2013).

3.3.1 General concepts of PLM in manufacturing industry

Schuh *et al.* (2008) define PLM as “a concept for the integrated management of product related information through the entire product lifecycle”, spanning from the initial idea to end-of-life. The aim of this integration is to overcome existing organizational barriers and to streamline the value creation chain enabled by recent advances in IT leading to faster innovation cycles (reduced time-to-market).

Grieves (2005) defines PLM as “an integrated, information-driven approach comprised of people, processes/practices, and technology to all aspects of a product’s life, from its design through manufacture, deployment and maintenance, culminating in the product’s removal from service and final disposal”. Stark (2011) adds that PLM manages both individual products and the product portfolio.

Although PLM is a relatively new theme, it stems from other ideas since the 80s, such as Computer Integrated Manufacturing (CIM) and Engineering Data Management (EDM) which later turned into Product Data Management (PDM). Although initial attempts to implement CIM failed, the integration of engineering and production systems data has been considered across the evolution of IT systems and related management concepts (SCHUH *et al.*, 2008).

Silventoinen *et al.* (2011) analysed the evolution from the scope broadness perspective: (a) EDM (predominantly departmental scope, i.e. engineering) aimed at organising the storage of CAD-data to reduce engineering cost by saving search time; (b) PDM (organizational scope) aimed the processes of creating product data, to reduce the cost of handling data and errors caused by using wrong versions; (c) PLM (covering the whole supply chain and all parties involved in product lifecycle) aims to share product data with the whole supply chain to reduce total lifecycle costs, and not only manufacturing costs.

PLM aggregate different technologies including CAD, CAE, CAM, PDM, ERP, SCM, CRM etc., depending on the scope, field of expertise and goals of the organization. Regarding to the scope of applicability, PLM covers both companies making identical or similar products and those making one-of-a-kind products, in which every product is customised to the customer's requirements (STARK, 2011). In this case, PLM provides control and visibility over individual products based on configuration management features and fits to the context of ETO systems.

A key idea is to serve up-to-date data, information and knowledge in a secure way to all participants (JUPP; SINGH, 2014). PLM provides a shared view as product requirements are translated into a tangible product and creates a repository of information to be used throughout the product lifecycle (GRIEVES, 2005). Developers attempt to provide solutions to manage unstructured data created within the system as well as data acquired through interfaces with external tools (ARAM; EASTMAN, 2013). From a commercial perspective, PLM vendors recognise that since many software are in use, PLM applications should not try to replace all them, but to interface with them (OTTER; PELS; ILIESCU, 2011).

A holistic PLM approach is, thereby, based on the understanding that PLM is an integrator of tools and technologies that streamlines the flow of information through various stages of the product lifecycle, and therefore, IT is not in the first line of action (SILVENTOINEN *et al.*, 2011). Instead, PLM systems has a collaborative backbone allowing people throughout extended enterprises to work together more effectively (SAAKSVUORI; IMMONEN, 2008).

3.3.2 BIM as an enabler for lifecycle management in construction

Early thoughts resembling to lifecycle information management in construction occurred even before the establishment and diffusion of the PLM concept. Reinschmidt, Griffis and Bronner (1991) discussed the integration of relational database containing non-graphical information (building product attributes) to the objects shown in the three-dimensional design model (3D CAD), and also to the project network schedule (graphic-integrated schedule generating a 4D-like modelling) to be used along the development process. Shortly after, Eastman, Chase and Assal (1993) proposed a system architecture for computer integration of design and construction knowledge, based on the interactive linkage of CAD systems with Engineering Data Model (EDM) and concerned with PDES/STEP (Product Data Exchange Specification/STandard of Exchange Product data).

Although initial ideas related to BIM in the construction industry date from the 70s, only recently BIM has reached an industry wide scale of diffusion and understanding. The concern with lifecycle can be found in Penttilä (2006)'s definition, saying that building product modelling is a “methodology to manage the essential building design and project data in digital format throughout the building’s lifecycle”.

There is an emerging discussion for integrating concepts and technologies of BIM with PLM, based on experiences from other project-based industries such as shipbuilding and aerospace (MIN *et al.*, 2008). Such robust PLM infrastructure would contribute to capture and consolidate information of current and past projects to enhance decision-making by promoting a better use of resources, and to support more agile problem-solving (ARAM; EASTMAN, 2013).

Jupp and Singh (2014) note that BIM and PLM concepts share fundamental similarities but are distinct in scope, and level of maturity in process integration and workflow management. It is argued that BIM practices can benefit vastly from unifying solutions to acquire, manage and make use of information and processes from various project and enterprise level systems, selectively adapting functionality from PLM systems (ARAM; EASTMAN, 2013).

Aram and Eastman (2013) noticed that only a few companies have been adopting PLM capabilities; and they are limited to collect basic information and perform project-portfolio management. In early implementation trials, deficiencies in the transversal use of BIM and PLM platforms occurred due to human interface problems (JUPP, 2013).

As an opportunity for migration, PLM platforms can be integrated with BIM servers, leveraging structured and rich data embedded to building and construction semantics in the object models for procurement, manufacturing and project management (ARAM; EASTMAN, 2013). If BIM-PLM integration remains unfeasible or difficult to manage, BIM itself keeps expanding the scope, functionality and value towards collaborative processes and shared resources enabling decision making to support whole lifecycle (JUPP; SINGH, 2014).

3.3.3 Working changes in PLM-based design and production

The increased amount of complex client requirements pull dramatic changes in organizational culture and coordination practices to achieve better process performance (SILVENTOINEN *et al.*, 2011). Despite of the urge for integrated solutions in all industries, it seems that

manufacturing is much ahead of the building construction in using these concepts and technologies (OTTER; PELS; ILIESCU, 2011).

Streamlining processes with standardized IT practices (required due to disruptive technology integration requirements) remain a major challenge even for those large companies. The implementation of PLM is typically divided and managed in a series of smaller stages at both strategic and operational levels to be carefully planned and coordinated (JUPP; NEPAL, 2014). The migration to PLM includes extensive changes in intra- and inter-organizational practices, covering cross-functional participants and often cross-organizational players.

Changing environments led by IT implementation open opportunities for new business models (STARK, 2011). In order to reach lifecycle integration through BIM, it is necessary to create an ecosystem for mapping the network of interacting actors, corporate business processes, project processes, activities, methods and technologies (JUPP; SINGH, 2014). New processes and working methods emerge together with new interfaces between engineering teams and PLM administrators (JUPP; SINGH, 2014). Therefore, high level consideration might take part of the technology strategy in order to enable the capture and share of product and production process knowledge to align new technologies with the goals of the organization.

3.3.4 Discussion

PLM functionalities offer integrated solutions for supporting product structuring and planning of custom product designs and specifications. A fabricator running PLM can better manage ETO operations and meet specific customer requirements after the placement of an order, based on reference models (SCHUH *et al.*, 2008; SILVENTOINEN *et al.*, 2011).

According to Saaksvuori and Immonen (2008), the benefits of PLM go far beyond operational savings generated by the use of the digital tools, but due to changes in the working methods gaining control over product lifecycles. Grieves (2005) states that individuals make subjective determinations of how well the outputs match the desired goals of the system since a large part of the work is in the realm of tacit knowledge. Hence, either BIM or PLM should drive to clearly-defined, well-documented, proactive activities so that it can provide maximised value (STARK, 2011).

The separation of building design from manufacturing and site assembly impose limitations in tracking and managing requirements, especially in the case of discrete units of products or

buildings components demanding high customization. Depending on the characteristics (i.e. size, cost and complexity) of the engineered product, the design and production will normally adhere to discrete stages to form a system lifecycle (JUPP; SINGH, 2014).

In customer-defined design parts of ETO products, hindrances to define and manage model changes at different granularities can be addressed by configurations management functions of PLM applications. New capabilities to synchronize the shared model views have becoming ever more useful as long as “units of information in design and engineering phases are often dynamically defined model views that are domain-specific partial models and mostly user-defined (ARAM; EASTMAN, 2013)”.

Given that not all required functionalities are available in the tools used by building systems fabricators, Jupp (2013) maps the challenges to implement PLM functionalities in an incomplete BIM context. This mapping should reveal interfaces to be addressed concerning teams and organizations; processes, information protocols; and lifecycle stages.

If on the one side BIM adoption has been driven by a push-pull strategy and are often tested in pilot projects, the migration to PLM is taken more from an enterprise perspective, aligned with product-technology strategies. PLM implementation plan stems from business innovation strategies and intersect many functional departments, which is not related to a discrete client request. In turn, this transversal approach enables the company to better coordinate functions in a multiple project environment, driving to a comprehensive management system for program and portfolio.

4 ENTERPRISE CONTEXT FOR VISION AND IMPLEMENTATION

This chapter introduces two of the main concepts related to strategic BIM planning and implementation approached in this study: Socio-Technical System approach and Technology Roadmapping for enterprise innovation. The discussion on these topics presents the line of reasoning used to ground the outputs of this investigation.

4.1 CONTEXT AND VISION CREATION PROCESS

This study features the analysis of the enterprise context in which organizations strategically plan and implement technology-based improvement ideas for business performance and innovation. In a first moment, it is often observed what is going on in industry (and out there) and what are the lessons to be learned from these trending topics. Here, the focus is on how prefabrication firms can capture BIM opportunities from technology releases, public policies, new forms of procurement schemes and contracts to approach the required process reforms adjusted to new production management philosophies.

Hartmann *et al.* (2012) still attribute the loosely coupled structure of the construction industry as a major barrier for implementation. Moving from the panorama in industry to enterprise context, technology planning explores how a new application can synergize with innovative management paradigms in order to achieve the business goals. Yet, a company can realize that available BIM tools and related methods do not fit perfectly with the business needs or operational conditions, but these contain concepts and functions insightful to the development or adaptation of innovative applications. According to Aram and Eastman (2013), “the efficient growth in the role of BIM can benefit vastly from unifying solutions to acquire, manage and make use of information processes from various projects and enterprise level systems”.

In the construction industry, vendors have uttered advantages perceived by early adopters of BIM authoring tools to highlight the benefits of their commercial solutions. However, as the success of an implementation depends on the corporate goals and several contextual factors, it does not mean all similar firms will fully perceive advantages, since the requirements and enabling capabilities are unique at each company, business function or functional department. Kiviniemi *et al.* (2008) state that the current business models and fragmentation of the AEC/FM industry do not support transformational change well, especially in terms of integrated BIM.

According to Smith and Tardif (2009) BIM requires attitude adjustments and system-minded building industry professionals who regard the information they create thinking on stewardship rather than ownership. An analysis of enterprise context identifies stakeholders, requirements and environmental trends articulated with business strategies to conceive a fundamental basis for enterprise architecture and business models. Organizations should detect the need for changes and consider opportunities for growth and sustainable expansion.

Technology Roadmapping (TRM) method is one possible mean to devise a vision encompassing the viewpoints of people, policies, process, and technologies. Private and public organizations have used TRM to express their expectations and strategies concerning the evolution of information technologies and new management paradigms. First records of roadmapping applications date back to the 80's integrating different organizational areas such as marketing, finances, manufacture and R&D (CAETANO; AMARAL, 2011). Cases of BIM and PLM roadmaps have been increasingly discussed at industry level, while firms have adapted those insights to the context of their businesses.

This investigation gathers trends in industry and endeavours to provide guidance on how to reach scenarios fitting to the context of individual companies. Having devised the vision and an implementation plan, organizations need to setup an enabling environment crossing technological infrastructure, educational programs and internal policies to manage the challenges of transition in order to guarantee the effectiveness of the implementation.

The company of the empirical studies strives for Lean improvements and enhancements of BIM and PLM uses throughout their management systems. In fact, Lean played a peripheral role in this research, but it is here considered because the company has a clear position that Lean achievements have contributed to improve performance and there is still a lot to do. The research community and practitioners have highlighted synergy aspects between BIM and Lean or PLM and Lean, bringing together technology developments and leaner design and production processes. Such positions endorse the company's efforts on this direction.

Despite of significant differences in scope and objectives, implementation strategies for BIM, PLM and Lean have been approached from a Socio-Technical System (STS) perspective. The sub-systems of People, Process and Technology are typically found in discussions concerned with these topics, even though not all authors evince the STS approach. Those concepts are here merged to form a reference basis for the devised roadmap and the proposed guidelines.

4.2 SOCIO-TECHNICAL SYSTEM APPROACH

Many working practices innovations are linked, facilitated or enabled by the introduction of new technologies; and whilst these changes are usually not explicitly called as such, they can be interpreted as socio-technical endeavours (CLEGG, 2000). According to Baxter and Sommerville (2011), the term Socio-Technical System (STS) describes “systems that involve a complex interaction between humans, machines and the environmental aspects of the work system” present in most of current enterprise systems.

Nonaka and Nishiguchi (2001) observed that in knowledge creation process – that is by extension a social process, embedded in a particular set of relationships among individuals, teams, and organizations – technology must be designed and implemented in accordance with other resources, in particular human resources. Large complex system projects fail because they do not recognise the social and organizational complexity of the environment in which the systems are deployed and system stakeholders inevitably have different concerns (BAXTER; SOMMERVILLE, 2011). Therefore, Socio-Technical System Engineering serves to bridge the system development and change processes, demanding improved communication between system stakeholders about socio-technical issues.

Morgan and Liker (2006) used STS models to describe the Toyota Product Development System, in a lean context. They acknowledged the socio-technical character of the “open-system”, referring to an existing interaction between what is inside the organization and the outside environment. That model describes three interdependent sub-systems organized as People, Process, Tools and technology, covering to a total of 13 principles.

From a BIM perspective, the rationale of STS can be implicitly found in BIM definitions and BIM implementation guidelines. For instance, Succar (2009) proposed a tri-axial knowledge BIM framework comprising of BIM Fields, BIM Stages and BIM Lenses. BIM Fields embrace three interacting and overlapping fields of Technology, Process, and Policies. In the study of Arayici *et al.*(2011), the strategic approach to BIM adoption incorporated People, Process and Technology equally and led to capacity building through improvements in process, technological infrastructure and upskilling of organizational staff to attain efficiency gains and competitive advantages. In addition, the understanding of PLM as an integrated information-driven approach comprises not only Technology, but also People, Process and Practices (GRIEVES, 2005; SILVENTOINEN; PAPINNIEMI; LAMPELA, 2009).

Even for those BIM aspects that are apparently more willing to a technological side (e.g. interoperability issues), a technology-only viewpoint may lead to unsuccessful or incomplete outcomes. In describing the history of IFC, Laakso and Kiviniemi (2012) suggest that IFC standardization process should be looked from a socio-technical process rather than only focusing on the output, since the organization behind it and the industry environment for BIM software also plays important role. Therefore, technology is not approached in a standalone fashion, but it strongly interacts with other dimensions or socio-technical sub-systems.

The STS approach demonstrates that technological implementation cannot be understood separately from the context of the implementing organization (SACKEY; TUULI; DAINTY, 2014). Therefore, the guidelines here proposed considers the socio-technical system approach within the roadmapping process. Based on previous experiences, this framework assumes the changing nature of the system's fields and intends to provide a general idea of an open, dynamic and prone to evolve system within this environment.

4.3 TECHNOLOGY ROADMAPPING APPROACH

Technology Roadmapping (TRM) was originally developed in the 70's to support improved alignment between technology and product development (product-technology planning), providing a structured visual depiction of strategy (PHAAL; MULLER, 2009). Roadmapping methods are flexible and have been adapted to meet different goals, supporting innovation, strategy and policy-making.

It helps to clarify a collective vision of the industry or firms to establish benchmark for technology and accelerate innovation in specific sectors and in a new product development process. A major benefit is the enhanced communication across functional and organizational boundaries. Roadmaps usually take form of a graphical representation, following a visual strategy, that provides a "one-page high-level view" of the system in question (PHAAL; MULLER, 2009). Multiple knowledge and expertise can mutually contribute to the forward-looking nature of the approach; and somehow, it ascertains that flexibility is achieved.

Organizations in process of defining technology visions may combine two technology-product integration strategies: "technology push" and "market pull" (CAETANO; AMARAL, 2011). In some cases, supplementary technologies can be developed by external partners in parallel with the organization's core technology. Thus, technology planning is likely to face some

paradoxical decisions to align the desired benefits of being in the frontier of new technologies with their core business objectives (HARTMANN *et al.*, 2012).

A roadmapping process brings together various key-stakeholders with unique backgrounds and perspectives, enabling both demand and supply side views to be represented while balancing market pull and technology push (PHAAL; MULLER, 2009). It is assumed to be simple and adaptable to accommodate strategic lenses through which the evolution of complex systems can be viewed. The roadmap highlights the enablers and barriers, and act as a reference point for dialogue along the consensus building process. The roadmap creation process can be even more important than roadmaps themselves, which are not static and need to be revisited as innovation matures and new goals are established.

As earlier discussed in Chapter 3, there are roadmap examples for BIM developed by public divisions, sectorial organizations, research and academic institutions, and technology developers – e.g. BSI B/555 nD modelling roadmap (BSI, 2013a), FIATECH’s Capital Projects Technology Roadmap (FIATECH, 2007), BIM 2050 GROUP Built Environment 2050 (CIC, 2014), etc. Recent BIM mandates in some countries (such as the UK, the US, Finland and Singapore) have accelerated the transition from traditional practices to BIM-based schemes and working practices.

Growing adoption has encouraged vendors and technology developers to design roadmaps to fit their offerings with R&D efforts and market demand. As noted by Laakso and Kiviniemi (2012), “prior to the year 2000, roadmaps for future development were largely absent, partly due to the lack of common vision concerning the content and purpose of the standard”. After that, common objectives fostered collaboration between international groups to form industry consortiums aiming to develop aligned visions for future solutions on interoperability.

Leading companies in innovation often sponsor study projects to prospect future trends in specific areas. Likewise, government agencies have used similar approaches, as in the case of the study “International approaches to understanding the future of manufacturing 2013”, commissioned by the UK Government Office, which mapped several related studies worldwide (O’SULLIVAN; MITCHELL, 2013).

The client-driven value creation has also been featured with notable examples from Japan and Germany. For instance, O’Sullivan and Mitchell (2013) highlight some international variations in manufacturing, which include the “new *monozukuri*” that is not well understood by the

Western community yet. These concepts bring new insights for lean management, referring to a “new Japanese-style production system” approach. Besides, they indirectly provide contributions to the STS approach, especially with *kotozukuri* and *hitozukuri* concepts. In Japanese industrial philosophy, *monozukuri* or “creating products” comes together with values such as “making things happen based on a market perspective (*kotozukuri*)” and “developing people or developing human resources (*hitozukuri*)”. The same report highlighted ideas of the German’s “*produktionssysteme und -technik*”, but still did not cite the concept of “Industry 4.0”, which has been diffused more recently with some overlapping points.

As observed in the literature review, the fast-evolving nature of technologies has led to the incidence of facts as: (a) current technologies are likely to be re-labelled after incremental innovations, even if their essence are preserved; (b) technologies have been adapted from one industrial field to be used within different contexts, oftentimes with similar functions and objectives but under different names or acronyms; and (c) new technologies are likely to emerge to fulfil existing gaps or to support bottlenecks that could not be addressed by the existing platforms.

The use of roadmaps can be beneficial to this particular context as it is a relatively consolidated approach, test in different industries and situations. It has been adopted by a number of construction and manufacturing organizations as discussed in the cases above. However, there is still a need to relate roadmapping methods with the perspectives of the socio-technical system approach to frame a suitable scheme for technology management and strategic BIM implementation at AEC companies.

4.4 DISCUSSION

The schematic multi-layer roadmap model proposed by Phall and Muller (2009) defines three typical viewpoints to be considered in TRM: (a) commercial and strategic perspectives; (b) design, development and production perspectives; and (c) technology and research perspectives. In addition, the STS approaches for Lean and BIM/PLM have stressed the importance of consider the socio-technical sub-systems of: (a) people and policies; (b) process; and (c) technologies.

“Technology” is a common point shared by both STS and TRM, even though treated unevenly. The other viewpoints may be interpreted or assigned depending on the nature of the concerned

product-service offerings. Although the vision creation process intends to combine viewpoints from both STS and TRM, the elements to be incorporated vary according to organizational characteristics and strategic goals. The vision remains flexible and open to updates because new ideas may emerge from experience as well as new innovations may be developed and made available.

The outputs of this investigation incorporate the structure of TRM to organize enterprise technology management strategies together with STS elements, essential to clarify some of the influencing viewpoints within the context of BIM implementation. The artefact plays the role of an analytical tool to support the design of strategies and prescription of steps to accomplish improvements in a scheme which is easy to understand.

The roadmap and proposed guidelines support the arrangement of ideas to enable managers to devise system architectures and enterprise architectures incorporating innovative technological platforms. TRM structure facilitates the generation of future scenarios and place milestones in a way to foresee and eliminate constraints and requirements for upcoming stages of the implementation agenda. One dimension of the framework is the time-horizon, and the other are the socio-technical sub-systems and perspectives to be considered.

It is worth noting the paradox of using roadmaps at organizational level and industry level. The scope, goals and level of detail should be set differently. The importance of the empirical part of this research is that the researcher, together with company's members, conducted experiments rather than just basing judgements on the experience they had in business or in external references (which is fine for a discussion at industry level).

A few sources in the literature suggest that PLM serve as a macro-context in which modules of CAD/CAM, ERP, PDM take part. In bringing this idea to construction, BIM – rather than a broad concept as today – can become another component member of such macro-context. However, how this transition will occur is yet unclear and will depend on the positioning of the firm's strategy and how a company sets BIM within the enterprise system architecture. Based on these definitions, the creation of a roadmap stands the company's position to advance in the evolution of their enterprise systems.

5 RESEARCH METHOD

This chapter describes the research method adopted in this investigation. It is organized as follows: (a) an introduction to Design Science Research; (b) a representation of the research design, providing an overview of the main phases of this study; (c) a description of the company in which the empirical studies were developed; (d) a detailing of the research process; and finally (e) the outputs of this investigation in conformance with the DSR approach.

5.1 DESIGN SCIENCE RESEARCH

Design Science Research (DSR), also known as Constructive Research, is the methodological approach adopted in this investigation. It is a sociotechnical approach, prescription-driven and focused on a problem-solving paradigm faced in the real world. It involves the design of an artefact and a practical-theoretical contribution (HOLMSTROM; KETOKIVI; HAMERI, 2009; KASANEN; LUKKA; SIITONEN, 1993; VOORDIJK, 2009).

The research problem falls within the realm of Construction Management Research. According to Voordijk (2009), contributions to research in construction management and economics stems from a range of different areas and the resulting knowledge is multidisciplinary. This investigation is result of a cross-disciplinary problem encompassing topics from Management Sciences, Information Technology, and Design and Engineering.

5.1.1 Definition and characterization

Kasanen, Lukka and Siitonen (1993) describe the constructive approach as problem solving through the construction of organizational procedures or models. A key-term is “to design”, encouraging managers to construct new systems which better address modern challenges. Lukka (2003) defines constructive research as a “research procedure for producing innovative constructions, intended to solve problems faced in the real world and, by that means, to make a contribution to the theory of the discipline in which it is applied”. The novel construction is not discovered but invented and developed. It is experimental by nature, and the researcher performs an explicit empirical intervention based on the belief that by a profound analysis of what works in practice, one can make a significant contribution to theory (LUKKA, 2003).

Four core elements of constructive research have been appointed by Kasanen, Lukka and Siitonen (1993) and then refined by Lukka (2003) as: (a) practical relevance of the problem and the solution; (b) connection to prior theory; (c) practical functioning of the solution; (d) theoretical contribution of the study.

March and Smith (1995) highlight the distinction in relation to the natural sciences. As said, “whereas natural science tries to understand reality, design science attempts to create things that serve human purposes. It is technology-oriented. Its products are assessed against criteria of value or utility (MARCH; SMITH, 1995)”. The constructive approach is characterized by close connections of scientific ideals of the applying disciplines to the problem-solving paradigm; and the design of useful managerial constructions tends to result in a consulting relation between the researcher and the firm (KASANEN; LUKKA; SIITONEN, 1993)”.

Van Aken (2004) distinguishes three categories of scientific disciplines: (a) formal sciences, such as philosophy and mathematics; (b) explanatory sciences, such as the natural sciences and major sections of the social sciences; and (c) design sciences, such as engineering, medical science and modern psychotherapy. Here, it is valuable to distinguish “design science” to “design practice”. Both are problem-solving activities. While design practice is related to “a particular, situated problem (or group of related problems) with particular stakeholders”, design science relates to “a generalised (or abstracted), type, kind, or class of problems that are relevant to typical, identified classes of stakeholders (VENABLE, 2006)”. Design science distinguishes from practice because it produces new knowledge to a community (VAISHNAVI; KUECHLER, 2007).

From an ontological view, Holmstrom, Ketokivi and Hameri (2009) argue that in explanatory research “the phenomenon to be studied already exists out there, and the goal of the researcher is to develop an understanding of it” as opposed to exploratory (or design science) research in which “the phenomenon must be created before it can be evaluated; the creation of artificial phenomena or simply artefacts is essential”. Both strategies assume a strong empirical focus, but design science need, at first, create an artificial phenomenon, an artefact. Under this premise, only after the artefact construction, data can be obtained and analysed.

Van Aken (2004) makes a distinction between organization theory and management theory. The first is a result of a description-driven research (explanatory in nature and to be used largely in a conceptual way), while the second is prescriptive-driven (to be used largely in an

instrumental way to design solutions for management problems). Therefore, management theory, aligned with design science, seems to fit to the context of this investigation.

Voordijk (2009) suggests that construction management can benefit from design science research to solve complex and relevant problems in the context of design, production, and operation of the built environment. AlSehaimi, Koskela and Tzortzopoulos (2012) argue that within the context of construction management research, “there is a need for research approaches that allow researchers to participate actively and influence practice while creating new knowledge”, and for doing so, non-traditional research approaches such as constructive or action research should be utilized to generate practical managerial techniques or to test extant techniques in new environments. Koskela (2008) also argue that research in construction management should be repositioned as design science, oriented towards solving relevant problems faced by the industry and simultaneously contributing to knowledge of this discipline.

5.1.2 Distinction of design science research to action research

According to AlSehaimi, Koskela and Tzortzopoulos (2012), non-traditional techniques such as action research and construction research have the potential to tackle some of the persistent managerial difficulties in construction, so to generate real contributions to practical concerns and theory to knowledge to this knowledge field. Due to the overlapping characteristics, it is relevant to clarify the position of this research as DSR and not as Action Research, since the strong researcher participation within the organizational activities can be found in both cases.

Lukka (2003) clarifies that action-oriented studies typically aim at careful description and thorough understanding of empirical phenomena without a problem-solving type of normative purposes. A constructive-oriented study, in turn, is centred in the problem-solving paradigm. Van Aken (2004) says that action research does not explicitly aim at developing valid knowledge that can be transferred to other context. Holmstrom, Ketokivi and Hameri (2009) argue that action research focuses on problem-solving processes or group dynamics in a specific problem situation without an explicit development of artefacts. On the other hand, design science must explicitly focus on the design and implementation of a means to an end.

In this investigation, the researcher adopted a position which is nearest to a “designer” to devise conceptual solutions, rather than a “facilitator” to transform and deploy lasting working practices in the specific environment of a single company.

It is worth noting that “empirical studies” used in this document refer to a set of construction projects in which the research activities have been developed as part of the DSR approach. It is here clarified to avoid misunderstanding about the research orientation, since “empirical study” here refers to an empirical element of DSR, in contrast to the “Case study” methodological approach widely used in Social Sciences.

5.1.3 Mission of the design science research

Design science research emphasizes the process of exploration through design. Thus, it seeks: (a) to explore new solution alternatives to solve problems; (b) to explain this explorative process; and (c) to improve the problem-solving process (HOLMSTROM; KETOKIVI; HAMERI, 2009). The mission of the design science is to develop knowledge for the design and realisation of artefacts that can be used by professionals of the discipline in question (VAN AKEN, 2004). In case a research project fails at a practical level, from the academic viewpoint, it still has significant theoretical implications (LUKKA, 2003).

Holmstrom, Ketokivi and Hameri (2009) highlight the importance of involving theoretically inclined researchers in the early phases – when the researcher conducts the groundwork – because: (a) theoretical expertise can prove useful in the iterative process of improving the solution design; (b) theoretical expertise can also steer the design scientists’ efforts towards fruitful theoretical insight; and (c) the theoretically oriented scientist can benefit from the possibility of actually taking part in the iterative innovation process instead of gathering information on the process after the fact with retrospective reports.

5.2 RESEARCH DESIGN

March and Smith (1995) state that design science consists of two basic activities: build and evaluate. The build-evaluate pair in design sciences parallel the discovery-justification pair from natural sciences. Building is the process of constructing an artefact for a specific purpose, and evaluation is the process of determining how well the artefact performs (MARCH; SMITH, 1995). These authors emphasize the importance of determining why and how the artefact worked or not within its environment. Accordingly, theories come to explicate the characteristics of the artefact and its interaction with the environment that resulted in the observed performance.

A typical research process, as proposed by Lukka (2003), is organised as follows: (a) find a practically relevant problem, which also has potential for theoretical contribution; (b) examine the potential for long-term research co-operation with the target organization; (c) obtain deep understanding of the topic area both practically and theoretically; (d) innovate a solution idea and develop a problem solving construction, which also has potential for theoretical contribution; (e) implement the solution and test how it works; (f) ponder the scope of applicability of the solution; (g) identify and analyse the theoretical contribution.

This research is organised in three main phases. The steps suggested by Lukka (2003) were used as the main reference to define and position the activities carried out along the research process described in the Research Design (Figure 1). The awareness of the problem and research problem statement definition are based on the activities held in Phase 1. The empirical studies carried out in projects of the steel fabricator company were held in Phase 2. Finally, the development of the artefacts and reflective evaluation were held in Phase 3.

Concerning the empirical part of this research, the exploratory study (Phase 1) was undertaken to obtain a broad understanding of the practical problem. A detailed study about the working processes and information management methods enabled the identification of barriers concerning a more extensive use of BIM. In four short empirical studies (Phase 2), some ideas related to implementation were tested in different project types and project stages. After that, findings were assembled to introduce the component elements to make part of the artefact.

The roadmap and guidelines (Phase 3) are grounded in the concepts of STS and TRM as discussed in Chapter 4. The elements and sequence proposed in the roadmapping were retrieved from recommendations and trends identified in the literature review (Chapters 2 and 3) and from findings of the empirical studies (Chapter 6). The empirical interventions within the company allowed the researcher to reflect about the limitations of technical and organizational circumstances impacting both project and routine management. In the design and evaluation of the artefact (Chapters 7 and 8), literature review and the devised guidelines were revisited to take conclusions on the research.

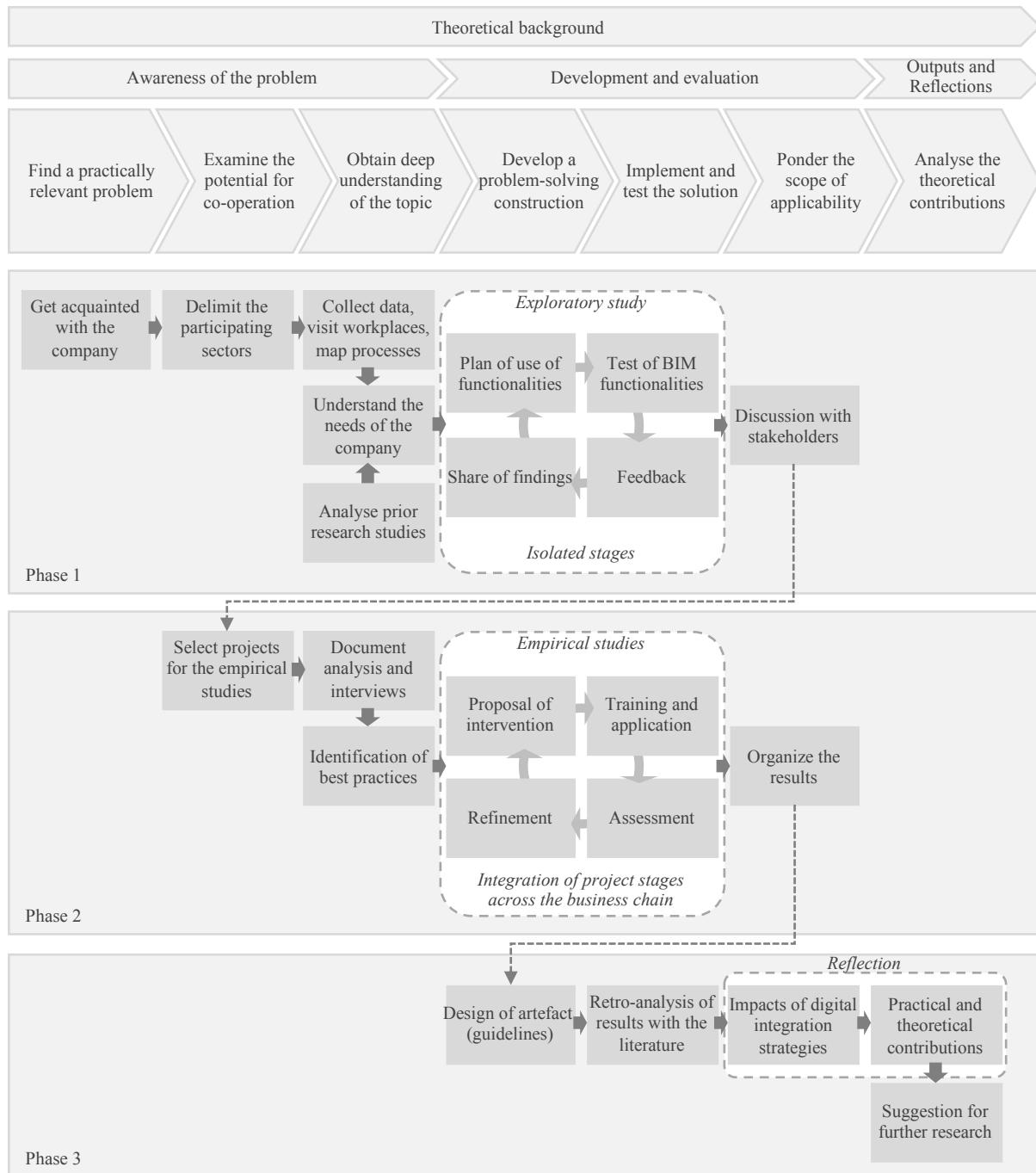


Figure 1: Research design

5.3 DESCRIPTION OF THE COMPANY

The company is based in Rio Grande do Sul state, southern Brazil, and is the largest steel fabricator in the national context. Currently, there are four manufacturing plants operating in three different cities in the country, approximately 200 simultaneous contracts, and around 2000 employees. The portfolio is managed into five main business units as follows: (a) light

steel structural systems for industrial facilities (industrial facilities for shorter hereafter); (b) multi-storey structural systems for high-rise buildings (multi-storey buildings for shorter hereafter); (c) civil structures, including bridges and off-shore platforms; and (d) fast delivery pre-engineered facilities; and (e) technical services for maintenance and retrofit.

Excepting the fourth business unit (fast delivery pre-engineered facilities, whose production system is closer to MTO/FTO), most of the company's operations can be considered as engineer-to-order (ETO), providing customized structural solutions according to specific characteristics of the building project and customer requirements. However, due to the unique features of their set of products, each business unit runs specific processes and often uses different software, machinery and supporting equipment. Internally, they cover many phases of the product development process including: sales, cost estimation, planning, design approval, design detailing, bill-of-materials, manufacturing, logistics and assembly on-site. Very often, these teams can be geographically distant from the project site.

Prior research projects developed by NORIE-UFRGS in partnership with the company were related to Master and Doctoral studies. The first one consisted in the development of a production planning and control system based on the Last Planner System (FABRO, 2012). Thereafter, the work of Wesz (2013), Viana (2015), Bortolini (2015) and Sanches (2015) involved studies on design and production planning and control, supply chain management, use of BIM for logistics, and standardized work, respectively. In parallel to this investigation, an additional research work related to logistics management was under development.

The first direct contact with the company was during a site visit to the main manufacturing plant in October 13th, 2014. This visit was conducted by the Coordinator of Logistics of the industrial facility unit. Around this period, previous and ongoing studies within the company were analysed to understand the context and to find out research opportunities. The very initial research scope was structured as a continuation of one of the projects under development. At this point, NORIE had developed research only within the industrial facility unit.

However, during a meeting with one of the Coordinators of Engineering in October 24th, 2014, the research group was informed about the use of BIM tools by the design team of the multi-storey unit. Then, research scope and objectives were redefined to include the multi-storey building unit, and to cover not only production stages, but also to analyse the influence of BIM-design in ongoing projects and the potential for improving design and production integration.

In November 2014, a decision was made to undertake an exploratory study in a multi-storey building project with the purpose of better understanding the development process and identifying improvement opportunities in parallel with observation of ongoing research projects (undertaken by NORIE researchers in the industrial facility unit). Issues and challenges identified in these projects helped to find out potential interventions to be tested and applied in the multi-storey unit.

Apart from the pre-existing partnership between NORIE and the company, the characteristics of the company and the challenges identified at the beginning of this investigation indicated that this was a fertile environment to develop the research activity. The company was under a changing process towards the adoption of new technology platforms, had a reasonable technology infrastructure, and had the support of managers to implement continuous improvement. However, there was a lack of knowledge about strategic and tactic solutions to overcome bottlenecks of implementation and about the use of available tools in the newly operating information systems.

By contrast, the nature of projects available for the empirical studies were very different among them, implying in additional challenges to link results to build up findings and comprehensive solution proposals. Due to time restrictions, the empirical studies were conducted in specific project stages, while the ideal was to carry out this investigation in whole projects and program. To some extent, discussions with other researchers were instrumental to identify the research problem and to build up the roadmap and the guidelines, taking advantage of prior studies to carry out analysis from an expanded perspective.

5.4 RESEARCH PROCESS

5.4.1 Empirical studies and literature review

The company provided access to project related documents, observation of routine activities and direct interaction with team members to collect data. Evidences to understand the research problem were collected during the initial activities observing the company's operation challenges through non-structured interviews, observant participation in meetings and work-routines, document analysis and plant visits. These observations were organized to consolidate the practical problem statement within this specific company, and then related to other issues identified in the literature to consolidate the research problem and objectives.

By analysing prior academic studies developed within the company, it became clear what had been done so far and what were the remaining opportunities (Figure 2).

Sources	Objectives/subjects
Fabro (2012) Wesz (2013) Viana (2015)	The main objective in analysing these studies was to obtain an overall understanding of the context of the company, as well as the interventions undertaken along the initial period of the partnership. Their description of the company and insights from the studies were used as a starting point for better understating the practical problem and identifying the gap to be continued. The challenges reported in the implementation of Fabro's study and the characterization of the PDP developed by Wezs were considered for defining the approach to be used in implementing BIM in design and planning activities. Viana emphasized the need of synchronizing the business chain of the company, giving details of existing and proposed mechanisms to improve integrated project development and delivery.
Bortolini (2015)	The main objective in analysing this study was to understand the impacts and challenges of using BIM functionalities by planners and builders not familiarized with BIM process. Insights could be obtained from Bortolini's presentations of partial results (unpublished) and in meetings together with the company's staff.
Sanches (2015)	Part of the field work of Sanches overlays with the exploratory study of this investigation. The scope was completely independent, but discussions with the researcher clarified bottlenecks in existing project information flow.

Figure 2: Prior NORIE research studies developed within this company

For the theoretical understanding of the problem, the literature review was undertaken as part of the research cycle and used a mix of sources and techniques as described in (Figure 3). Based on issues identified during the early empirical observations, an exploratory review was conducted to better understand the fields of study involved with the practical problem aiming to find out some potential practical solutions with theoretical contribution.

Apart from the academic papers, further industry reports, international standards and national guides were examined looking for state-of-the-practice examples to benchmark and learn from successful and unsuccessful cases in industry.

Type of review	Objectives/topics
Exploratory reading	Initial search focused on process integration in engineer-to-order operations, as suggested by previous research studies. IT has been extensively assigned as a solution to integration issues, and in specific context of construction sector, BIM was pointed as a trending topic for discussion.
Industry reports and standards	Surveys published in the last five years from North America and Europe provided a broad understanding of the current state of BIM implementation, as well as the benefits and challenges perceived by professionals. Then, guidelines, contractual documents and national standards provided by government and professional associations from the US, UK, Finland, Singapore, Australia and New Zealand were consulted. Documents from other countries of Scandinavia and Asia-Pacific were just overseen due to language barriers.
Literature review	From the exploratory review, the researcher could identify the main databases from where relevant papers could be retrieved, as well as the key-words and exclusion criteria to meet the objectives of the review. Since some of the topics are relatively new (mainly those related to trends in technology), part of the consulted literature comes from conference proceedings, technical reports and websites. These papers were used to identify the gap in knowledge and to structure the literature review chapters.

Figure 3: Types of review

Concerning the empirical activities, an exploratory study was initially developed with the goals of understanding the company's routine processes and analyse pre-identified bottlenecks in a real project. It was possible to observe a recurrent problem caused by deficient interface between design and production teams, with special attention to data exchange and information flow. After a deeper analysis at organizational level, four empirical studies identified specific barriers and opportunities related to the implementation of BIM in view of improvements of working practices at different project phases and product typologies (Figure 4).

Despite of the broad range of new technologies discussed along this document, the empirical studies concentrated on BIM-related technologies. The main reason is that levelling BIM awareness represented a major challenge at the company, which has not taken advantage of the powerful conditions they had in hands. CAE and CAD/CAM-based tasks and data exchange were relatively well-established, whilst ERP has been managed in parallel (not emphasized in this study). About CAD/PDM of the new PLM platform, the researcher had limited access to the development progress, although received some explanations about the ongoing activities.

Categories	Projects
Exploratory study	Issues of design representation for fabrication and assembly <i>Furniture manufacturing plant in Bento Gonçalves</i>
	Study of simulation of assembly schedules in early stages <i>Hangar for airline hub in Campinas</i>
Empirical studies	Merge of architecture-structure models for visualization <i>High-rise office buildings in São Paulo</i>
	Study of erection and logistics planning using BIM <i>Hotel in Rio de Janeiro</i>
	Study of the product development flow enhancement through BIM <i>Healthcare facility in Campo Grande</i>

Figure 4: List of empirical studies

Exploratory study: Furniture manufacturing plant

A research study on this project had been conducted by Sanches (2015) who was interested in the management of site operations, mainly focused on applying standardized work concepts in assembly tasks. The project referred to the structural system of a single floor furniture manufacturing plant in Bento Gonçalves. The starting point for analysing this project was a problem raised from the incompatibility between shop drawings specifications and the fabricated components, which did not meet the assembly requirements. Although this study was carried out in the same project as Sanches (2015), the scope in this dissertation had a different focus and objectives.

Empirical study 1: Hangar

A member of the continuous improvement department first notified the possibility to undertake a research study in this project during a plant visit. The project referred to a large-scale hangar of a major air hub in Campinas. The researcher met the design team in charge of this project and obtained an overview about the design in progress. The researcher was asked on how to retrieve BIM information from the applications in use (BIM authoring tools for structural steel) and which were the requirements to perform 4D simulations, even before the confirmation of the research study. After that, simulations were prepared according to the request of the assembly coordinator.

Empirical study 2: High-rise office buildings

This empirical study was conducted in collaboration with engineers of the multi-storey unit. It was developed for a large scale high-rise office building project (170.000m²), comprised of two-wing towers connected by five footbridges located in São Paulo. The main contractor belonged to the same group of the owner. The architectural practice was remarkable for designing corporative buildings and was said to be one of the most experienced BIM users at national scenario since 2009. The steel fabricator company was subcontracted for providing the steel part of the building structure, including the footbridges. BIM collaboration was not an owner's requirement and deeper collaboration with the architectural practice was not possible due to contractual reasons.

Empirical study 3: Hotel

This study aimed to test situations in which BIM could support the management of logistics and assembly process and operations. The project referred to a luxury hotel in Rio de Janeiro, located in the heart of a touristic area. Constrains were related with narrow configuration of the site to place inventory and machinery, as well as time limitations to access the site. Site layout and equipment synchronization with other subcontractors who were simultaneously working on the site were some of the struggling factors due to the urgency to deliver the building since the owner intended to operate it during a mega-event to be held in the city.

Empirical study 4: Healthcare facility

This study was carried out throughout the development process of a healthcare facility within the multi-storey unit of the company. The project referred to the expansion of a hospital located in Campo Grande owned by a large health insurance provider, from 3.000m² to 23.000 m² distributed in three phases. A critical factor was that part of the existing building needed to keep operating during the construction works.

5.4.2 Sources of evidence

Multiple sources of evidence were used to learn about of the organization and the project process of each empirical study. Their core objectives are explained in Figure 5.

A comprehensive examination of the running business process was undertaken in the early phases of the empirical studies. The main sources and activities are described as follows:

- Set of interviews with the technical staff to understand the ongoing changes in enterprise operations; and compare these new schemes with pre-existing process models.
- Analysis of project and contractual documents (i.e. company's performance records, terms of responsibility for sharing information, standards and manuals, etc.).
- Observation of data transfer mechanisms of the information system, commercial software packages in use, and IT expansion plans.

Site visits to manufacturing plants, offices and construction sites to see routine operations and to perceive existing peculiarities between business units and functional teams.

Source	ES	E1	E2	E3	E4	Objectives
Non-structured interviews	x			x	x	Understand the team's routine and how it connects to corporative objectives; and identify issues and opportunities from the staff point of view.
Document analysis	x	x	x	x	x	Deepen the comprehension of the company's practices and standards; collect project data for structuring research interventions.
Direct observation				x	x	Understand specific operational activities; compare best-practice recommendations and real practice; and collect evidence for future proposals.
Participant observation		x	x	x		Understand the running processes in the office and plant; retrieve empirical evidence of technical and process issues; and demonstrate the potentiality for new interventions in the workplace.

Figure 5: Source of data in each study

Exploratory study: Furniture manufacturing plant

- Four non-structured interviews (approx. 15 min each) with the assembly coordinator. about problems of design representation and non-conformity of assembly requirements.
- Two non-structured interviews with other NORIE's researchers in this project about the side effects of deficient communication requiring costly and time-consuming procedures.
- Analysis of reports and site photographs (sent via e-mail by the assembly coordinator) to be compared with fabrication/assembly documentation generated by design team.
- Comparison of design documentation sent by the design team with BIM models tested by the researcher using other software (the researcher did not have access to the same software used by that design team in the laboratory) to understand the root-cause of the problem.

Empirical study 1: Hangar

- Participation in three meetings (approx. 30 min each) with the contract manager, the assembly coordinator, and a member of the continuous improvement division. In the first meeting, the researcher received the request for collaborating in this project.
- Review of the design model (scheme design) and planning information (batch division, outline schedule, line of balance) to perform the assembly phasing simulation.

Empirical study 2: High-rise office buildings

- Meetings with a BIM officer to define the merge of models and to collect project files.
- The BIM officer visited the laboratory twice to see the preparation of the models to perform BIM simulation of the of batch installation sequence.
- Collection of project model files to be merged in an external application. Copy of large files need permit of the company's IT division. File processing was managed at campus.

Empirical study 3: Hotel

- Four participant meetings (approx. 40 min) with the contract manager and the assembly coordinator) to understand the project scope and challenges.
- Analysis of documents (i.e. assembly schemes, schedules, crane planes, etc.) and review the content of design, planning and site information to perform the tasks. Design models and documents were collected by e-mail straight from the designers.
- Site visit (approx. 1h15) to a local project of similar characteristics accompanied by the assembly coordinator and the assembly leader on site to identify site logistics bottlenecks.

Empirical study 4: Healthcare facility

- Participation in regular meetings (approx. 1h per week for almost two months) with designers and the BIM officer to collect updated models. Two of these meetings had the participation of the former design coordinator. Total of four months monitoring activities.
- Consultations with: the structural designer in charge of structural conception and cost estimation; two designers in charge of approval and detailing design (a design assistant joined the discussions); and the person in charge of product structure management (PSM).
- Collection of non-project related files (product model samples) to understand technical characteristics of the information systems used in this project.
- Collection of project related documents to review the content of design, planning, manufacturing and logistics information to set up the proposed interventions.

- Two days *gemba* visit to the manufacturing plant, watching all stages of fabrication, quality assurance, packing, inventory, transportation tasks of a production batch.
 - Interview on the plant with: one plant scheduler, one quality control supervisor, three designers, two expedition leaders and one truck driver, and informal conversations with welders, painters and assemblers, a health and safety leader, and with the plant manager.
- Feedback from the departments involved in a workshop conducted by the researcher after a plant visit in one of the manufacturing units

5.4.3 Limitations concerning the empirical studies

A major limitation of the empirical studies is that most BIM related activities were not part of the company's routine process and operations. Those activities driving to the creation of an integrated workflow were explored with a strong interference of the researcher. Not all in-house staff accompanied the research process in detail. Therefore, outcomes were communicated only to the involved teams (not the whole company), which implied in an incomplete absorption of the lessons learned.

Most actions were conducted with the participation of middle managerial participants who were very active, so that suggestions could be turned into practice. By contrast, as the top management was not directly involved in the investigation, permissions to access information took a long time, and not all proposed improvements could take place. Another issue was that important resources used along the studies were not owned by the company. Some gadgets belonged to the researcher; whilst software was licensed to academic use only. As a result, after the research close-out, some activities did not continue to be undertaken.

5.5 OUTCOMES OF THIS INVESTIGATION

According to Van Aken (2004), academic research in design sciences combines description-driven and prescription-driven research. However, the research object is more “what can be” rather than “what is”, so that a DSR outcome is essentially a prescription.

March and Smith (1995) describe the types of DSR products as: (a) constructs or concepts constitute a conceptualization used to describe problems within the domain and to specify their solutions; (b) model is a set of propositions or statements expressing relationships among constructs used to describe tasks, situations; (c) method is a set of steps (an algorithm or guideline) used to perform a task; and (d) instantiation is the realization of an artefact in its

environment. March and Smith (1995) keep theories (that are the ultimate products of natural science research) out of the list. Other authors propose a fifth category: (e) better theories, which are described as an artefact construction as analogous to natural sciences (COLE *et al.*, 2005; PURAO, 2002; VAISHNAVI; KUECHLER, 2007).

Voordijk (2009) proposes alternative categories of outputs to designate knowledge useful to “design a specific process to produce a certain desired outcome or performance in design, production and operation of the built environment”. The three kinds of are: (a) technological laws (related to models) are empirical generalizations based on statistical data analysis; (b) functional rules (related to methods) is a concept that specify what to do, if a certain result is to be attained under given circumstances; and (c) socio-technical understanding (related to instantiations) are about insights in the interrelationship between design, production and operation of the built environment and social practice.

Regarding the outputs of this investigation, the concepts of socio-technical understanding functional rules and are combined. Voordijk (2009) cite Ropohl (1997) to define socio-technical understanding as “a systemic knowledge about the interrelationships between technical objects, the natural environment, and social practice”. About functional rule or method, Voordijk (2009) states that it “can be an act, or a sequence of acts, but can also be a process or system”. A functional rule works like a user instruction connecting the solution concept with the field problem, in which indication and contraindications are included. These rules can be stated as “verbal instructions, diagrams, protocols or charts”, serving as prescriptions which can be applied without being understood in a theoretical way.

However, the outcomes of this investigation have not reached the status of a rule. Rather, it would be better to consider them as “functional solution concepts”, as the goal was to understand the context for devising more specific solutions in future research and enabling the development of improvements in similar companies.

As the expected outcome, this investigation aimed to provide a better understanding of the context of implementation of new technologies, which can be regarded as the first step for the development of further innovative solutions and the creation of artefacts capable to effectively address real world problems. The main artefacts of this investigation are a roadmap and guidelines, fitting the “method category” of Design Science Research outcomes.

6 EMPIRICAL STUDIES: DEVELOPMENT AND RESULTS

This chapter presents the empirical studies carried out in this investigation. The first section provides an overview of the company's working practices at the beginning of this research study. Then, the results of an exploratory study and four short empirical studies made clear some of the challenges related to the implementation of BIM. Finally, these findings are summarized to indicate the component elements of the artefact of this research.

6.1 PROJECT FLOW AND SUPPORTING TECHNOLOGIES

The company's portfolio is organized in five business units corresponding to the typologies of product-services (Figure 6). Due to the characteristics of distinct products and services, some of the working practices are different at each business unit.

Business unit	Description
Light steel structural systems for industrial facilities*	This unit delivers highly customized structural solutions for industrial facilities, hangars and warehouses. The set of products includes the primary structure, roof tiles, gutters, zenithal lighting, thermos-acoustic insulation, etc.
Multi-storey structural systems*	This unit delivers steel solutions for multi-story buildings including corporative towers, hotels, healthcare, parking and shopping centres. In these projects, the company is subcontracted for the design, fabrication, logistics and site assembly of the steel structure.
Civil structures	This unit deals with large contracts such as steel mills, mining, oil & gas and infrastructure.
Fast delivery pre-engineered facilities	This unit delivers fast warehouse buildings using modular and pre-engineered light structures adaptable to a range of facility types.
Technical services	This unit is responsible for preventive and corrective maintenance, refurbishment of existing steel buildings and minor expansions.

*The objects of study in this investigation are the industrial facilities unit and the multi-storey unit

Figure 6: Business units of the steel fabricator company

This investigation has conducted empirical studies in projects of the industrial facilities unit and multi-storey unit (as explained in Chapter 5).

The business process of one unit differs from others in several ways, including: (a) client involvement; (b) procurement methods and contract arrangements; (c) components typology; (d) calculation methods; (e) modelling software; (f) interference with external designers and consultants; and (g) fabrication and site constrains

6.1.1 Departments and project phases

A generic process map considers the main functions involved in a typical project. Prior researches have schematically represented the main phases of the product development process (VIANA, 2015; WESZ, 2013). At this point, a linear map was simplified by the author to provide an overall understanding of the ordinary process (Figure 7). It does not show design iterations with external disciplines neither simultaneous tasks which are coordinated based on strategic working batch definitions from detailing onwards.

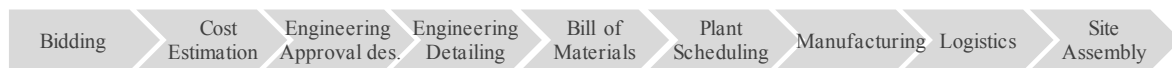


Figure 7: Generic process of the steel fabricator

Apart of the teams directly involved in product development stages, other departments serving the organization also took part of empirical activities as described in Figure 8. Contract management and continuous improvement staff looked after many projects simultaneously and used to have a high-level view of processes and awareness on new technologies.

Department	Roles
Contract management	Manage client's relationship and contracts of projects from bidding to closeout, communicate requirements and constrains with other suppliers to designers, planners and site managers.
Continuous improvement	Provide internal consultancy in different sectors of the company. It was first established on lean directives to enhance production process and operations. The innovation department played a similar work but focused on product development (did not take part of this research).

Figure 8: Departments assisting multiple projects

The main departments involved in this investigation are described in Figure 9. There were also other departments that did not take part of this study (e.g. sales, purchasing, auditing, etc.) and later changes in the organizational configuration not detailed below.

Department	Roles
Planning	<p><i>Project flow</i>: plan, control, and coordination of master schedules.</p> <p><i>Support</i>: support cost estimation of projects under negotiation, coordination of plant scheduling, and purchase of raw materials.</p>
Design and Engineering	<p><i>Cost estimation</i>: prepare scheme design and cost estimation based on the overall building configuration.</p> <p><i>Structural calculation</i>: perform structural analysis, engineering simulations, and structural calculation.</p> <p><i>Approval</i>: design and model structural systems, deliver client approval documents and 3D models for design coordination.</p> <p><i>Detailing</i>: detail all components at fabrication level, including miscellaneous and assembly elements.</p> <p><i>Bill of Materials (BOM)</i>: define the product structure and list the required materials and quantities.</p>
Fabrication	<p><i>Plant scheduling</i>: plan and control the fabrication of components of different projects in manufacturing lines.</p> <p><i>Manufacturing</i>: manufacture, pre-assemble (if specified), control quality and tag ready-to-expedite components.</p>
Logistics	<p><i>Load planning</i>: coordinate the load plans of skids and trucks in alignment with batch definition (sub-stage division).</p> <p><i>Yard and Expedition</i>: control inventory in the plant yard, manage outsourcing, ship and provide invoice of the delivered components.</p>
Site assembly	<p>Plan, execute and control the assembly process on site. Control site yard storage and require the shipment of incoming batches.</p>
IT	<p><i>IT</i>: provide general support in information technology.</p> <p><i>ERP</i>: assist the deployment and management of the ERP system in the company.</p> <p><i>PLM</i>: customize CAD and PDM software in partnership with the external vendor.</p>

Figure 9: Main departments involved directly in the research

6.1.2 Use of digital technologies

Regarding the use of digital technologies, it is worth mentioning the fast-changing nature of IT for engineering and management. Software are often replaced by new applications or, in some cases, renamed to new acronyms. In this company, not all designers used the same software and versions. Some teams run structural analysis in STRAP or Bentley RAM, while the ones

involved in scheme design used MBS, TECNOMETAL or SDS/2. Another example was the gradual discontinuity in the use of UPC Barcode to the adoption of QR code apps for tracking components in the field (e.g. most recent projects are using QR code apps for smartphones).

The situation described below represents the current state of use (Figure 10).

Tech	Description
CAD	<p><i>Tools:</i> AutoCAD and open viewers.</p> <p><i>Uses:</i> design visualization (external designs), detailing design (only for some projects and some components types), fabrication and assembly drawings.</p>
CAE	<p><i>Tools:</i> STRAP, Bentley RAM, MBS.</p> <p><i>Uses:</i> Scheme design for cost estimation, structural simulation and calculations.</p>
CAM	<p><i>Tools:</i> a set of different CNC machines.</p> <p><i>Uses:</i> generation of digital fabrication order to cut and drill.</p>
BIM	<p><i>Tools:</i> TecnoMETAL, SDS/2, Solibri Model Viewer, Tekla BIMsight.</p> <p><i>Tools with educational licenses only during the investigation:</i> ArchiCAD, Revit, Navisworks, BIM Field 360, Synchro Pro, Solibri Model Checker.</p> <p><i>Uses:</i> Product modelling (approval design and detailing), document generation, model visualization, 3D coordination, 4D simulation.</p>
ERP	<p>SAP system has been implemented since 2012.</p> <p><i>Uses:</i> process status update, bill of materials, product structure management, document management for the CAD/CAM systems integration.</p>
PDM	<p>The setting of Siemens Teamcenter was underway by the PLM team. The company planned to run it in integration with Siemens NX.</p> <p><i>Uses:</i> manage product data and process-related information in a central system. This information includes CAD data, modes, parts information, manufacturing instructions, requirements, notes and documents.</p>
Other	<p>eFact LPS (Last Planner System).</p> <p><i>Uses:</i> project management tool based on the concepts of the Last Planner System of production planning and control. It accesses the ERP database to collect and provide planning information in visual panels and reports.</p> <p>UPC barcode and QR code mobile reader app.</p> <p><i>Uses:</i> is used for remote control of component status to a central database. Tags are scanned in plant expedition and site receipt to update the system.</p>

Figure 10: Set of digital technologies currently used by the company

A recently acquired manufacturing plant is yet under migration to the main standards, so it keeps using a mix of old tools (e.g. modelling software and tracking systems). Concerning PLM, a dedicated team is customizing the software modules (CAD and PDM). However, the company's approach for PLM is not holistic and initially foresees the incorporation of a limited set of applications and functionalities, focused in a narrow section of product lifecycle.

6.2 EXPLORATORY STUDY: IMPACT OF DESIGN ISSUES IN FABRICATION AND SITE WORK

Practical problems relying on poor integration in the design, manufacturing and assembly were pointed out by operators and coordinators of each departments. Getting to know this problem from a real project, an evidence was the size of the holes of the base plates which had not been drilled wide enough for bolting. The holes were specified and fabricated with the same diameter of the bolts without any clearance. Although the plate's fabrication was done in accordance with the design specifications (milling machines drilled the plates according to the numerical programming), it did not meet constructability requirements.

This issue was only identified after the fabricated components arrived at the construction site. As a countermeasure, the holes were enlarged using a blowtorch next to the installation place. This implied in: (a) additional care about health and safety issues and quality control during site operations; (b) unforeseen schedule delay; and (c) additional cost for renting of equipment and labour hours.

Moreover, interdependent tasks could not be executed, affecting not only the erection schedule, but the whole site logistics and operations. It also generated several RFI, non-compliance feedback to design and planning teams, and new manufacturing orders.

Following the prevailing practice, component detailing starts once approval design and structural calculations are finished. Then, shop drawings provide a comprehensive set of information for components manufacturing. Profiles and plates are uniquely fabricated according to the engineer-to-order operations (custom specifications), and three types of outputs are produced: fabrication programming files to CNC machines (.nc1); fabrication drawings (.dwf); and assembly drawings (.dwf).

This design of this project specifies 50 columns, among which 12 (4 different types) had problems with the holes of the base plates (24%). Columns are individually designed in accordance with calculation requirements to be safe, structurally well-performing and cost-effective. This project also came to face constructability problems of similar causes in subsequent stages, but in the bracing connecting plates.

Figure 11 shows the shop drawing of the column and the base plate. A highly customized ETO product is engineered on-demand to generate shop drawings to manufacturing. Assemble schemes are later provided with in consideration of erection planning requirements and constrains.

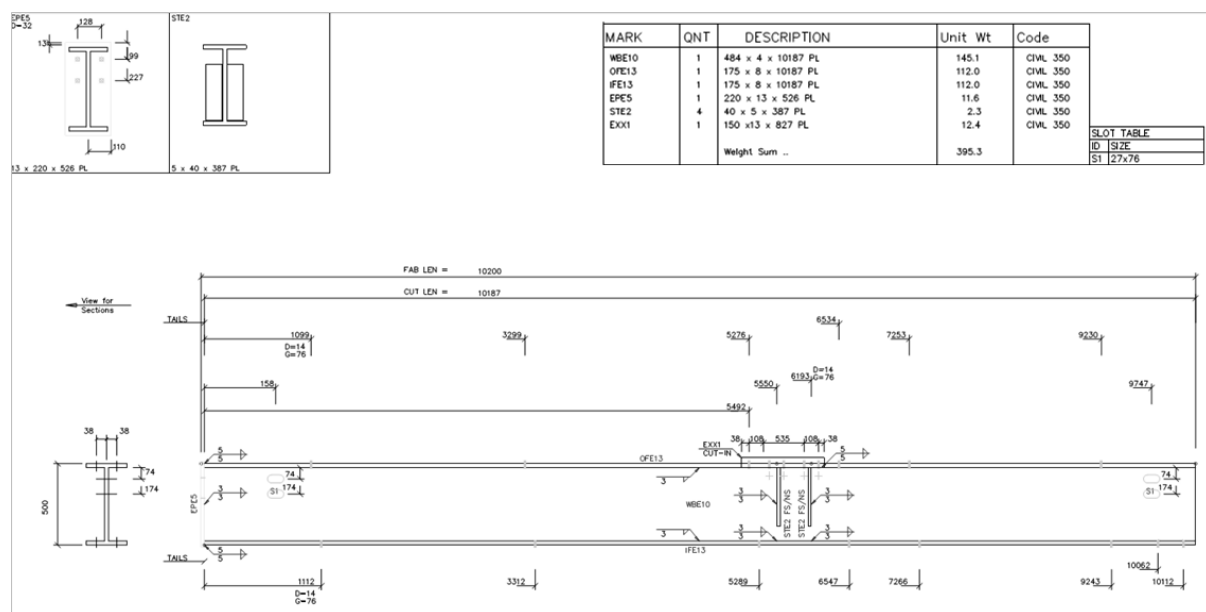


Figure 11: Fabrication drawing for new and highly customized ETO component

By contrast, some of the components can be highly standardized up to the point of being specified as repetitive types fitting in many projects. As in the example below, the placement of the base plate component follows the main project, whilst the anchor detailing is cross-referenced from a set-based design detailing library (Figure 12). These products are produced in a make-to-order operation, based on a set of pre-defined design solutions to meet a range of performance requirements (e.g. anchor bolts, steel decks, etc.). In this case, after the approval design, specifications are linked to options available on a detailing catalogue, and then, fabrication is ordered.

As part of the scope of investigation, a 3D model of this design was modelled using BIM applications (i.e. Tekla, Revit, and an unsuccessful trial in Autodesk Advance Steel). The first challenge was to collect product information which were spread on 5 different drafting and spreadsheet files (design layout, column fabrication drawing, base plate detailing drawing, anchor bolt detailing drawing, and specification tables) to finally join the required inputs for modelling the structure components. In this company, by default, construction documentation was provided as traditional 2D drawings even though the approval design was developed in a 3D application that is partially interoperable with BIM applications (export-only). However, not all teams were aware of the potential of using BIM information along the process.

The exploration of other BIM applications aimed to understand how specification methods can affect the design process and the delivery of legible information. Some of the observed points were: (a) specification fields in steel modelling tools work as a sort of design “*poka-yokes*” (mistake-proven) avoiding that important specification fields are not assigned, or is at least, they are checked by the designer (if intentionally let the field in blank). In another project, of similar characteristics, (b) a “clash detection” was used with the aim of analysing tolerances.

In Figure 13, BIM clash detection identified insufficient clearance of the holes, colliding components (holes not specified in the plate caused by the lack of design check after applying an automated command to generate holes based on anchor’s position), and possible difficulties for accessing the assembly space during site installation. However, because the researcher was not an official member in this study case, a corrective intervention was not implemented.

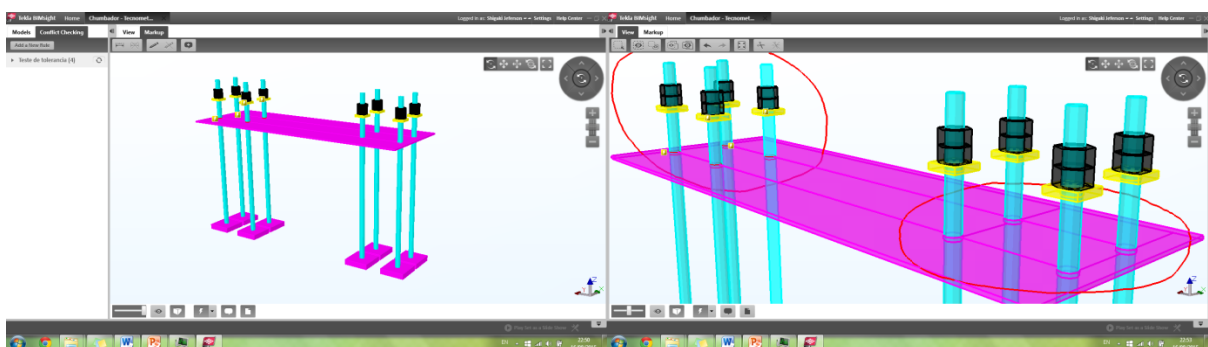


Figure 13: BIM clash detection used for clearance assurance

The same issue of incompatibility between base plate holes and anchor bolts specification occurred in a later project of similar characteristics. The design team was not the same of the study in the furniture manufacturing plant, but they followed a similar strategy in the

engineering process. The recommendation of using graphic information from the 3D model for clearance checking in addition to the 2D drawings was lately given to this other team.

After that, the researcher recommended a feasible and effortless change, encouraging the use of 3D pdf files exportable from the design software, so that the 3D geometry and the main product properties became visible, easy to manipulate, and accessible in most computers on plant and on site. An alternative was the use of BIM viewers (same objective of 3D pdf), enabling the access to even more information embedded to BIM models. A list of free software supporting IFC files was suggested to the IT supervisor of one manufacturing plant who installed them in computers of key-users (engineering, quality control, preassembly on plant).

In fact, the use of clash detection for tolerance analysis is not as effective for the design process as the use of specific modelling tools with automatic design functions to avoid specification mistakes. Nevertheless, design checking is still a strategy to detect design conflicts since deviations from tolerance definitions can be quickly identified and controlled. Alternatively, specific change management systems could be potentially integrated to design to generate automatic report and give iterative feedback to the design and manufacturing process.

In other words, production-oriented design criteria set in design tools can be programmed aiming to meet constructability requirements. Technical standards and lessons learned on field can be translated in design parameters to be incorporated in design, documentation, and visualization tools. Tacit knowledge from site operators could be translated to controllable design requirements, avoiding the occurrence of mistakes in downstream phases.

6.3 Working process and information management

6.3.1 Product development process

Problems like those elucidated in the exploratory study are frequently registered in non-compliance reports used for feedback. In analysing their root causes, many occur because of deficient communication of requirements between design and production activities. The lack of holistic understanding of the Product Development Process (PDP) by functional teams impeded them to understand the impact of their efforts upstream and downstream project life.

The company itself did not have a formal PDP model. Recently, prior researchers had proposed a few versions to explain their intervention intents. One barrier to the establishment of a

reference model is that organizational structure had constantly changed over the years, resulting in frequent: (a) human resources reallocation, (b) functional team splits and merging, and (c) top management rotation deploying new managerial philosophies and working practices. Another source of barriers come from portfolio management decisions and the creation of new production unit designations affecting the organizational structure. As the scope of products and services enlarge, new organizational requirements emerge.

In addition, the modernization and acquisition of new production units implied in several changes in the business model added to the need of introducing more efficient exchange means between them. Recent adoption of the ERP system and BIM functionalities led to another collection of technical, processual, contractual and educational implications. Likewise, upcoming PDM/PLM related changes may entail amendments to the model, as PDP stages and divisions tend to be modified.

Generic process models were adapted by the researcher to clarify and share common views of the workflow and main stages, based on the practices in place by the start of this research. However, at each business unit, the flow of activities undertaken are strongly influenced by the type of product-service delivered (e.g. warehouses, high-rise buildings, infrastructure, etc.), by the typology of production situation (e.g. MTO, ETO, etc.), and by the role assumed by the company in project procurement (degree of external interference in the project).

The criteria for schematizing the PDP (Figure 14) were: (a) use a team-oriented perspective (stages corresponding to teams in charge of the stage); (b) generalize the stages as possible to suit different business units of the company; and (c) focus on design and production processes (focus of this research study), whilst recognizing the importance of pre- and post-development stages. Moreover, it was considered the batch size reduction strategy established by the company, in which a project is divided into stages and then sub-stages with concurrent tasks. After scheme design is approved by the client, design and production control is based on those sub-stages (not represented in this simplified map).

A major finding of the mapping process was the realization that different business units put integration efforts in different sections of the process depending on the product characteristics and typology of production situation. In these points (dashed lines), stakeholders in charge of different disciplines or product lifecycle stages get together to make joint decisions.

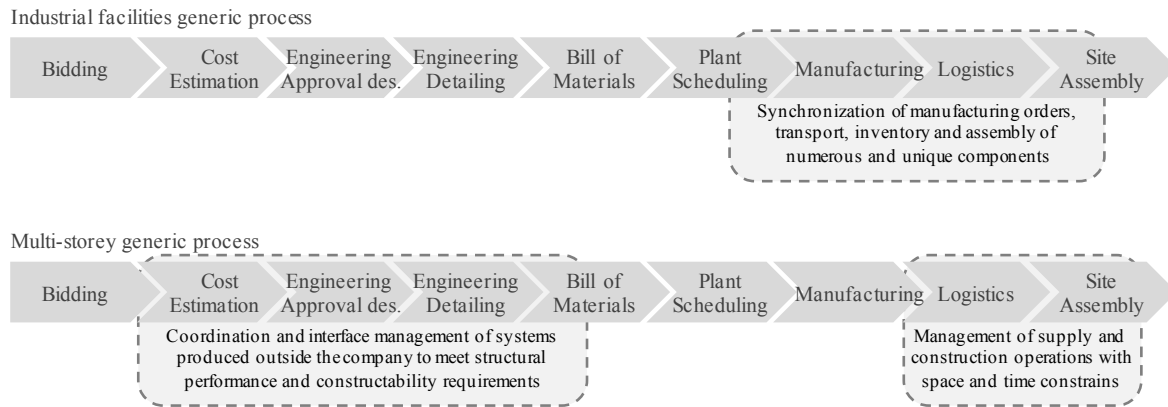


Figure 14: Integration efforts in industrial facilities vs multi-storey generic process

In the industrial facilities projects, for instance, major integration efforts were employed downstream (from plant scheduling to site assembly). Despite of the installation batch division, components of different batches can be manufactured in parallel, requiring a careful coordination between plant and site (especially concerning inventory yards and expedition times) to avoid mixing parts of different batches struggling the installation sequence, and not overfill the inventories with components to be installed much later.

In the multi-storey project site, large steel components are easy to identify (considering size and shape characteristics) whereas they are difficult to handle, requiring an ostensive use of lifting equipment. Steel related activities need to be coordinated with other disciplines on site sharing inventory spaces and equipment. Furthermore, upstream process requires multidisciplinary collaboration with external teams for adjusting system interfaces (e.g. architecture, cladding, etc.). The inherent characteristics ETO operations imply in complex engineering and challenges to design coordination and change management.

Points of integration efforts also relate to procurement and project delivery methods. In the industrial facilities unit, the steel fabricator is usually contracted directly and maintain straight communication with the owner. Other suppliers are usually concrete (foundations, floors, precast structure, cladding panels, etc.) and MEP/HVAC subcontractors. However, structural steel is treated as a critical path and one of the most important suppliers in the project. In multi-storey unit, the steel fabricator can be directly hired by the client or subcontracted by a main contractor or an owner's representative (project manager). Procurement method is usually design and build, and the steel fabricator has much less influence in the negotiation of site

conditions if compared to projects of the industrial facilities unit. Even though the company is responsible only for a single discipline, it plays a longitudinal participation across the project.

In short, the industrial facilities unit employs large efforts to coordinate production process, dealing with a huge amount of components types and quantities. Otherwise, in poorly integrated processes, elements could be lost, or the delivery can be late to accomplish the targets of installation schedule. By contrast, the multi-storey unit endeavours to coordinate product design process in a way to manage interference with external stakeholders and constructability constrains. For both, the owner's requirements pull the development of new solutions at each new project leading to even more complex ETO operations.

As the design is produced in-house, there is a strong overlapping between design detailing, fabrication, logistics and assembly activities. Moreover, in typical design and build projects, other suppliers can share the site to execute their tasks simultaneously, increasing logistics and construction operations complexity. At last, there are two flows to be coordinated: (a) the internal process flow from design to site assembly and commissioning activities executed by in-house team; and (b) interfaces with other design disciplines and site stakeholders, especially to overcome the prevailing "over-the-wall" practice to more collaborative approaches.

6.3.2 Use of BIM before this investigation

The company have already employed BIM authoring tools for design and engineering in some projects of the multi-storey business unit. In a first stage, BIM software replaced old CAD systems and was simply used to modelling and generation of design documentation, but still in a traditional way (paper-based workflow and discrete data exchange).

A few years before, a consulting firm was commissioned to remodel architectural and structural designs and to 3D model temporary construction objects into a BIM exchangeable formats in order to apply clash detection in a pilot project for a client of the hotel sector. However, 3D coordination did not become part of the company's routine practice. A similar work was done again as part of the empirical studies of this research work, years later. The researcher was requested to merge the structural model developed in-house with architectural models developed by an external architectural studio to be presented in a vendor contest and not for constructability purposes aiming to actually improve project performance.

At this point, BIM Project Execution Plans and BIM protocols (as those cited in the literature review) have not been used by the company to streamline and speed up data exchange agreements. The management of information exchange with other teams were conducted by designers, the assembly coordinator and the contract manager without discussing classification systems, standards, and neither legal and contractual aspects of BIM exchange.

On the one hand, the company acknowledged the importance of process alignment and database management, which were constantly under improvements. On the other hand, effective digital collaboration using BIM had not been achieved in any other project so far, and improvements have been delegated to external consultants when required.

A major reason for not achieving BIM integrated workflow is that benefits obtained were limited to specific projects and knowledge creation had not been entirely retained. Also, external firms involved in these projects were not capable to deliver short-term benefits, while partnering with project stakeholders were not agreed in a long-term perspective. Therefore, the main opportunity was to internalize BIM management and assume wider control of the exchange relationships based on the partial achievements experienced in information flow.

6.3.3 Internal data exchange and interoperability

Despite of the use of BIM authoring tools, projects were not managed as a comprehensive BIM approach, part of a wider business strategy. Broadly speaking, teams in each unit had reached different capability levels in managing BIM. In the multi-storey unit, predominantly using SDS/2, modelling tasks have been internally accomplished in an advanced level, even though the level of BIM awareness and technical capabilities varied inside the unit. Meanwhile, in the industrial facilities unit, designers used MBS and TecnoMETAL to model in 3D, generate documentation and fabrication data, but not as an integrated BIM process. Activities were done in a stand-alone fashion and project data was “thrown next”. Nevertheless, despite the possibility of “working BIM” with the existing resources, design teams of both units could not reach a comprehensive BIM approach to the product development process.

Earlier in the process, engineers used CAE tools for analysis and simulation. The interface between analytical models developed in CAE and BIM tools to continue structural modelling for approval and detailing was done via CIS/2 scheme. For example, in a multi-storey project, project data generated in Bentley RAM was exported to SDS/2 via CIS/2. Then, SDS/2 recognized the analytical model and object properties to converted them into BIM elements.

After modelling completion, designers generated specific files (readable in CNC) for production programming. Alternatively, SDS/2 offered direct connection with CAD/CAM and MRP functions. In addition, design documents were exported via .dxf to fabricators and assemblers and external stakeholders including architects, MEP/HVAC consultants, design coordinators and clients. The generation of IFC was limited to a few requests from the client side for other purposes, irrespective of the company. But, as reported in the interviews, owners and project managers did not use any type of IFC specifications to request a model.

The researcher strived to extend the use of BIM information, given that a huge modelling effort had already been spent along the engineering process and embedded information of the models could be reused in further applications. Among the tools available in the company, Design Data SDS/2 (v. 7.323 64bits) was one certified by Building SMART (CV2.0-Struct) to export IFC2x3 files¹⁶. In order to check how SDS/2 outputs would behave in other applications, an IFC model from a random project (not used in any empirical study) was provided (Figure 15).

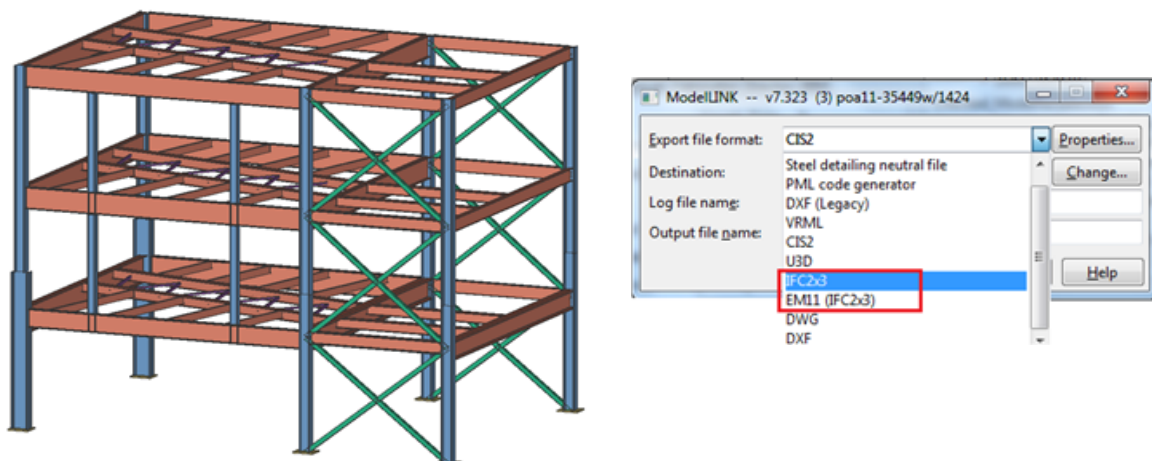


Figure 15: IFC export test from SDS/2

This IFC2x3 file was imported in different software, (Figure 16). As could be expected, the degree of visualization and manipulation of geometry and non-graphical information varied in each software. Model integrity was unsatisfactory when imported to Autodesk Advance Steel (version 2015). All other BIM applications gently accepted IFC import.

¹⁶ “Exported IFC files retain the exact structural organization and geometric shapes as they exist in the native SDS/2 model (BuildingSMART IFC certification for Design Data SDS/2, 2015)”.

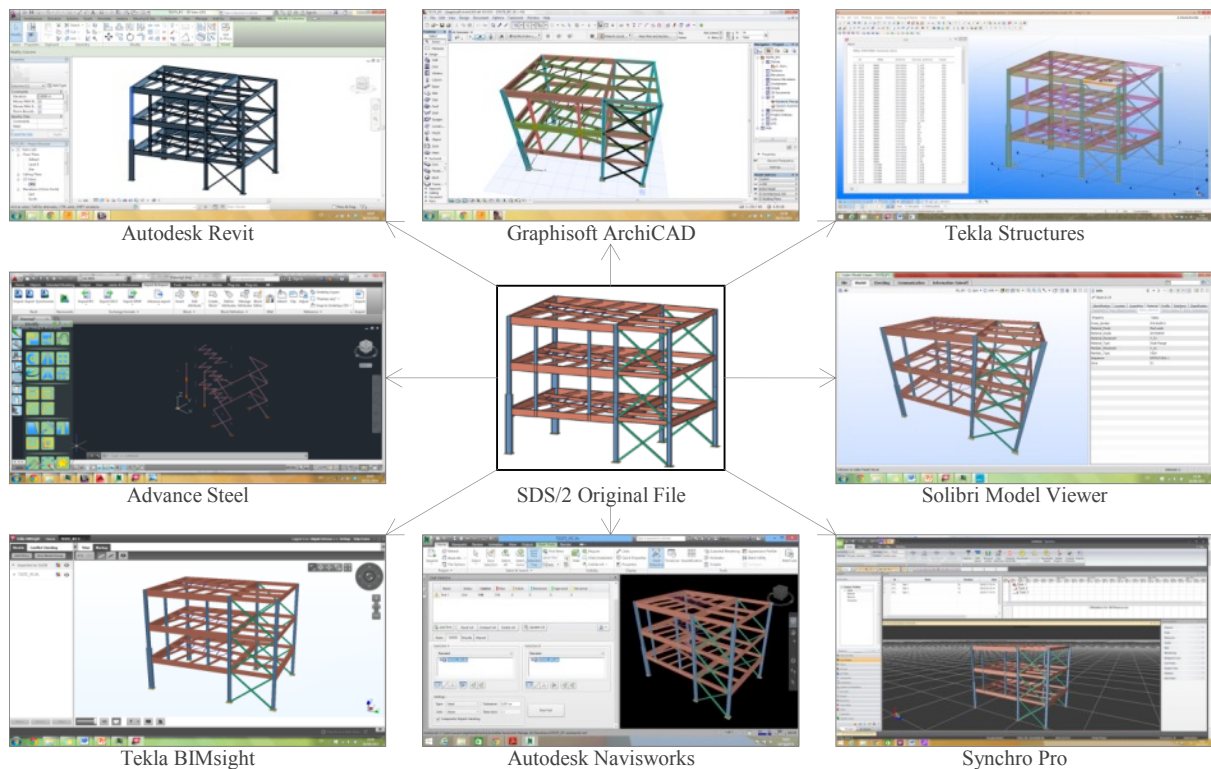


Figure 16: IFC export-import test with SDS/2 file

The other part of design teams used to use TecnoMETAL, an application not certified as an IFC exporter. Nevertheless, empirical studies of this research used IFC generated in TecnoMETAL to enable 3D visualization and other BIM related activities (e.g. schematic 4D and clash detection tests). As expected, not all information could be visualized when transferred to other software (e.g. some quantity information fields were readable in Solibri, but not in Naviswork). For a model exported from SDS/2, the same field could be equally identified in both applications. Despite of this, it was more convenient to use such incomplete or deficient IFC file than modelling the structure all again for 3D visualisation and 4D simulation purposes.

Considering the modelling tools available at the company and those using educational licenses (computers in the laboratory of the University), an expanded use of BIM could take advantage of model information extracted from SDS/2 to be reused in other BIM functions in addition to those enabled by the tools already in place (Figure 17).

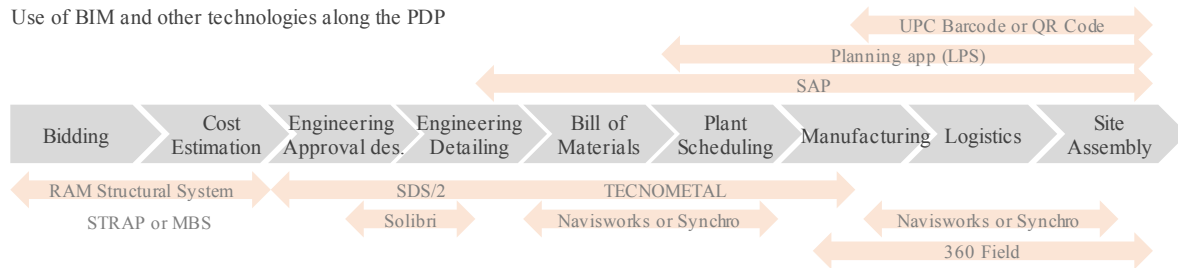


Figure 17: Generic set of technologies used in processes of the company

A last data exchange test was performed with Siemens NX, anticipating future uses based on models generated in NX, which tends to replace current modelling tools in the next few years. A major concern was on how to interface NX to integrate structural modelling workflows in BIM environment, especially through CIS/2 and IFC schemes. For uses not requiring specific semantic information (e.g. geometry only), a provisional alternative was to export .dxf or .xml files, and then, import them in a BIM application (e.g. Navisworks) to perform 3D geometric coordination, 4D simulations, and other uses suitable to the company's operations.

6.4 IMPLEMENTATION IN EMPIRICAL STUDIES

6.4.1 Study of simulation of assembly schedules in early stages

This project referred to a hangar for airline hub in Campinas. The notification to develop an empirical study in this project was communicated during a plant visit aiming another research study. The researcher had the chance to meet the team in charge of this project and obtain an overview of the design early in the process. In this occasion, the researcher and structural designers exchanged some ideas on how BIM information could be retrieved from the models. It was the first time this design team was working BIM instead of the traditional workflow. The modelling tool was TecnoMETAL and they have never been required to export IFC so far.

The researcher briefly explained the utility of IFC scheme and discussed opportunities of using those models in BIM viewer applications by other functions of the manufacturing unit (e.g. preassembly, quality control, expedition, etc.). Representatives of quality control team, plant scheduling team and the loading supervisor joined the engineering office to watch demonstrations of export files produced in TECNOMETAL imported in BIM viewers. These demonstrations were useful, especially because when the study case started, the team could send the models as required, following the procedures taught by the researcher during the visit.

A few weeks later, the contract manager arranged a meeting to explain the project status, because he speculated using 4D BIM to visualize scenarios of assembly sequence. Project size and complexity were very demanding in terms of engineering and logistics, so the contract manager (aware of BIM potentialities) requested a 4D simulation of the master plan for visualizing erection phasing alternatives and gross estimating the required resources.

To make the simulation, the 3D model was collected from the design team. A hand-drafted sketch defining the erection batch division was used as the reference to link model components to the batch phases. The provisional master schedule was yet in an Excel spreadsheet, as well as the Line of Balance (LOB). The spreadsheet data was imported to Synchro Pro, and then assigned to structural model components. Complementary site elements (e.g. access roads, cranes, etc.) were requested to be part of the visualization. The research team used Revit to model the site delimitation, while equipment objects were imported from Synchro Library.

The outputs were videos from different viewpoints and speeds. Simulations were used internally by the contract manager and the planning team for collaborative scheduling and estimation of resources; and externally for a presentation to the owner before the final contract signing. Although simulation models were not detailed due to time constrains, simplified 4D schemes aided the planning team to test scenarios and make decisions based on visual features (Figure 18).

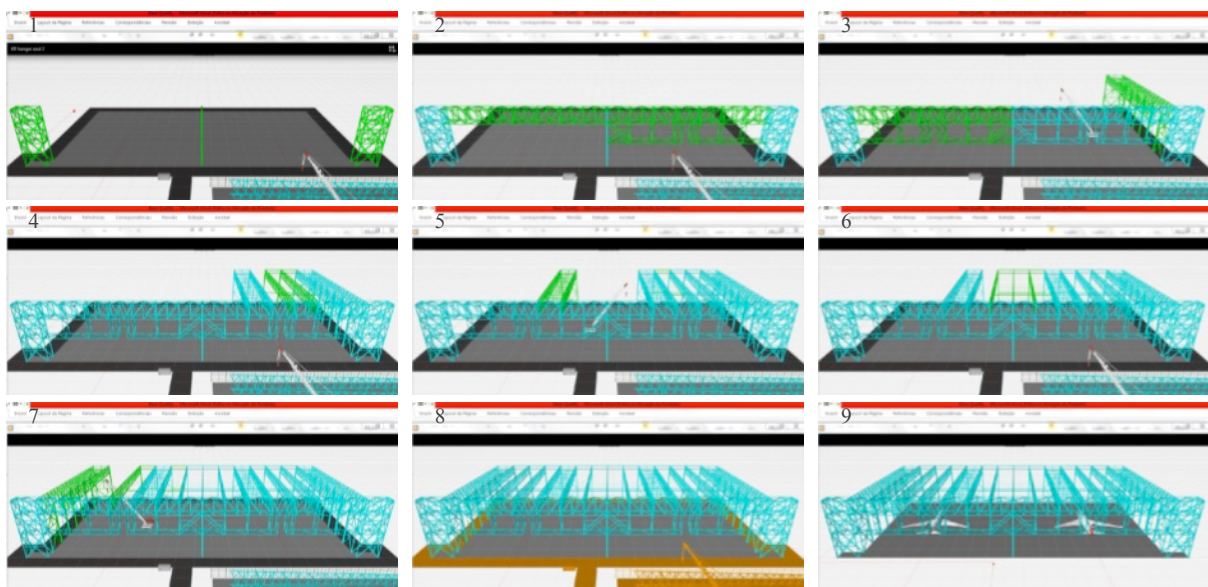


Figure 18: Screenshots of a 4D simulation of the assembly master plan

A case of the so-called “early involvement” could be seen in this project. Design, planning and assembly teams got together to discuss integrated engineering solutions to improve the efficiency of site operations. For example, the definition of first erecting the front porch raised from the assembly coordinator who intended to first preassemble profiles on the ground and then lift the spatial truss. To make this possible, design team reengineered a more suitable solution considering the assembler’s request. Product information embedded in BIM models were reutilized to quickly generate simulations leading to more consistent decision-making.

The main benefits achieved in this study were: (a) scheduling considered constructability issues; (b) erection strategies were simulated to optimized resource utilization; (c) and multiple stakeholders shared a common view and understanding of the possibilities and project status. As side effects, the simulation enabled more reliable early cost estimation with visual features, and foreseeing constructability issues before the fabrication of components.

6.4.2 Merge of architectural-structural models for visualization and coordination

High-rise office buildings in São Paulo

This project referred to a high-rise office building in São Paulo. This research study started when the construction was almost finished. Thus, the research outputs were not directly applied in a way to benefit design and construction process. The company requested a merge between the detailed structural model (developed at the company) and an architectural model (developed outside). The objective was to create visuals for an international contest organized by a BIM vendor, and not for contributing to the project itself. In the future, it could serve as an experience to make model federation in integrated BIM workflows.

Although the architecture company and the steel fabricator were both considered relatively experienced BIM users (in modelling) in the Brazilian context, this project did not benefit from BIM collaboration. The architecture side was not willing to share the latest models since the request was not from the owner and there were no contractual clauses about model sharing.

Structural analysis was performed in Bentley RAM Structural Analysis while structural modelling was entirely developed in Design Data SDS/2. By default, design team creates separate files containing a partition of the building structure corresponding to the batch definition (installation batch). Figure 19 illustrates separate BIM models exported in IFC.

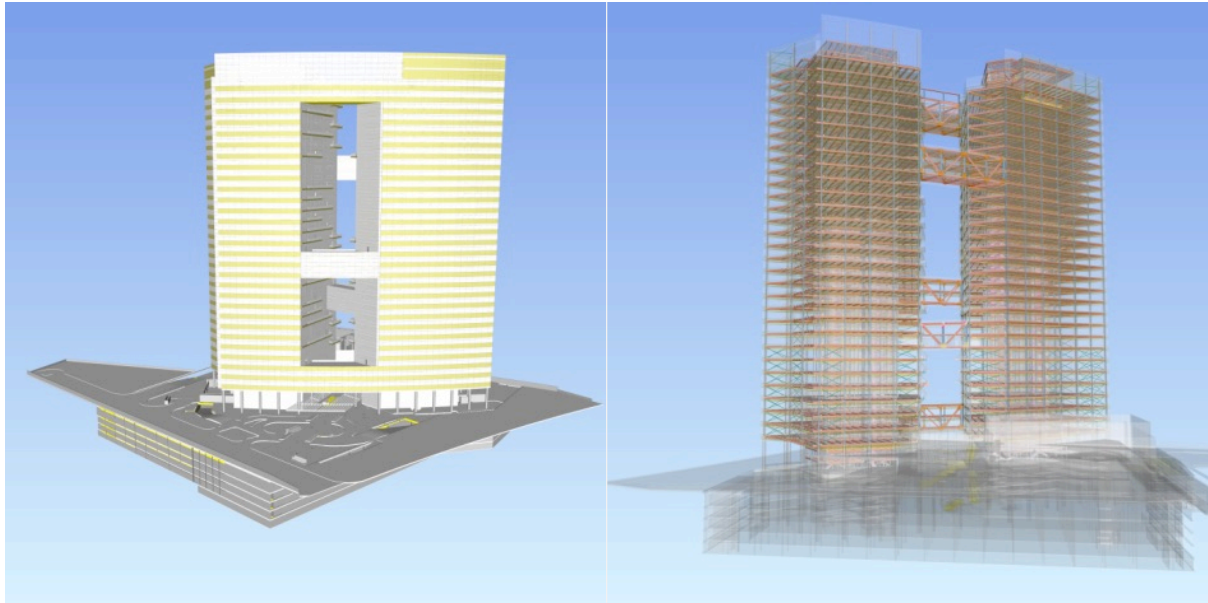


Figure 19: Architectural model and structural model – separate files

In this project, there was a total of 36 batches (16 batches for each wing plus 4 batches for the 5 footbridges). To create the merged model, it was necessary to add all structural batches files and the architectural model into a single model. As could be expected, detailed structural files became very large, so that trials to append all them in Navisworks were troublesome and slow.

Even in a more powerful computer (hardware), it was still difficult to manipulate the model. For this reason, IFC have been individually handled in Solibri IFC Optimizer to reduce file size. The results were expressive, with no apparent information loss (Figure 20).

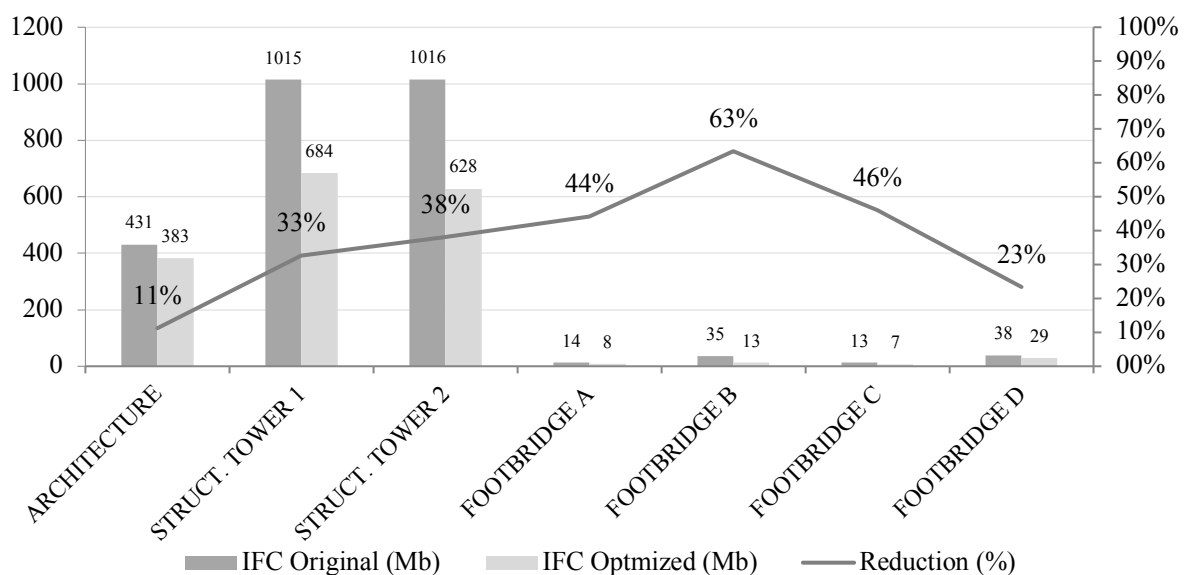


Figure 20: IFC optimization procedure of large files

After all files have been appended to Navisworks, the location of architectural model was adjusted to the (0,0,0) coordination point. The function “selection tree” was very handfull to select groups of components, retrieve their properties and change appearances for specific modes of visualisation.

The merged model also enabled an immersive navigation. The company used this images and animation to presentations in the award ceremony of an international BIM contest¹⁷, being a project finalist in the category innovation in structure of the annual competition. Then, the visual material was forward to other internal stakeholders to show opportunities for BIM uses in further projects, particularly in terms of design coordination (Figure 21).

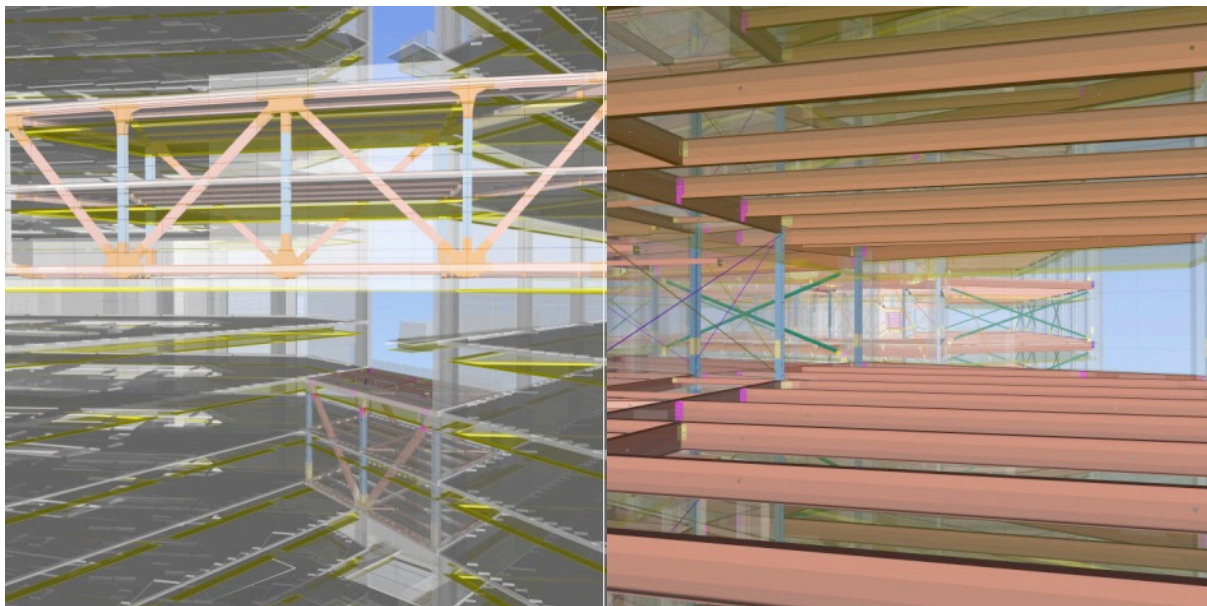


Figure 21: Merged model navigation and visualization

Based on the available information, a quick clash detection rule set was defined to exemplify what could be done with those models in case clash detection was formally required. Among the hundreds of coalitions, it was easy to check conflicts between structural bracing and dry walls partition, and steel beam colliding to the solid concrete core of the staircase (Figure 22).

¹⁷ Finalist of the Be Inspired Awards competition for BIM advancements in infrastructure, Bentley Systems 2015.

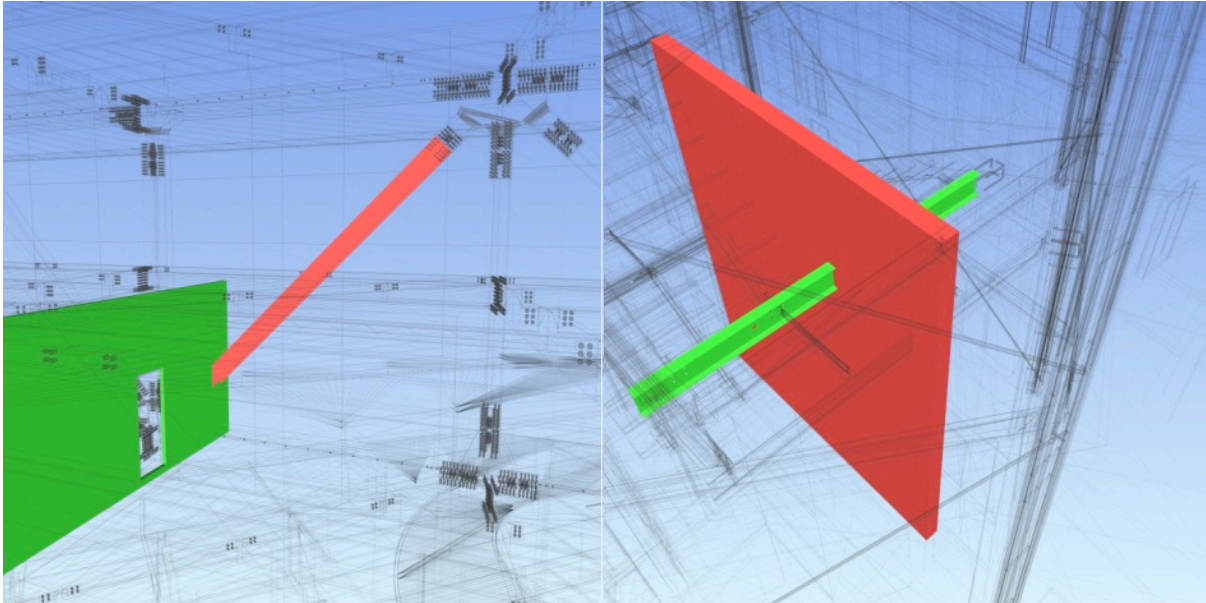


Figure 22: Clash detection: architectural wall vs bracing and concrete wall vs steel beam

As a learning for future projects, the company needs to foresee contractual clauses relative to BIM-based collaboration. Templates of protocols adjusted to the company's expectations and strategies need to be established in a manner to allow necessary amendments to be easily and quickly adjusted according to stakeholder's goals and delivery capabilities. Since Brazil does not have a BIM standard yet (a national standard is under development), the role of BIM protocols becomes even more significant for managing projects. In addition, BIM Project Execution Plan (PEP) can be added as an addendum to contractual documentation.

Although the company owns great part of required infrastructure and experienced users of technical functions of BIM, it keeps struggling to establish a streamlined information workflow and collaboration with first-time partners and inexperienced stakeholders, failing to benefit from product and process improvements enabled by BIM (e.g. integrated decisions concerning system interfaces and logistics of operations to generate cost and delivery time savings), as projects face complex delivery constraints there are interdependent. Finally, the assessment of the BIM capability-maturity level seems to be relevant to position themselves in terms of the deliverable assets, and to aware stakeholders of the improvements required for delivering effective and reliable outcomes.

6.4.3 Study of erection schedules and logistics planning using BIM

This project referred to a hotel in Rio the Janeiro. At the beginning of this project, the contract manager identified the main challenges involved, which could be summarized as: (a) time constrains, given the strict deadline for delivering the building due to a mega event to be held in the city; (b) critical location, short time allowed to do some specific operations on site, and schedule restriction to access heavy trucks and machineries; (c) narrow site configuration, given the limited space for storing and handling inventory, and concurrent activities with other subcontractors (earthmoving and concrete suppliers during the early stages, and MEP/HVAC and glazed façade subcontractors in during the tower stage).

Another key-factor was the use of an additional site to store loads of components fabricated in distinct manufacturing plants to promptly serve the construction site, which was not large enough to a receive large amounts of inventory. So, a central element of this project was the use of an external inventory site to store components fabricated in distinct manufacturing plants spread in the country to speed up production and quickly feed the installation place.

This yard was located 60km far from the installation site, arranged to receive and re-organize skids, in a controlled supermarket scheme which dispatch daily orders to the construction site. Thereby, materials flow three main spaces: (a) manufacturing plants; (b) the auxiliary yard; and (c) the construction site. Transportation between them was done by trucks (laid on the flatbed trailer or in skids), whereas components are lifted by tower cranes or crane trucks.

As the speed of installation was the priority, the endeavours were to unceasingly feed the yard with fabricated materials (concurrent fabrication at different plants increased fabrication speed, whereas logistics became the bottleneck), and many assemblers were allocated to this project to handle the workload. At the end of the day, the critical path was the productivity rates of lifting equipment, which could not be added anymore due to other site limitations.

Under these conditions, sub-processes were configured as: (a) expedition of components from the manufacturing units; (b) receipt of the load units/skids at the inventory yard; (c) checking received components using bar code (UPC) and QR code technologies; (d) rearrangement of components according the installation needs in new batch configurations; (e) daily expedition of the re-arranged loads to construction site; (f) pre-assembly on the ground (and eventually a short time storage of assemble parts on specified bays); (g) lifting and installation.

In terms of information flow, the project was supposed to be run in a traditional approach – CAM/CAM files sent on demand for each production batch (controlled in ERP). Due to the challenge of synchronizing manufacturing, logistics and assembly sub-process, the contract manager asked the researcher to use 4D BIM simulation to support the coordination between expedition at plants, inventory yard, and the construction site.

The first step was to recover design models (at a detail level, because of the geometry accuracy and component coding systems) to create easy to understand visual representations and simulation of the logistics process. Separate models corresponding to production batches and temporary equipment affecting the workflow needed to be merged into a single file to link set of components to tasks in schedule. In fact, as detailed model files were gradually becoming available (following the strategy of detailing batch after batch), the generation of the simulation model was a continuous process of appending partial models.

Another issue was that the fabrication batches did not necessarily correspond to an erection phase (and so the models made available from engineering). Therefore, the link of components to tasks in schedule could not be automated, requiring a careful and laborious selection of elements. In this regard, additional “selection sets” have been created to associate an erection stage information to model objects aiming to facilitate 4D simulations (Figure 23).

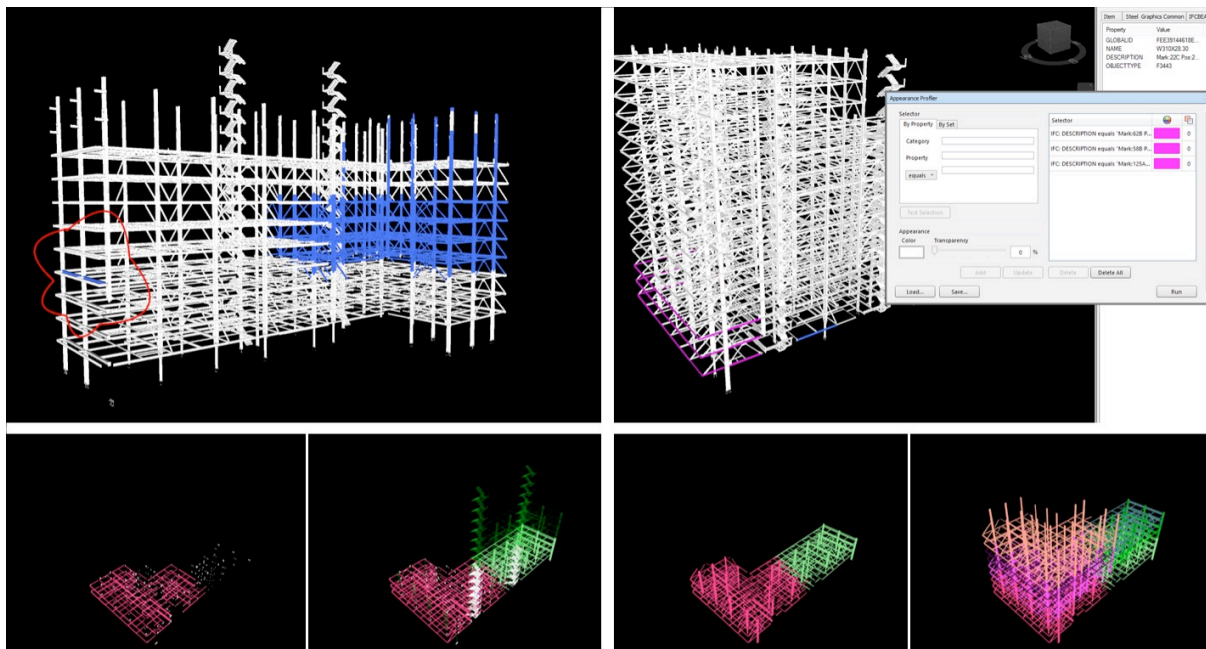


Figure 23: Default model based on fabrication batches (left) vs adjusted to erection (right)

By understanding the context and challenges of making a simulation dealing with such level of interdependence, the conclusions of the first part were: (a) start with an approval model (susceptible to be outdated) for illustrating main erection stages, as detail models are not available from the beginning; (b) modelling of site elements are necessary to enable a more reliable visualization of the erection process; (c) Production System Design (PSD) should be simultaneously done for both the erection process on-site, and operations in the auxiliary yard; (d) 4D simulation are limited in the sense of not including constraints and interferences caused by other tasks on site, besides steel structure.

Shared understanding of the overall flow would facilitate communication among the teams spread in three workplaces, and thus, increase reliability of timing and installation pace definitions. Discussions supported by the visualization of simulations could stimulate the elucidation of constraints and the exposure of knowledge acquired from previous experiences.

In a conventional process, site layout is discussed with the general contractor and the project manager to define schedule alignments, equipment sharing rules, and other specific operation permissions. The contract manager (of the steel fabricator company) is the person in charge of negotiating these decisions on behalf of the steel fabricator's interests and to offer the necessary working conditions to the internal teams (e.g. truck drivers, storekeepers, assemblers, etc.).

In multi-storey projects, the steel structure plays a major role in defining the construction pace (many tasks of other disciplines rely on the erection of the steel structure), so that many decisions should rely on the steel fabricator. In this project, it was initially planned that the installation of steel structure would only start after the completion of foundations and concrete structure of the lower. Thus, a representative model of the concrete structure was modelled and appended to the 4D simulation (Figure 24).

Due to the schedule delay, the general contractor ordered the release of steel installation before the completion of the concrete structure. This implied in sharing equipment, access gates and inventory spaces, which turned the initiation of assembly process much complex and planning less reliable. Therefore, the site layout and physical configuration could not be adjusted for optimizing logistics operations as initially desired.

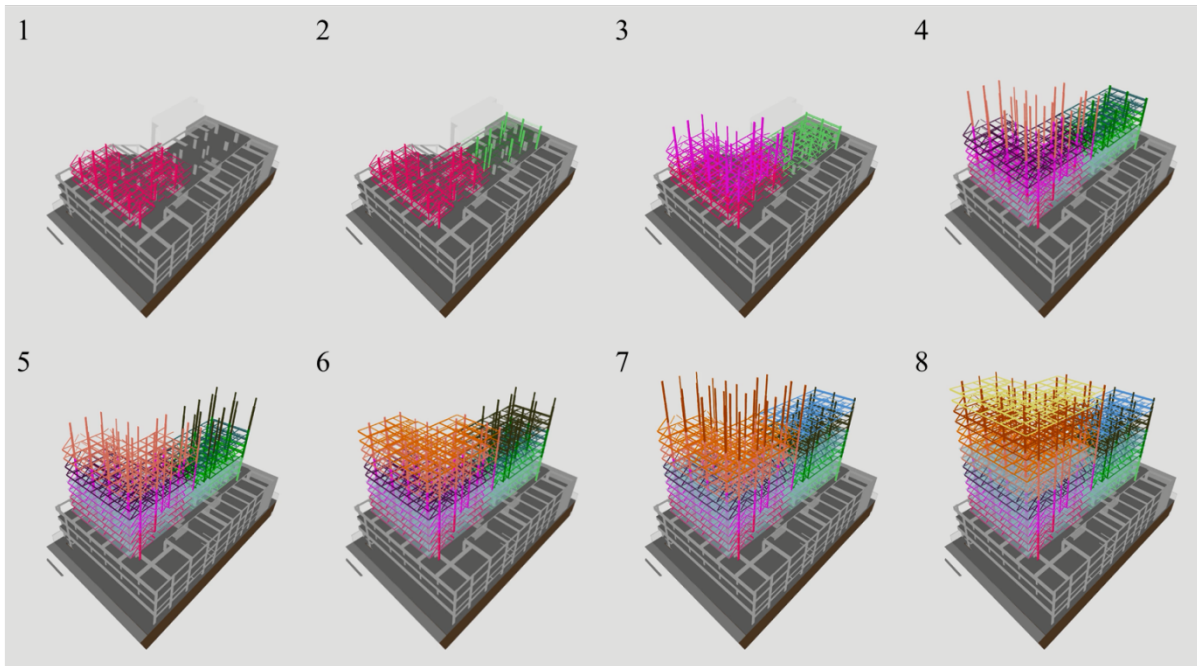


Figure 24: Screenshots of a 4D simulation of an erection master plan

The calculation of inventory turnover was based on crane productivity rates in the construction site and yard feed capacity from the auxiliary site, considering the transport and access restrictions regulated by the city council. Since the operations of the yard faced much less interferences if compared to the construction site, the study of scenarios of yard operations was set to facilitate erection operations. The resources on yard were estimated together with the layout of the yard, considering arrivals, loading, and departures of trucks, safety and productivity rates of moving materials to rearrange the skids.

The initial idea was to use 4D to generate scenarios showing up the skid rearrangement process. Then, information of the arriving batches should be collected (QR code and RFID) and adjusted to the short-term planning criteria of erection on site. For doing so, supplementary modelling of the yard had to be done to represent the working site. A simulation model of the external inventory area was helpful in clarifying working process for first-time running operations inserting elements of the production system design, even though it requested extra modelling efforts (Figure 25).

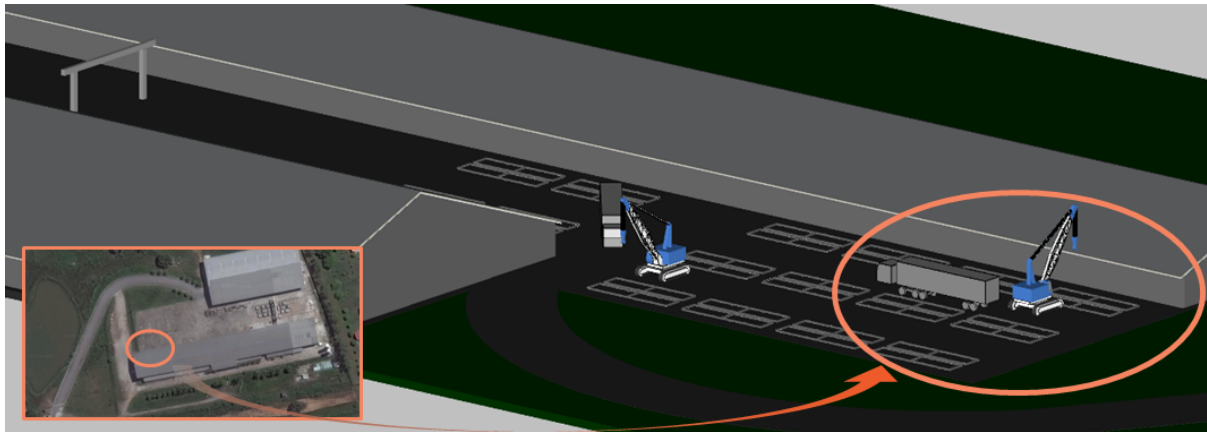


Figure 25: Complementary model of the external inventory area

However, there were technical limitations for 4D regarding uncertainty (variability in material availability, randomness in supply delays, interruptions due to weather conditions or health and safety issues, etc.) and time scale issues for representing faster and slower operations in the same video (Figure 26). Moreover, preparing a visual simulation of every single batch was highly demanding, since it was not automated with ERP data.

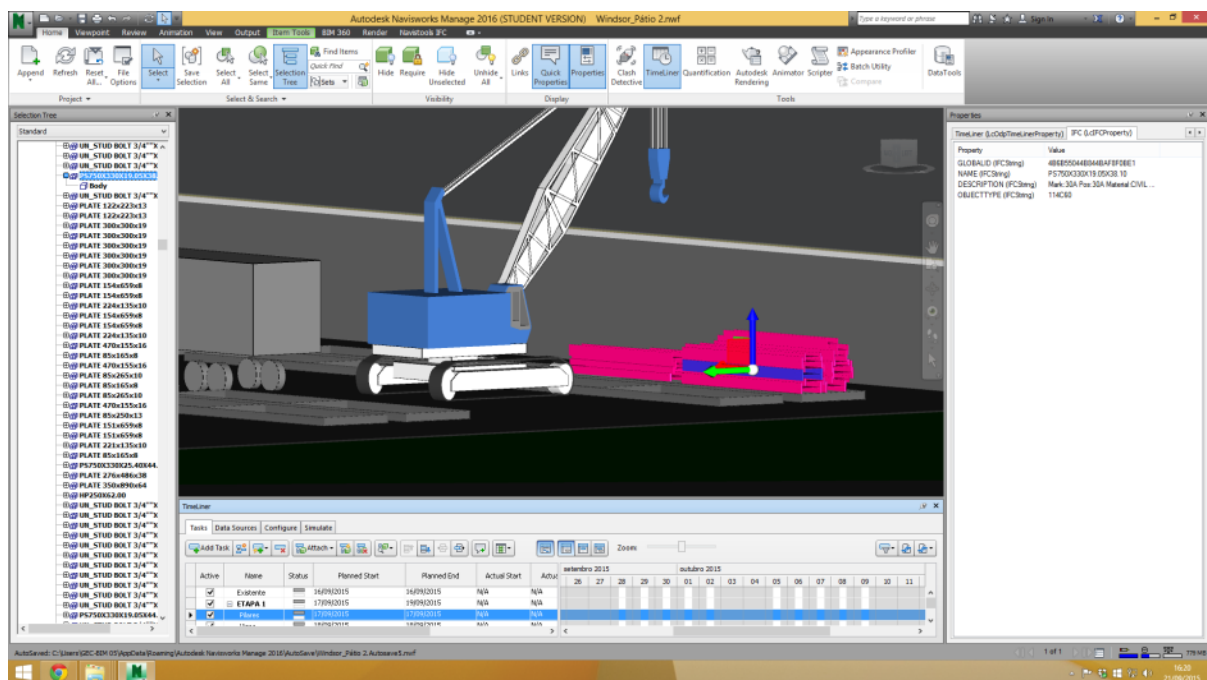


Figure 26: Simulation of skid rearrangement on the auxiliary yard using 4D BIM

Although the use of detailed 4D BIM seems a practical alternative, there are still many technical limitations. In fact, it enables a “sequence visualization” rather than a *de fact* simulation, since

4D BIM scheduling functionalities use a different rationale of a Discrete Event Simulation software for plant process simulation as used in other industries.

The newest CAD/PLM system under implementation is capable to interoperate with 3D logistic modelling and discrete simulation tools and can provide 4D visuals. However, discrete event simulation tools are not as easy to use as 4D BIM tools and may not be flexible enough to respond to the uncertain nature of construction projects. Thus, it would be difficult to define the inputs for simulation and to guarantee that the planned sequence is executed on site.

This study explored how the use of production sequence visualization and process simulation using recovered model data can assist planning and site coordination through a shared understanding of logistics scenarios. Process synchronization can be easier achieved by establishing a commonly agreed production system among the participants of a project stages. Nevertheless, a definite tool or method to perform such simulation could not be specified in detail. As a future recommendation, testing advanced simulation applications could express some advantages for production planning, while adaptations may be required to consider types of variability occurring in construction projects.

6.4.4 Study of product development flow enhancement through BIM

This project referred to a healthcare facility in Campo Grande. This study was the longest in this research work, being divided into several stages, which corresponded to different product development phases. A central point of this study is that design team was using a BIM authoring tool (SDS/2) along the whole design process. In most projects, design teams use a mix of BIM and CAD to generate detailing drawings and specification. There are cases of outsourcing detailing activities to an external company, which delivers on traditional methods.

As previously verified, IFC (IFC2x3, by default) from SDS/2 can be imported and used in other BIM applications. This study explores BIM uses beyond product modelling and shop drawing generation as established in the current product development process.

The flow of study was divided in two parts: (a) early design development of the overall structural solution, until design approval; and (b) progress of the one production batch from design detailing to manufacturing and site expedition. The topics below report the monitoring of the project (company's activities), as well as the test and implementation of BIM functions (researcher's activities).

This study covered the receipt of non-BIM documents from the architecture office in the bidding phase, going through the structural analysis in CAE at early engineering phases, the structural modelling and detailing in BIM authoring tools, the fabrication of steel components using CNC. Then, it introduced new BIM functionalities in the PDP, such as 4D simulation of the erection batch schedule, 3D visualization in the plant and construction site with mobile devices, and simulation of transport and site logistics and operations until the assembly phase, when this study was concluded (Figure 27).

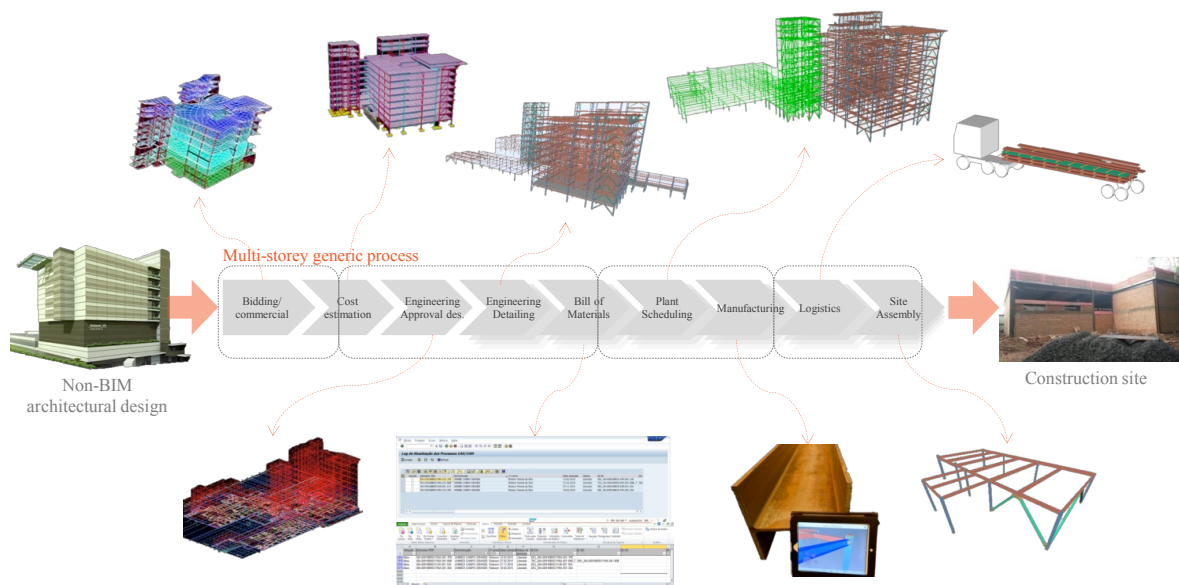


Figure 27: Use of multiple applications along the project process (as proposed)

During the first two weeks, the researcher observed the designers' routine to understand the design process and how information was added to BIM models along the development process. Non-structured interviews with designers, cost estimators and planners of the multi-storey unit helped to understand their perception of the BIM process versus the traditional workflow operating with other CAD systems. The interviewees agreed that BIM in design and engineering process helped to increase productivity and information reliability. The submission of approval design documentation became 30% faster, while the delivery of design details got twice as fast as compared with the former workflow. It also contributed to reduce the number of RFI and design changes over the months they have been working under this new approach.

An interview with three structural designers (two of them were involved in the whole project, and the third one was appointed to help the team in a critical phase due to the short deadline) revealed the advantages perceived by them in using BIM compared with other traditional

projects: (a) ease of use of automated modelling and specification commands, previously programmed in the software by the engineering leaders; (b) reduced rework in updating design changes; (c) quick generation of fabrication and assembly documentation; and (d) modelling accuracy and better visualisation reduced the amount of request for information (RFI) and change orders by plant and site stakeholders.

At that moment, the outline BIM process was established only in the design phases of multi-storey projects. This process was not formalized in a business process model, and it had been continuously refined based on the experience of designers and tacit knowledge of project managers. Nevertheless, many participants allocated on plant and site operations were unaware of the basic concepts of BIM. Therefore, one of the challenges of this study was to educate participants of downstream phases about BIM potentialities and the impact of the research interventions in their daily work, starting from this project. In addition, the design and engineering teams was geographically separated not only from the client's site (1420 km), but also from the other units of the company (200 km away from the planning department and 450 km away from the manufacturing plant).

a) *Receipt of design data and information flow*

This stage starts with the receipt of the owner's brief. It usually comes together with the architectural scheme design, cost, schedule and production requirements. In some cases, a structural scheme design produced by consultants hired by the client is part of the introductory kit, although the level of collaboration with these firms varies from project to project.

For this study, architectural design was received in traditional 2D drawings, whereas planning documentation was not provided by the main contractor in a first moment. Structural design was entirely developed in-house. The team in charge of this project was familiar with BIM modelling for about one-year, since the implementation of the SDS/2 package.

Before getting into SDS/2 modelling, a scheme structural model was generated in Bentley RAM Structural Analysis. This model was used as a reference for preliminary cost estimation, and the first version of the long-term schedule, in which the project is divided into stages (related to the production batches). At this point, commercial and contractual issues were underway, still without the final client's signing.

Then, approval design was modelled in SDS/2. The outputs of this design stage were submitted to client approval. The 3D model can also be used for geometric coordination with other disciplines, often carried out by a project manager hired by the owner. The steel fabricator exports .dxf drawings for design and schedule reviews. Design detailing begins when design is approved by the client. Production batches break down the structure in smaller parts, and guide detailing and fabrication priority. The outputs of this stage were the component's information for the BOM, programming files for the CNC machines (digital manufacturing), and a set of assembly and erection drawings (paper-based exchange).

However, despite of the capabilities to export data in various file formats, design team members confirmed the perception of sub-utilization of BIM information in downstream phases. Therefore, IFC export and import verifications have been done with the files developed up to that point (i.e. the approval design model, and a detailed model of the first production batch).

Concurrently, the researcher presented some case studies and results of previous experiences of activities supported by BIM to encourage the involved parties to collaborate with the research activities. The target were the designers, an internal BIM officer, and a continuous improvement representative, who did not hesitate to collaborate in exchanging files and giving feedback. Production teams out of the office in Porto Alegre were much difficult to exchange with, as the meetings were not periodical, and they did not receive the same level of advisory support from the beginning of the investigation.

b) *Interoperability between CAE (structural analysis) and BIM (design modelling)*

Data exchange from structural analysis to design development was already a consolidated process. Furthermore, the involved teams share the same workspace and benefit from face-to-face collaboration. Despite of using software from different vendors, CIS/2 resolves project information exchange. In this case, analytical models developed in Bentley RAM are sent to approval design modelling in SDS/2 via CIS/2 scheme (Figure 28).

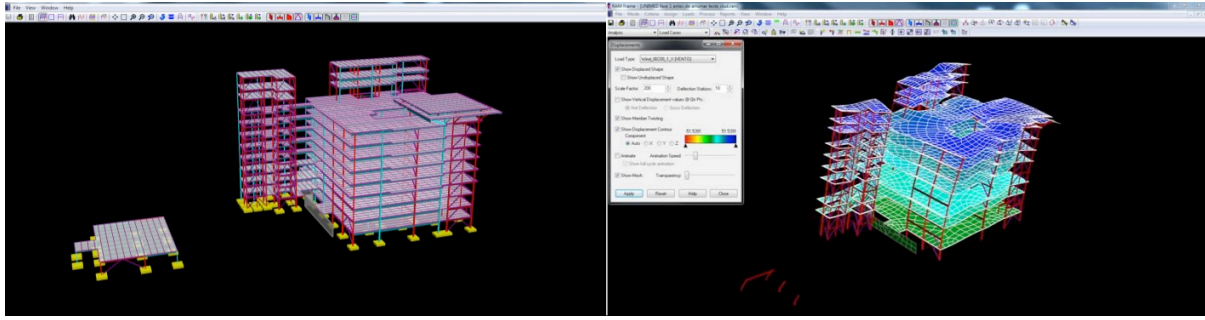


Figure 28: Structural analysis in CAE tool

Components type, profile, sizing, and placing data were transferred from Bentley RAM to SDS/2, which automatically recognizes the parts of structural analytical model and convert them into native elements (Figure 29). Hereafter, designers take advantage of specific parametric modelling functions to work at the design solution and approval documentation with no need of remodelling it all again.

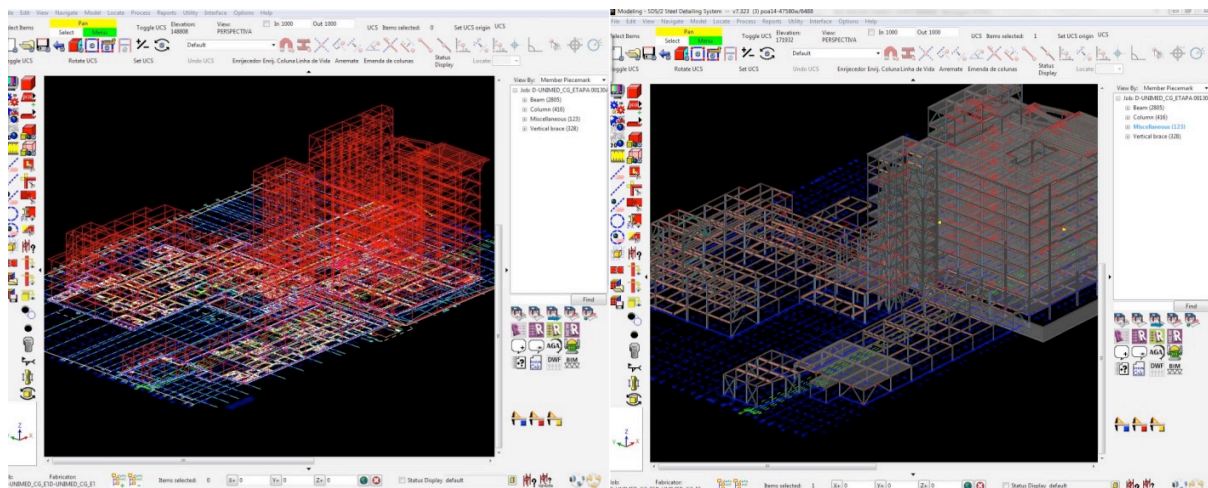


Figure 29: Conversion of structural analytical model to parametric model

As discussed in the literature review, the AISC has recently announced a new strategy considering the use of IFC for cases in which CIS/2 still takes place. Although this exchange is not an issue for the company, the demand for IFC exchange with external stakeholders are likely to increase, so that new versions of IFC and open standards need monitoring.

c) *Verification of model consistency in design development*

The first procedure was to collect structural models (during the approval design stage) via IFC and check embedded information of the merged model using Solibri Model Checker. This

verification is applicable in different moments of the design process according to the checking objectives. For instance, it can be employed for checking the model before generating documentation and export files to coordination, or for a final verification at the completion of each detailed design batch prior to the generation of fabrication orders.

In case this model checking becomes a formal task in the design process, these rulesets can be customized to meet: (a) working parameters (including machinery capacities, constructability issues, limitations related to suppliers, technical standards, local authorities' rules and regulations, etc.); (b) specific project conditions communicated by the project manager or subcontractors; and (c) owner's specific requirements.

In this test, model checking used the default structural checking ruleset contained in the Solibri Model Checker (Figure 30). Model checking at this stage reported two types of major problems: (a) semantic inconsistencies in component specifications; and (b) physical coalition of components due to the lack of connection detailing

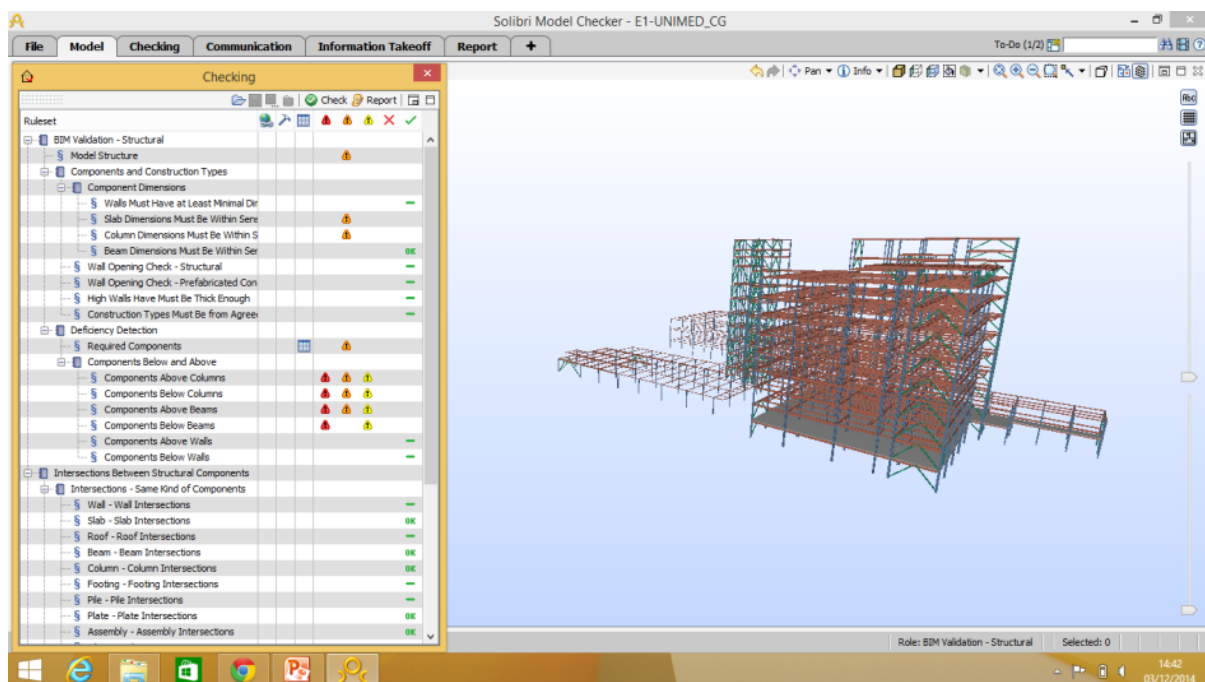


Figure 30: Approval design model checking

As an example of the first case, some composite steel columns at the lower floor that were modelled by mistake as concrete piles (the geometry were identical, but the specifications were incorrect). Although they look the same, it would imply in problems downstream (e.g.

inaccurate quantity take-off). A list of semantic inconsistencies in the model was reported to designers who become aware of the impact of accurate modelling specification.

For the second type, the rule checker assigned colliding elements (i.e. columns crossing concrete slabs and bracing ends clashing steel beams) in hundreds of points (Figure 31). However, most of these issues were not exactly design errors, but it showed up that the model was not complete yet. Once connection details were defined, these issues would disappear from the rule checking report.

E1-UNIMED_CG Structural validation						
Model Name	E1-UNIMED_CG Version: 8.1					
Checker	Jeferson Shin-Ili Shigaki					
Organization						
Time	12/3/14 2:39 PM					
E1-UNIMED_CG	Time: 2014-12-01 10:51:26-02:00 Application: SDS/2 v7.323 IFC: IFC2X3					

BIM Validation - Structural	Acc	Rej	Maj	Nor	Min	Comment
Model Structure				x		
Components and Construction Types				x		
Component Dimensions				x		
Walls Must Have at Least Minimal Dimensions	-					
Slab Dimensions Must Be Within Sensible				x		
Bounds						
Column Dimensions Must Be Within Sensible				x		
Bounds						
Beam Dimensions Must Be Within Sensible	OK					
Bounds						
Wall Opening Check - Structural	-					
Wall Opening Check - Prefabricated Concrete	-					
High Walls Have Must Be Thick Enough	-					
Construction Types Must Be from Agreed List	-					
Deficiency Detection			x	x	x	
Required Components				x		
Components Below and Above			x	x	x	
Components Above Columns			x	x	x	
Components Below Columns			x	x	x	
Components Above Beams			x	x	x	
Components Below Beams			x	x	x	
Components Above Walls	-					
Components Below Walls	-					

Intersections Between Structural Components	Acc	Rej	Maj	Nor	Min	Comment
Intersections - Same Kind of Components	OK					
Wall - Wall Intersections	-					
Slab - Slab Intersections	OK					
Roof - Roof Intersections	-					
Beam - Beam Intersections	OK					
Column - Column Intersections	OK					

Footing - Footing Intersections	-					
Pile - Pile Intersections	-					
Plate - Plate Intersections	OK					
Assembly - Assembly Intersections	OK					
Object - Object Intersections	-					
Intersections - Different Kind of Components				x	x	
Wall Intersections	-					
Slab Intersections				x	x	
Roof Intersections	-					
Beam Intersections				x		
Column Intersections				x		
Footing Intersections	-					
Pile Intersections	-					
Plate Intersections	OK					
Assembly Intersections	OK					
Object Intersections	-					

Model Revisions Comparison - Structure	Acc	Rej	Maj	Nor	Min	Comment
Model Comparison	-					

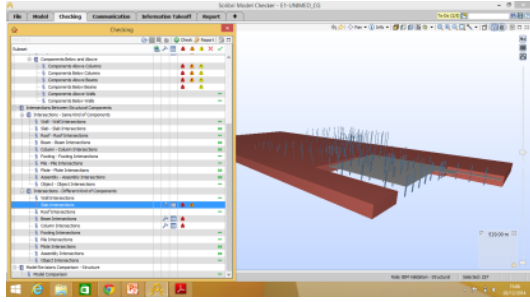


Figure 31: Report sample of structural validation using default structural rule checking

Programming rules in the modelling tool could avoid specification mistakes and omissions, but as the current workflow does not support it, a verification tool could prevent inadequate information to be forwarded, causing rework and additional costs due to change orders. If design rules are difficult to set up, defining tolerance values in checking applications would be faster, even though not the most efficient technique. Only for clash detection purposes, a similar procedure was replicated also in Navisworks as shown in Figure 32.

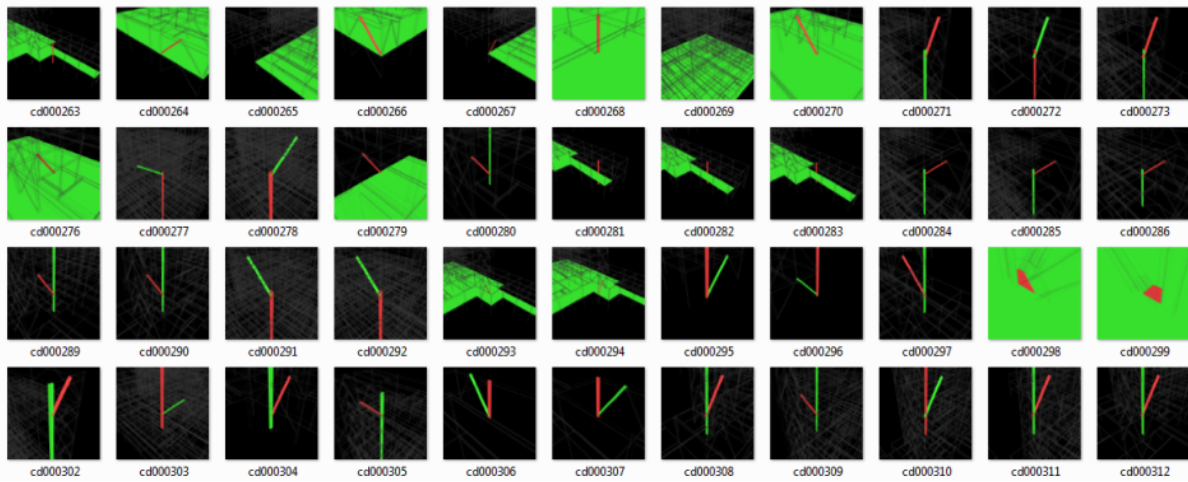


Figure 32: Clash detection in approval design model for tolerance checking purposes

Navisworks enables checkers to quickly manipulate permissible tolerance values and analyse existing clashes under customized criteria (Figure 33). The visual identification enabled a fast and easy design fixing task. Reports generated at both tools (Solibri's rule checking and Navisworks' clash detection) were useful to express the utility of checking models before submission to the owner or external designers.

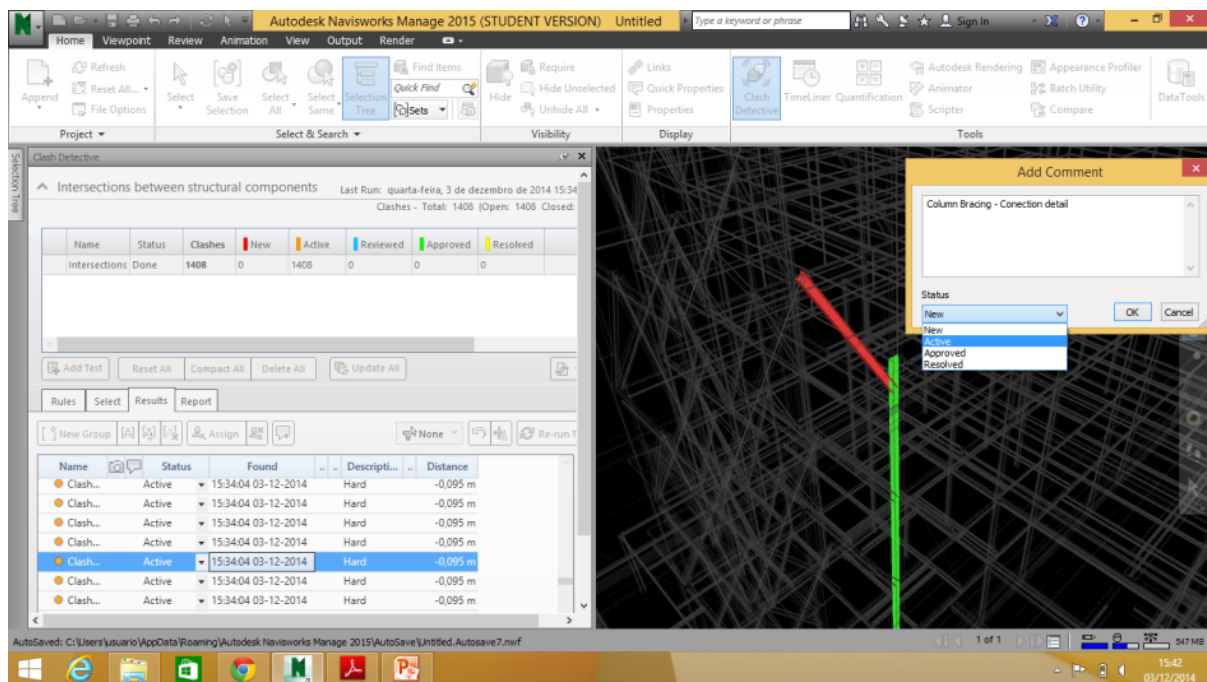


Figure 33: Check and management of acceptable design detailing incompletion

This checking was done with a model containing only part of detailed design (first production batch), while the major part of the model was kept like in approval design models. As a result,

the number of clashes assigned in the detailed part was very low compared with the non-detailed part. Presumably, the definition of the Level of Development (LOD) played an important role when applying rule checking and clash detection to the BIM models. At that time, design team did not follow any standard concerning the expected or minimum LOD for each component type at each delivery stage of the product development process (Figure 34).

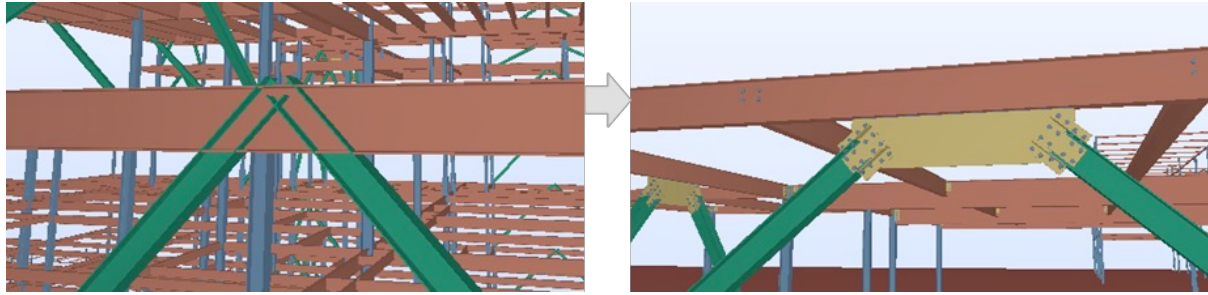


Figure 34: Level of Development (LOD) corresponding to delivery stage

Hence, the researcher suggested to define a table with the LOD to be delivered at each stage. This definition becomes more important as owners and external designers demand BIM collaboration and model exchange, for uses such as design coordination and clash detection, 3D site layout, 4D, 5D and so on. For each purpose, different LOD and content of the structural model is required. So, the AIA E202-2008 and AIA G202-2013 (combined with their complementary documents) were used as reference to propose the LOD to be internally developed, and then, to be agreed with the construction project team.

It was also observed that some components, LOD could not be strictly defined (Figure 35). For instance, steel decks are not modelled nor in approval or detailing models, because they are produced in a make-to-order scheme and specified according to standard details.

Component	Estimating	Approval	Detailing	As-built
Columns	100	300	400	
Beams	100	300	400	
Bracing	-	200	400	
Stairs	-	200	400	Not performed
Steel deck	100	Specifications pre-set CAD details		
Foundation	100	External subcontractors design		
Cladding	-	Only for industrial facilities		

Figure 35: Proposition of reference values for LOD in the design of multi-storey typology

However, for specific uses (e.g. 4D simulation and site logistics planning), these elements can be important, requiring complimentary modelling for these objects (e.g. steel deck, which is not 3D modelled by default). Since the objective is to provide a visual communication of the erection schedule, a very low LOD for such objects would be enough. If foundation or concrete structural models are provided by other design teams, they can be merged with the steel model. Despite of the reference table, there are some object types that are just modelled in some projects or project-types, so it would be valuable to revise the LOD table at each new project.

d) *Generation of BOM and connections to ERP*

The activities covered in this stage are performed by the Product Structure sector which is responsible to for the Product Structure Management (PSM) and the generation of Bill of Materials (BOM) describing the product required for manufacturing in a hierarchical classification of materials, components parts, sub-assemblies and other item definitions.

After the completion of approval design, the first production batch begins to be detailed. As soon as detailing of each production batch is completed, the tasks is forwarded to PSM/BOM. The company defined a strategy to deliver separate detailed model files as soon as they get ready (from the Design team) to the PSM team, and then, to the Plant Scheduling team. The person in charge of PSM also supports the management and update of CAD/CAM process related to subsets of a production batch (Figure 36).

Seleção	Elemento PEP	Denominação	1º nome	Data Liberação	Status	ID DS	ID I
	MA-009188R03.FMA.001.1PE	UNIMED CAMPO GRANDE		12.03.2015	Liberado	DEL_MA-009188R03.FMA.001.1PE	
	MA-009188R03.FMA.001.80B	UNIMED CAMPO GRANDE		27.02.2015	Liberado	TEC_MA-009188R03.FMA.001.80B_T	DEL
	MA-009188R03.FUR.001.10A	UNIMED CAMPO GRANDE		27.11.2014	Liberado	DEL_MA-009188R03.FUR.001.10A	
	MA-009188R03.FMA.001.30A	UNIMED CAMPO GRANDE		18.02.2015	Liberado	DEL_MA-009188R03.FMA.001.30A	

	A	B	C	D	E	F	G	H	I
	Seleção	Elemento PEP	Denominação	1º nome	Data Liberação	Status do processo	ID DS	ID DS	ID DS
6965	false	MA-009188R03.FMA.001.1PE	UNIMED CAMPO GRANDE	Robison	12.03.2015	Liberado	DEL_MA-009188R03.FMA.001.1PE		
7858	false	MA-009188R03.FMA.001.80B	UNIMED CAMPO GRANDE	Robison	27.02.2015	Liberado	TEC_MA-009188R03.FMA.001.80B_T	DEL_MA-009188R03.FMA.001.80B	
8260	false	MA-009188R03.FUR.001.10A	UNIMED CAMPO GRANDE	Robison	27.11.2014	Liberado	DEL_MA-009188R03.FUR.001.10A		
8376	false	MA-009188R03.FMA.001.30A	UNIMED CAMPO GRANDE	Robison	18.02.2015	Liberado	DEL_MA-009188R03.FMA.001.30A		
8544									
8567									
8568									

Figure 36: Product Structure/Bill of Materials of a small batch (sub-stage) in ERP system

In the ERP system, product structure function enables the connection of product and business process knowledge, by including, for instance, capacity planning, logistics and material procurement. Product information are retrieved from CAD and BIM design applications, since components were modelled at the shop drawing level of detail. In this company, the person in charge of PSM used to sit next to the Production Planning and Control (PPC) and Material procurement teams at the plant offices, but for this project, the workplace of the PSM staff was transferred to the design office, facilitating the access to updated BIM models.

SDS/2 can automatically generate BOM as well as CNC setup and reports. Another important task is grouping Working Breakdown Structure (WBS) elements for Material Requirement Planning (MRP). Then, status can be checked directly from the ERP system, or from an exported spreadsheet in case of people with limited access to the system (e.g. external consultants, site operators, etc.).

e) *4D simulations for visualizing the project master plan*

The use of 4D simulation aimed to provide a visualization of the long-term erection plan based on the batch division production strategy. Additional uses were limited to recommendations for future projects such as: (a) look-ahead planning update; video comparison of “as planned” and “as-built” schedules; (b) simulation of what-if scenarios of site layout configuration and logistics; (c) scheduling clashes; (d) risk analysis involving health and safety and equipment installation; and (e) use of associated mobile technologies for production and quality control.

These extra activities could not be deployed in this study, given that the researcher could not monitor the progress of site operations and provide adequate training to field operators – the construction site was too far, implying in long trips. Besides, there was also an unclear overlap of responsibilities between the steel fabricator and the general contractor which hindered the full access to project information.

The inputs for setting long-term erection plan simulations were the approval design model, which was appended to a 4D application (Synchro Pro) via IFC, and manually linked to the schedule (Figure 37). The tasks have been separated into major batches and sub-divided based on the type of steel components. This simulation consisted only of objects that have been 3D modelled by the design team (e.g. columns, beams, bracing, etc.), ignoring other structure elements (e.g. floors, etc.) and systems from external suppliers (e.g. foundations, cladding, pipes, etc.).

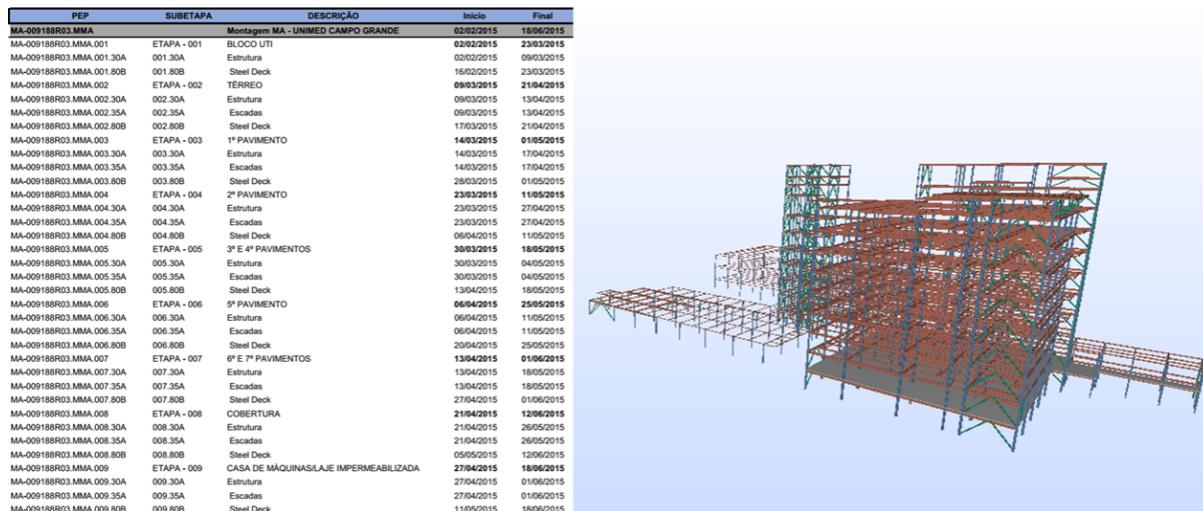


Figure 37: Input for an outline 4D: erection schedule (left) and 3D structural model (right)

At this point, it was not possible to make use of the entire detailed model because only one batch was available at this point. Nevertheless, the use of approval models led to a new condition which was faster and easier to prepare simulations, since there were not all small connecting components to be linked to the schedule. (Figure 38). Even after possessing the detailed models, it was agreed to exclude connecting elements from the 4D, because they would not contribute to the schedule visualization and make simulation much difficult to prepare due to the large file sizes.

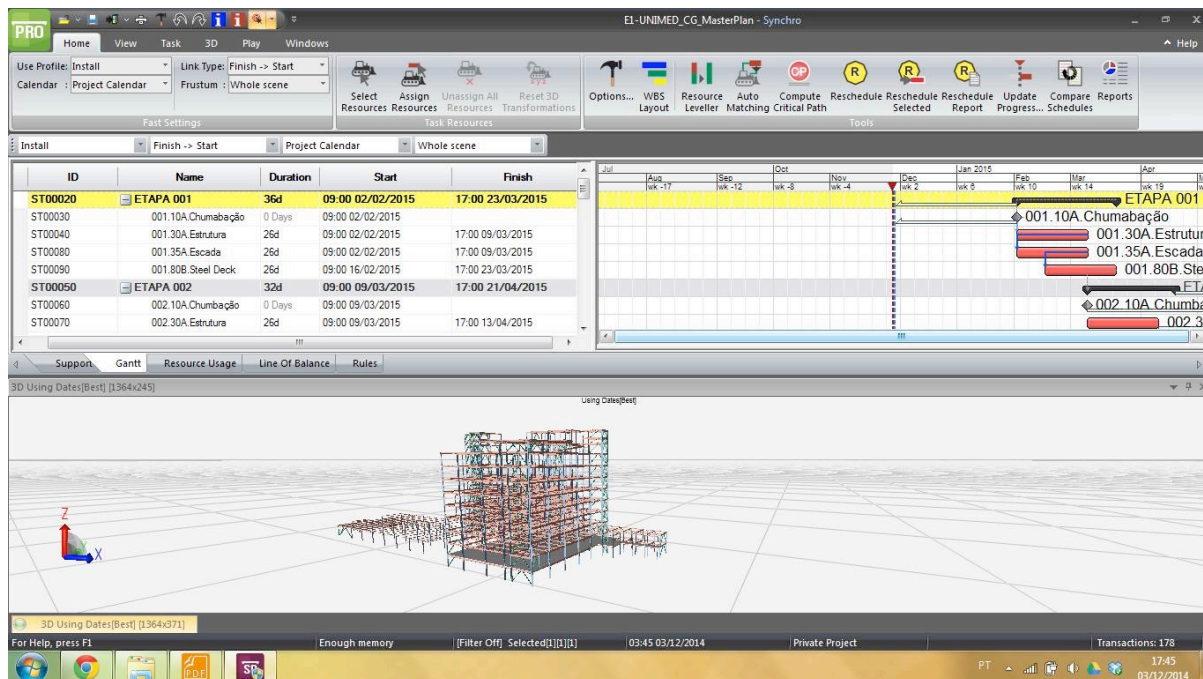


Figure 38: Master plan 4D simulation

As discussed in the initial meetings, the use of 4D for supporting logistics planning would require additional modelling of elements not available in the structural design (e.g. architectural design; temporary site elements such as inventory and machinery; site delimitation, etc.). Additionally, the site layout had not been formally defined by the construction manager to model the site layout, while limited information was gathered in interviews with the assembly coordinator. Finally, due to the large amount of uncertainties on site with other subcontractors and suppliers, it was decided to not proceed with a detailed 4D simulation.

f) *BIM and CAD/CAM integration for digital manufacturing*

Fabrication was a relatively consolidated step of the workflow. Scribing, punching, drilling, cutting and marking tasks in the plant were computer-assisted. Design and detailing software enabled the integration with CAD/CAM equipment. Furthermore, fabrication outputs (i.e. fabrication orders, MRP data, technical reports) could be extracted from both CAD and BIM applications, exchanged to ERP, and sent to specific CNC equipment systems, enabling to manage a large amount of production information.

One of the challenges in the manufacturing plant was on how to track sub-components (materials) that are fabricated in different machines and place them together for transport and pre-assembly operations (e.g. welding stiffener plates). Even though each component has an identification mark, they are in high number and similar geometry, making the process of locating and matching sub-components considerably slow. As the materials list has no graphical information, it was checked the possibility of utilizing 3D-visualization to ease materials tracking on plant. It could be facilitated by combining the fabrication lists plotted with identification information with a graphical mobile device like a tablet or a smartphone.

The detailed design model delivered by the engineering team is accurate. Thence, objects of the 3D model can be associated to each sub-component data in the shop list, following the corresponding mark. So, most product information could be double checked in advance, providing increased reliability in moving materials in the plant and avoiding re-work.

Besides, some manufacturing activities were not automated (e.g. welding, painting, etc.) and used to require consultation of design information during field operations. Specifications were spread in different documents (e.g. assembly diagrams and quality assurance checklists). Assemblers often struggle to interpret non-scale diagrams demanding a careful check of mark and placement specifications, beyond the visual identification (Figure 39)

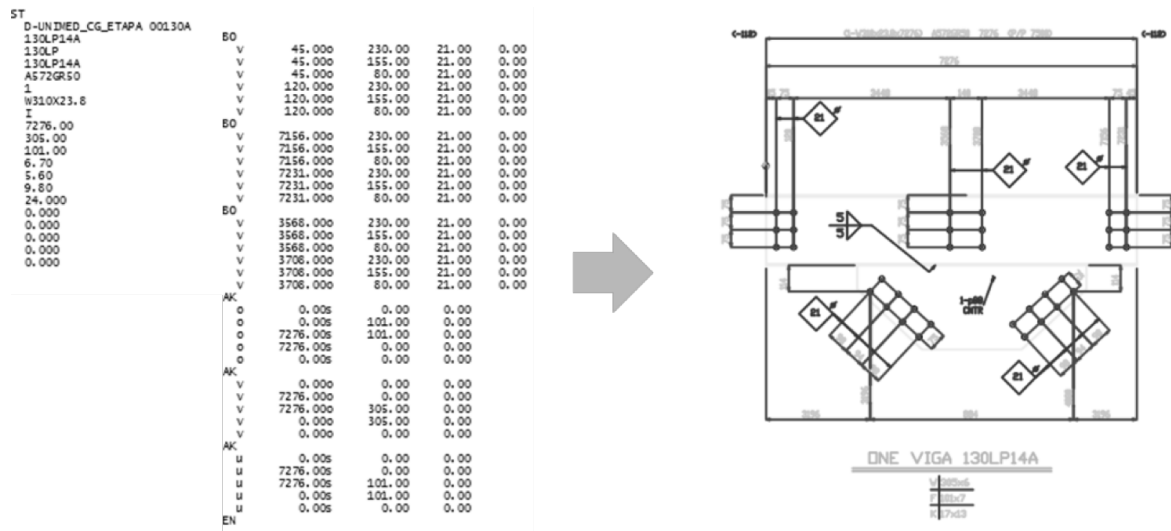


Figure 39: CNC fabrication file (left) and a 2D non-scale assembly diagram (right)

In this regard, the initial idea was to provide 3D visualization in tablets aiming flexibility and facility of use. Model viewer tools enabled plant teams to consult reliable design information and specifications (e.g. mark, dimensions, weight, sub-stage, etc.) from product models that were already available for use, by extracting them from the 3D design models (Figure 40).



Figure 40: Tracking and matching of sub-components with mobile visualization

Assemblers were asked about the facility of use (of using BIM viewer tool to consult component information) and their perceived advantages. The interviewees were positive about the new experience, believing their tasks could benefit from information reliability and avoid re-work for assembling the wrong component or in the wrong position.

However, despite of the positive feedback, the use of tablets as visualization tools could not be fully implemented for two main reasons: (a) health and safety issues: operators must use gloves in operations and touchscreen of the available type of tablets would not work well; and (b) motor sensitivity: since they operate heavy machinery, their manual coordination for using stylus pens are compromised, and tablet would require more resistant screens to rough touches.

In addition, two interventions were required: (a) installation of BIM model viewers in the computers and mobile devices with permission of the IT administration; (b) training of engineering teams to import the model into the model viewer application. One of the most enthusiastic participants in the field was from the quality assurance department. The quality coordinator himself also persuaded the IT team to install the required applications and to provide him more access to data. Desktop versions of the model viewer were installed. Then, the researcher carried out a few extra demonstrations with the quality team, assemblers and IT assistants. After the receiving the instructions from the researcher, the engineering team was enabled to generate the 3D visualisations with their own resources.

The suggested steps were: (a) merge sub-stage models as convenient for purpose adopting a common (0,0,0) reference point; and (b) export files in appropriate file extension according to the applications to be used for visualization purposes. Then, viewers only need to (c) receive and open the file in the desired application. The researcher had an extra step of obtaining permission from IT to collect the model, which would not be required in a routine process.

Alternatively, one easier way to start 3D visualisation on the workstation was to extend the use of 3D pdf, which was barely used up to this point. When a contract manager or site coordinators demanded, the engineering team provided a consultation file known as “RFI pdf” consisting of a 3D model (whole building or just a selection of batches) in 3D pdf format (Figure 41). It can be opened in most pdf readers (e.g. Adobe Reader) and no training to manipulate the model is required. The disadvantage is the reduced capability to add or change project information, for example, status update when required.

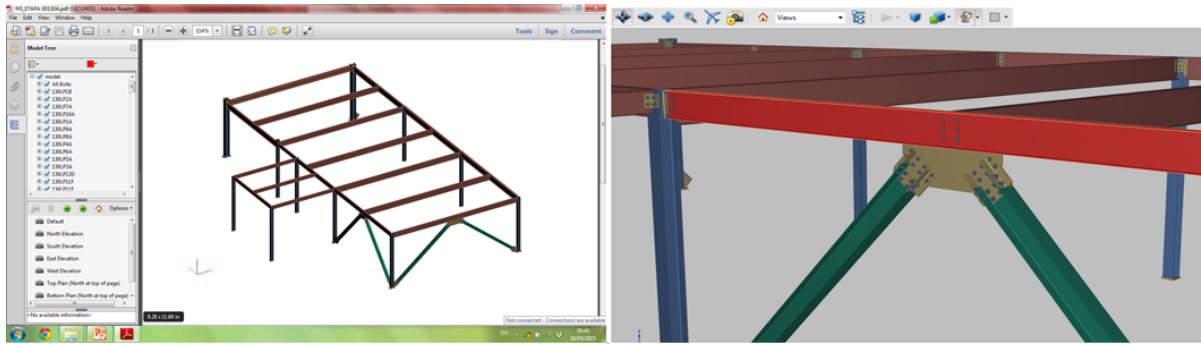


Figure 41: 3D visualisation of the model in pdf format

g) *Load planning and logistics operations simulation*

The development of load planning strives to coordinate site demand and fabrication release, and thus, better control the storage levels on both plant yard and construction site yard based on the synchronized release of fabrication batches. In the former workflow, production batches used to be produced based on plant capacity to achieve the tonnage targets (which was the performance evaluation criteria). Instead, a workflow assisted by a structured load planning has the intent to promote a shift from a push production (tonnage goal) to a pull production (right batch at the right time) planning orientation.

The first required change was a better coordination of plant and construction site teams in order to achieve smooth flows across fabrication order, loading, shipment, and site distribution. Therefore, an adequate management of batch sequences should become a fundamental element of the process. A major output of this new process was the conception of a “load plan design” supplementing the packing list. In short, the load plan design defined the layers and positioned the components to be accommodated in the truck body (flatbed trailer) or on a pre-loaded skid. The development of pre-load skids was discussed by Viana (2015).

The strategy of the load plan design had been consolidated within the logistics sector of company in partnership with other research projects. Instead of randomly lifting components to the truck body or to the pre-loading unit (i.e. trestle or skid), the larger and heavier components (i.e. beams, columns, bracing) were individually positioned according to a load plan design following the criteria: (a) each truck carry the exact components demanded by the site, so that sub-stages shipped are those requested to the assembly sequence; (b) heavy components are preferably on the lower layers of the arrangement, and the distribution might

balance right-left, front-back weights; (c) if possible, discharge sequence for erection lifting or yard accommodation should be considered to reduce the number of lifting operations.

Accordingly, logistics planners deliver schematic drawings indicating the layers and arrangement of component's sketches and marks (Figure 42).

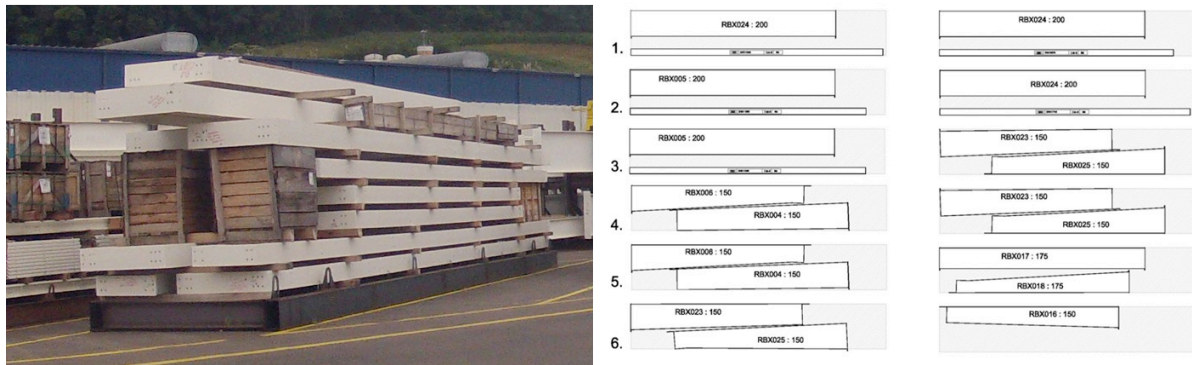


Figure 42: Example of a pre-load skids and a load plan design (courtesy of Viana, 2015)

Despite of the time-consuming work, it contributed to reduce risky, time consuming and costly operations. The impacts of introducing the development of load plans in the process were: (a) affected the prioritization of detailing sequence to release inputs to BOM and fabrication orders; (b) increased the role weight of plant scheduling, responsible for establishing batch sequence prioritization according to the site pull and not plant capacity; (c) adjusted the fabrication sequence in order to alleviate shipping bottlenecks.

This study suggests that BIM can support the process of planning loads by using BIM models retrieved from the design team and load sketches prepared by the logistics coordination. Then, the logistics team might provide 3D schemes of charged truck bodies or skids which are easier to understand by the loading staff. Taking advantage of detailed 3D models (with embedded information including the maximum sizes, component weight, mark, etc.), it might enable an optimization in terms of total load, geometrical arrangement and loading sequence (Figure 43).

In addition, as far as the process matures, rulesets may be configured to automatically define maximum weight, clearance tolerances, unbalanced configuration alerts, and others as required when schematizing the load design.



Figure 43: 3D load plan model (left) and actual random load (right)

A 3D load model can be created from the manipulation of component objects using basic commands such as “move” and “rotate” to fit the selected components in the loading unit. The expected implications were to reduce lifting operations to feed the skids and trucks and facilitate tracking and checking of loadings in the layers (Figure 44).

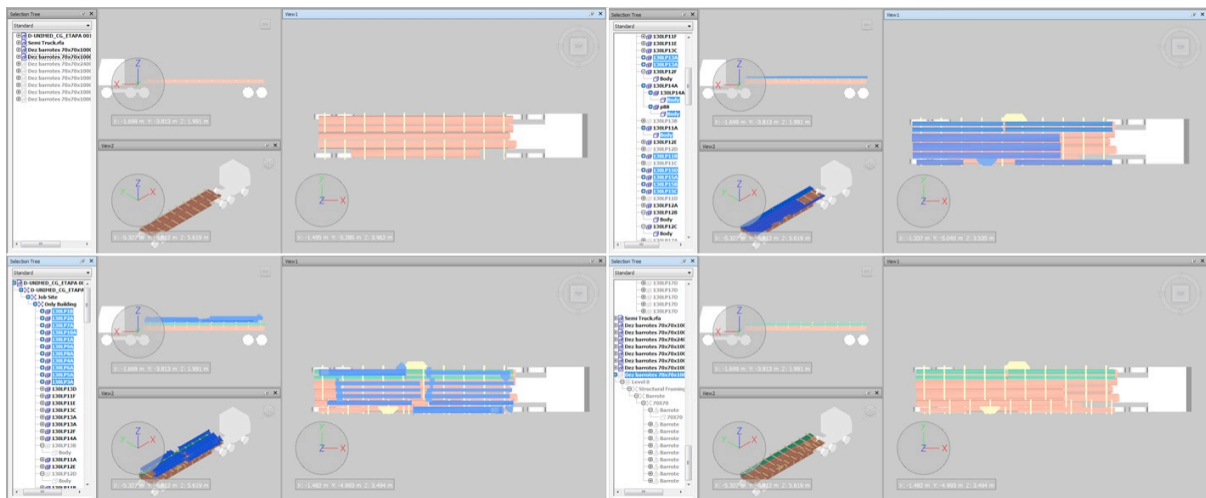


Figure 44: Load plan design – layer display using 3D modelling (as proposed)

By the end of the study, logistics operators reported their opinions in case this approach was implemented as a routine task in the plant. They highlighted opportunities concerning: (a) potential to increase reliability in forecasting carried tonnage, especially when dealing with components of complex geometry; (b) assurance that layout meet the transport regulations (components should fit into the body of the truck not exceeding the boundaries), which is

currently time-consuming due to trial and error operations; (c) potential to increase the ability in forecasting the amount of wood (levelling studs) consumed; and (d) ease to choose the better location for bulk boxes with the miscellaneous in the truck.

h) *Site visualization of product model*

When trucks reach the site, received materials are checked using UPC barcode or QR code technologies (the latest projects have used QR code). According to the new load planning schemes, components can be lifted straight from the truck or skids to the installation position. Depending on the inventory yard conditions, components are discharged to specific storage bays or the entire skids are laid down in a designated position according to the construction site layout. After that, components or kits must be tracked to pre-assembly (if planned to be pre-assembled on the ground), and then, lifted and installed.

By using BIM 3D model visualization (which was not a routine practice of the company), site operators could visualize the geometry, installation position (and the interfacing components), and other properties (including the identification mark). For doing so, the detailed design model had to be made available for the site stakeholders, including assembly coordination and quality assurance (Figure 45).

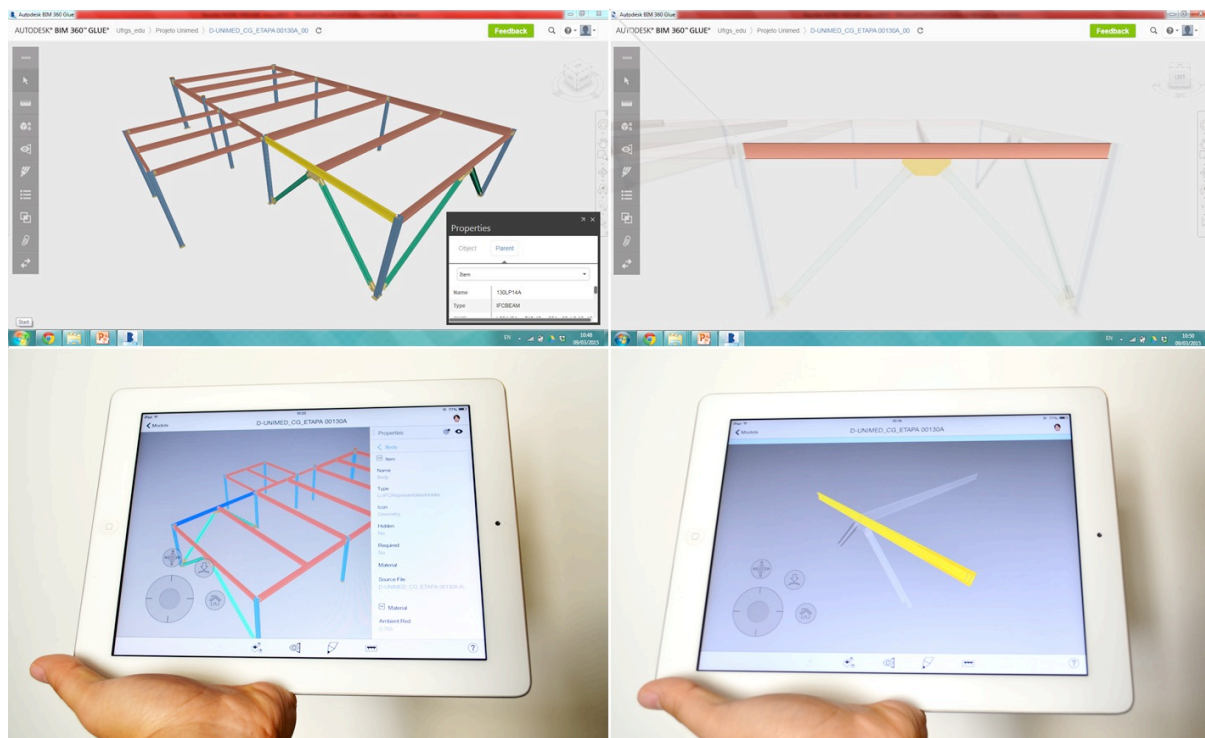


Figure 45: Mobile visualization of the detailed 3D model

Another potential advantage for further applications is the employment of 3D visualization to facilitate shared decision-making with other stakeholders with simultaneous activities on the site (e.g. earthmoving, foundations, cladding, piping installation, etc.) with concurrent activities or sharing resources like cranes or inventory spaces. Thus, the development of Production System Design (PSD) integrated with other disciplines would enable better site coordination between suppliers and subcontractors. Also, it could be used to generate reports comparing design as modelled with the as-built on site (Figure 46).



Figure 46: Instantaneous comparison of as-modelled and as-built

Additionally, the recovery of detailed model information for production and quality control purposes could be used at other BIM applications, not evaluated in this research. The IT application for production planning and control – based on the Last Planner System (LPS) – used in the company does not interface with BIM. Regarding mobile technologies, Autodesk BIM 360 Field and Tekla BIMsight Note were tested, but their uses were discontinued at the end of the research study.

Another possible constrain for production control or quality checking, which requires updated versions of the model, is that the BIM models retrieved for visualization are prone to be modified (approval design version), while detailed models become available too late and are difficult to handle in the mobile devices due to the large file sizes.

6.5 SUMMARY OF FINDINGS IN EMPIRICAL STUDIES

The empirical studies were conducted at different project stages and for different building typologies. Studies 1 and 3 had a greater emphasis on the production side, while study 2 highlighted opportunities in the design side, and study 4 covered both design and production. In short, these studies pointed out challenges related to the impact of upstream decisions in downstream process and opportunities to integrated teams to notify constructability requirements on time and providing reliable and ease to understand project information (product and process) via BIM and other technologies. Some of the suggestions have been instantiated in the empirical studies, while others were limited to the identification of opportunities for further implementations, due to time and information access constrains.

Exploratory study: Furniture manufacturing plant

- Since ETO products employ different levels of customization, advanced calculation and modelling applications (CAE and BIM) enables fast development of unique engineered solutions. Parametric design functionalities (e.g. size specification fields, tolerance ruleset) and non-graphical information makes digital modelling a more reliable approach for exchanging project data within the complex design-fabrication-logistics-assembly flow.
- Connecting components produced in MTO or MTS schemes take advantage of pre-engineered solutions and set-based detailing databases, and reuse data in CAD format. Although it does not affect the flow smoothness, operations on site need to manage sets of information in different standards, which could be facilitated in an all-digital approach, particularly for interfacing BIM with ERP and mobile devices.

Empirical study 1: Hangar

- The development of early scheduling simulations with 4D BIM encouraged the realization of meetings with representative of distinct departments to jointly devise collaborative solutions (in a future state, these meetings could evolve to a sort of a “big room”). This study demonstrated that design, planning and erection (site assembly) teams co-developed scenarios to optimize the resource utilization rates within the estimated schedule.
- The early stage involvement enabled stakeholders to share a common view of the design solution and the production process. Accordingly, they agreed to change the engineering solution (despite of being effort-demanding, it is possible in ETO situations) to facilitate erection operations. Early change prior to the fabrication avoided time and cost waste.

Empirical study 2: High-rise office buildings

- Despite of the relatively advanced achievements in BIM modelling, a wider scope leading to an integrated BIM workflow was not a reality. One major reason was the lack of a “policy approach” focused in collaborative procurement systems and information exchange, losing opportunities to deliver value, especially when working with other BIM experienced participants.
- At project level, the inclusion of BIM Project Execution Plans and BIM protocols in contracts could enforce the commitments for the development of collaborative activities. Basic issues to be tackled internally were the definition of LOD parameters of development and delivery, and then, IDM and MVD to configure BIM applications to aiming to deliver the required file standards with the expected set of information.
- An evaluation of the company’s own capability-maturity level in terms of BIM would allow the contract manager to better position the company’s responsibilities in the project team and BIM assets and deliverables. Internally, it indicated limitations in the current BIM-based design and production processes to establish new targets for continuous improvement programs.

Empirical study 3: Hotel

- Recovered product models (from the approval design stage) can be used to generate production sequence visualization to support site managers to demand the batches from plant or inventory yards to better control the levels of inventory in the site. Detailed models (separated in the pre-defined production batch) can be manipulated to simulate material handling operations and temporary layout of materials, matching the 3D digital object to the mark of each physical component.
- The uniqueness of each ETO component required a tough control of the batches being moved to the site. ID and other properties information embedded to BIM models facilitate to manage their locations on the plant, inventory yard and construction site. 3D visuals were prepared to simplify checking tasks at the start of an operation to ensure that the right component is moved and assembled.
- Simulations for optimizing materials arrangements require inputs not available in conventional BIM applications. These functions can be possibly found in DES plant simulation software used in other industries, but its practical use remains complicated due to the difficulties in controlling the execution, due to uncertainties of the construction environment.

Empirical study 4: Healthcare facility

- Although the company benefitted from BIM functionalities in the engineering process, the integration with the whole business chain remained an issue. More than interfacing project phases as in the other empirical studies, managing the information across the whole life through different technology platforms was even more challenging, as it required the involvement of many functional departments with distinct operational priorities.
- The newest BIM functionalities represented vast opportunities for expanding the BIM scope with only few additional efforts if grounded on a systematic information recovery. Due to the vertical structure of the ETO delivery chain, a reformed framework needed to support variable information demands, interoperability schemes, and policy issues concerned with the complexity of the product itself, but also with the productive process.
- Pilot implementations in this study could achieve better results in uses with high levels of involvement of the staff. Technology push actions struggled due to the unbalanced amount of efforts to generate low impact outcomes in the process (e.g. monitoring of erection progress on the construction site failed without the presence of the researcher). By contrast, initiatives with direct support of managers fastened implementation trials (e.g. the interventions in the manufacturing plant, for using mobile devices).

Discussion

Challenges concerning design and production integration in complex ETO operations led to the experimentation of alternatives to improve the use of product information across the development process. Uncertainties related to uniqueness of ETO products for new projects had been addressed so far through an improved use of BIM. However, the full potential could not be reached as the information flow was not integrated among the departments in charge of the product life phases – in this case, in post-design phases.

The use of BIM helped to prevent mistakes through the configuration of rulesets. Digital information flow facilitated early collaboration, which is important in ETO systems, given the high susceptibility to deliver incompatible design solutions with production constrains (manufacturing or assembly process). Constructability issues and resource optimization could be managed in joint agreements between designers and site operators prior to the field work, reducing operational costs and risks.

Tacit experience from the workplace were informed yet in engineering phases, although it could not be translated in functional rules to improve automation and fast decision-making yet. Another emerging proposition for further exploration was the possibility to integrated change management systems to the design and engineering software packages. Feedback (recorded in non-compliance reports, RFI reports and Change Orders) coming from the plant, logistics and the construction site of multiple projects should be reported and forwarded to the design teams who has a tough work of engineering ETO products to specific field conditions.

The idea of performing simulation of erection and logistics process meets the idea of virtual prototyping, in the sense that identified installation and logistics constrains addressed technical feedback on time for product re-engineering, anticipating issues that could be only perceived on plant or site. Thus, overflowing RFIs and Change Orders are likely to be avoided, reducing the impacts on schedule, cost and quality.

Early prototyping and simulation were enabled by bridging information from design and assembly. In this sense, logistic information updates were communicated to the researcher, who connected them to the product model, generating a shared vision of the solutions under development. For doing it, the use of BIM information requires specific model content retrieving, and this might impact upstream modelling process.

In a BIM workflow for a steel fabricator, there are several means of exchanges to bring together information from CAE, CAD/CAM, and ERP systems. Presumably, as far as forthcoming platforms get matured (i.e. when PLM can be finally implemented), the management of product lifecycle stages and their associated technologies will need to be better integrated with socio-technical challenges of business process reform, delivery methods, and field implementation.

The insights cited above stemmed from evidences and discussions related to the empirical studies and are connected with previous theories. Henceforth, the next chapter expects to provide reflections about the context of implementation based on a strategic roadmapping approach.

7 BIM IMPLEMENTATION STRATEGY FOR ETO FABRICATORS

This chapter presents the three main outputs of this investigation: (a) roadmaps to support strategic technology management for ETO prefabrication companies; (b) a set of guidelines for the gradual implementation of the envisioned scenario; and (c) reflections on the major impacts concerning the use of roadmapping in BIM implementation contexts.

7.1 ROADMAPPING APPROACH TO DEVISE A VISION

As discussed in the literature review, a roadmap enables fabricators to look at future states of computer-integrated systems which can be aligned with their corporate goals. Apart of learning how to evaluate and choose complex technologies suitable to the company's operations and business, the implementation of envisioned targets is a challenge itself. The vision creation process should collect tacit and explicit knowledge from strategic and operational players to identify drivers for change.

Phaal and Muller (2009) argue that roadmapping approach is flexible and scalable, and can be customized to suit different strategic and innovation contexts. Regarding BIM implementation context, on the one hand, firms delivering similar products types and working with similar scope and can take advantages of generic roadmaps to oversee potential technology routes to set their technology management strategies. On the other hand, the combination of specific viewpoints enables organizations to design their own roadmaps, customizing the steps to meet unique business objectives in complex implementation contexts.

It is worth noting that a roadmapping process held at organizational level is different from those at industry level in terms of scope, goals, and dynamics of a specific environment. A company can take advantage in using a TRM (in complement to, for example, Panel of specialists or Delphi Method that are used in broader scenarios) to design plans considering the peculiarities of an organization or target clients. In practical terms, a roadmap should be built by people with empirical understanding of hands-on work and deep sense of the contextual limitations.

Regardless of the techniques used to conduct the roadmapping process (e.g. supported by ideas from Design Thinking methods), the interaction between people from different functional

departments or supply chain members (with distinct background, experiences and perceptions) may create an enriching environment for innovation and led to the co-design of more consistent and feasible visions and implementation plans.

The vision is composed of viewpoints adapted from elements of the schematic multi-layer roadmap model (TRM) of Phall and Muller (2009) and sub-systems (STS) associated to BIM implementation context. They can be summarized in: (a) commercial and strategic (business and market); (b) design, development and production (products and services); (c) technology and research; (a') people and policies; (b') process; and (c') technologies.

In this conceptualization, technology is an overlapping viewpoint for both approaches. The other viewpoints to be considered in the vision vary according to the types of business model, types of deliverables, and long-term strategic goals. Besides, people and policies were considered separately, while process was divided into the “temporary construction project process” and the “ETO business chain” referring to the internal vertical chain.

The viewpoints are selected to meet the contextual requirements of the company. Roadmap developers must ensure that vision remains flexible to respond to the fast-changing environment for market needs and technology releases. The framework foresees openness to adjust milestones or methods when new ideas emerge, and these innovations suit the business context, while pointing a clear strategic direction.

For each viewpoint, roadmap developers must devise a future state, i.e. ideal scenarios or levels of practice to be pursuit. The players involved in the development of the roadmap should build consensus on the envisioned state. The viewpoints set time frames in which tactical actions should be allocated. Intermediate stages to reach such a vision situate the state-of-the-practice and time span to be implemented: short-, medium- and long-term implementation objectives, influencing the definition of priorities.

The definition of the envisioned states presented below is based on the researcher perceptions accumulated from interviews and feedback from participant staff of the company. Thus, it does not necessarily correspond to the company's view. For some of topics, it was also based on trends indicated in the literature review. Therefore, these envisioned states are possibly beyond the concrete targets of the company either because of time constrains as technology infrastructure and training at the moment of the conceptualization (Figure 47).

	Viewpoints	Envisioned state
Business (portfolio)	Business units (product typology)	Mature program management and portfolio management
Procurement (market and supply)	Procurement and contracts (benefit and risk sharing)	Partnering, Alliancing, and Integrated Project Delivery
Products (production situation)	Engineer-to-order (set-based concurrent engineering)	Modularization and mass customizable product configuration
Services (extension of scope)	Whole-life support (extension to post-construction)	Full lifecycle management
Technology (platform)	BIM interoperability (information available on demand)	Governance, security, and cyber- physical integration through BLM
Process (construction projects)	Temporary team collaboration (horizontal integration)	Integrated workflow, shared milestones, and delivery targets
Process (ETO business chain)	Coordination of functional teams (vertical integration)	Value chain synchronization, flexibility, and adaptability
People (People development)	Individuals, teams (leadership and growth)	Trust, collaboration, and knowledge management
Policies (approach and records)	Working strategies (digital information exchange)	Systematic standard/protocol utilization and feedback loops

Figure 47: Envisioned states for the selected viewpoints

In a practical situation, not always the envisioned state is strictly accomplished. The roadmapping process should consider the existence of uncertainties and the occurrence of change in business conduction according to a variety of factors (e.g. emergence of new technologies, economic mood, governmental mandates, regulatory changes, business strategy re-orientation, etc.) and new business aspirations.

Despite of the relevance of the outputs, the roadmapping process can, in some cases, become even more important than the roadmap itself, as it forces the company to understand the enterprise context and external trends to define turning points towards the strategic goals. Roadmaps and the roadmapping process should be designed to provide a common language and structure for both development and deployment of strategy (PHAAL; MULLER, 2009).

The accomplishment of a milestone allows the team to take the next step of the roadmap. In some cases, learning outcomes may lead the incorporation of additional points or step deviations of the original strategy. Advancing the roadmap may induce the team to revisit the

long-term vision and reposition the targets according to new business orientations – configuring new versions of the original roadmap.

The Figure 48 expresses that in the long term (L.T.) the company shall reach fully integrated BIM-PLM, taking advantage of improved product and process information governance, data security mechanisms, and cyber-physical integration – led by advancement and diffusion of IoT and AI. At this future state, major problems concerning data exchange among project participants using different software and fragmented processes (as occur with in current process) might be solved by standardized and automated exchange protocols.

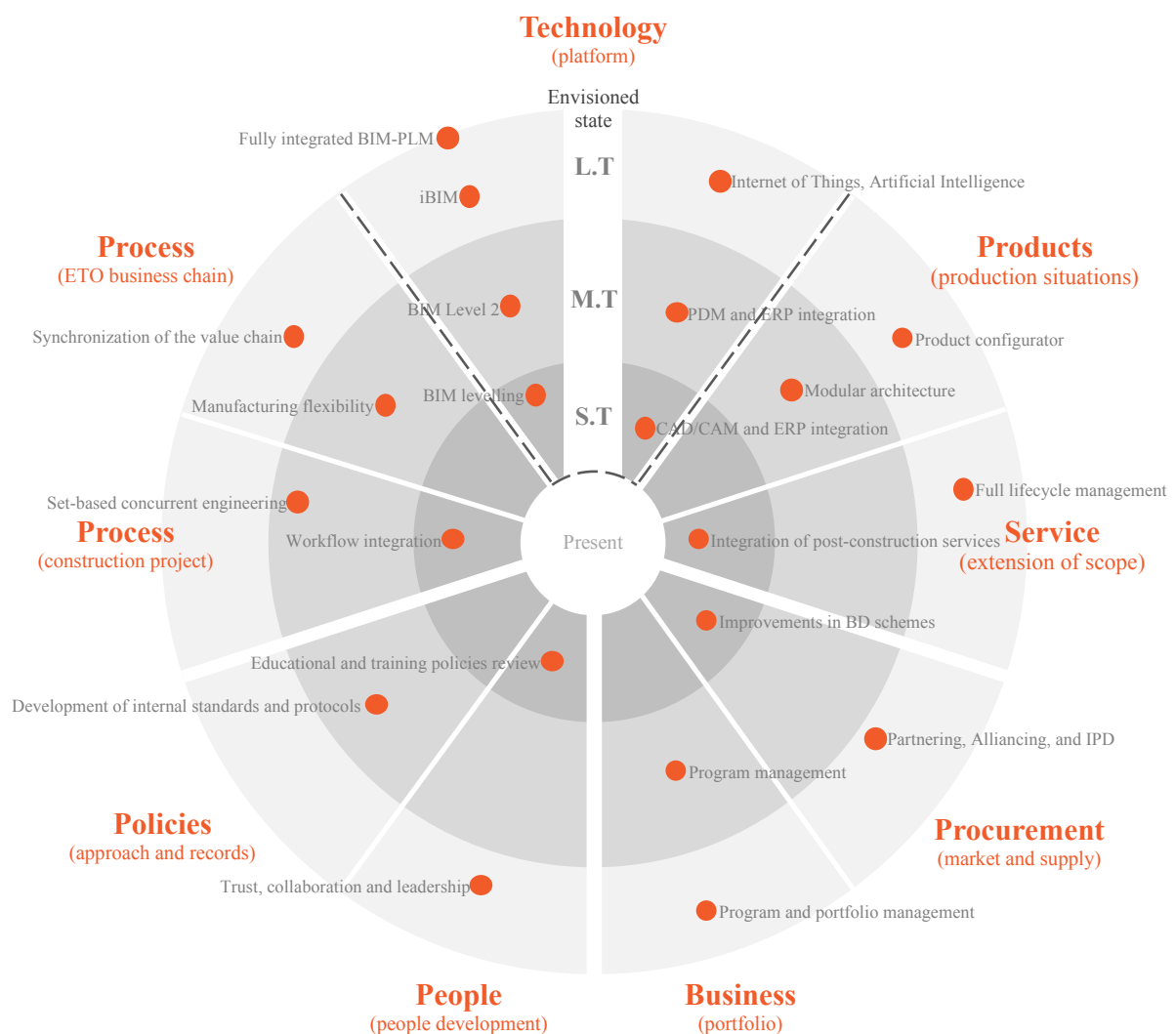


Figure 48: Vision for prefabricated steel structure enterprises

The first step for moving towards this scenario is the promote little BIM-related improvements – beginning by spreading BIM awareness and levelling – across the product development

process in the short-term (S.T.). Bunches of data that are exchanged on demand (non-automated yet) should meet collaborative requirements to manage projects in an integrated way not only within the functional departments of the organizations but also with project participants of the temporary project team and supply chain partners. The impacts of a step of the roadmap in the technology viewpoint are related to required steps of other viewpoints (e.g. process, procurement, services). Here, it is clear that the transition from the implementation of BIM functionalities to a fully integrated BIM is not only a matter of technology. As long as BIM functionalities are implemented, and BIM processes are deployed in pilot projects, the organization gets more prepared to reach higher levels of BIM maturity.

The next step is to comply with BIM Level 2 criteria (M.T.). At this point, the current practices should step on collaborative working methods with more efficient exchange data management. Although there was not a BIM mandate in Brazil by the time of this empirical studies, internationally accepted definitions are helpful to position clear targets based on proved experiences which are possible to benchmark.

Even though this type of representation indicates several viewpoints to be considered simultaneously, it is possible to emphasize specific viewpoints using customized roadmap layouts that suit the company's priorities and aspirations. Furthermore, the roadmap can be used not only to support technology strategy, but program management and partnering schemes with supply chain members. Ideally, workshops with multi-level hierarchy members from multiple functional areas contribute to gather knowledge backgrounds and experiences to foster a broad outlook vision. Moreover, references from advanced study cases and best practices (either organized by government or industrial sector organizations) together with benchmark analysis can support the creation of more comprehensive systems.

Due to the focus of this research, major emphasis is put in the "technology" viewpoint. As identified in the research problem, the company has a long-term goal to promote better computer-system integration to facilitate a more consistent knowledge management by means of a PLM platform, which is currently under development for soon implementation in pilot projects. However, it was identified that not all in-house teams were sufficiently aware and mature for such shift in working practices (migration from traditional to PLM-based process).

The transition to BIM has been troublesome for many construction organizations, but it is here seen as an opportunity to soften an even more drastic shift to PLM. In prefabricated building

systems, the overlapping characteristics with other manufacturing industries (e.g. metal-mechanics, in case of steel structures) has led to the will of adapting PLM systems, which is probably even more complex to adapt than BIM. This is because there are significant differences between PLM's target industries and AEC characteristics, so it may that require tailoring of some aspects of current PLM technology (ARAM; EASTMAN, 2013).

In fact, PLM migration includes extensive changes in intra- and inter-organizational practices and requires new types of skills and capabilities, and even large cultural and strategic changes (SILVENTOINEN et al., 2011). Nevertheless, the short experience from BIM can contribute to make a less traumatic transitioning to an integrated BIM-PLM platform.

It was perceived that many changes required to establish a PLM workflow overlap with mature BIM workflows and practices. Thus, tactics for the technology viewpoint could begin with a better levelling of the internal use of BIM together with supplementary technologies, an increase of the BIM capability maturity level, and the expansion of lifecycle functionalities to finally be able to reach PLM/BLM features. Hence, a gradual implementation process is required; and roadmapping can be a supportive approach for the transition, together with the improvements considering technological and human aspects concurrently.

7.2 GUIDELINES TO SHIFT FROM VISION TO IMPLEMENTATION

In order to promote the shift towards the envisioned scenario, strategic programs define several related projects aiming to achieve the implementation mission by engaging gradual improvements through pilot projects or even major business process reforms. Shaping an implementation process enables organizations to install implementation programs to progressively put ideas into practice and generate the expected outcomes.

The steps proposed here do not intend to provide rigid implementation rulesets. Rather, the timeline parameter does not apply deterministic values in order to remain flexible concerned with the fast-evolving technology environment. The guidelines below provide general guidance on how to drive fundamental changes towards the vision. The idea is to set up enabling conditions based on observation in the empirical studies.

As first step, it is necessary to include a preparatory stage to reach a basic level of awareness among participants before starting implementation (Figure 49). The goal of this preparatory

stage is to level the awareness among the participants of implementation process and to set a pragmatic environment to lead the changing process. The guidelines to the preparatory stages are explained in section below.

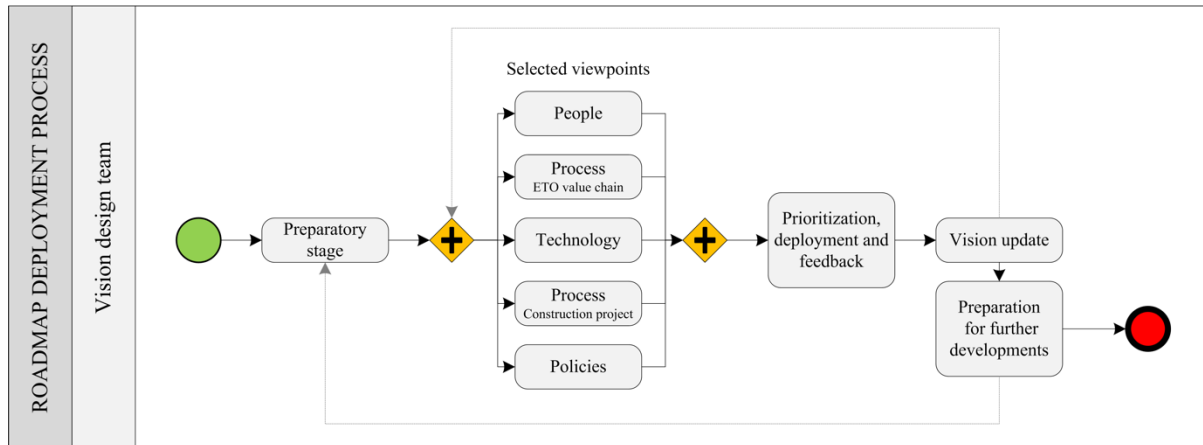


Figure 49: Steps of the roadmap deployment process

After that, the organization selects the most critical viewpoints of the technology roadmap. A breakdown analysis of each viewpoint may help the deployment team to understand the current situation and to predict bottlenecks concerning the envisioned states (Preparatory stage). At this point, the team has already discussed their targets and are in the way of streamlining processes to work on pilot projects and to deploy new working practices.

Next, the team defines the steps of strategic development (Selected viewpoints). Due to the characteristics of each viewpoint in the enterprise context of implementation, the team strategically defines how to actually evolve from the current situation towards the envisioned state. Trending technologies and market push are drivers to set up the steps according to the long-term business objectives, technical infrastructure, operational requirements, training levels of human resources and characteristics of the running business processes.

Since BIM is the focus of implementation, the focus turns back to the technological viewpoint concerning product and process information management through BIM. Regarding the characteristics of ETO operations, BIM interoperability with information available on demand plays a central role in the current product development process. However, aiming improved governance capabilities, data security, and cyber-physical integration through BLM, there is a need to select priority actions, to gradually deploy new processes and functionalities, and to

continuously assess the system to assure its best possible performance (Prioritization, deployment and feedback).

As the steps are deployed, it is natural that organizations reassess and update their vision and technological objectives. The full implementation takes time while new technologies are released, and new business and operational issues emerge (Vision update). Moreover, technical and human challenges to implement BIM and other platforms may reveal alternative ways of achieving the business objectives. Finally, the team is able to prepare further developments either keeping the plan of the original roadmap or by deploying new steps of an updated version of the roadmap.

7.2.1 Preparatory stage

The preparatory stage aims to promote “awareness and sensitization” among the staff of the company and with those external stakeholders involved in ongoing and upcoming projects, as proposed by Baxter and Sommerville (2011). Once the strategic roadmap has been designed, the deployment process starts with the vision sharing and working alignment among teams and individuals. Designated actions for each viewpoint are further detailed after establishing a common understanding of the plan and collective engagement.

Two aspects of the preparation should be considered. The first is the continuous development of internal teams, who own the potential to generate deeper and lasting transformation outcomes. The accumulation of experiences nurtures better-performing routines to be gradually incorporated into projects and programs. The second is that for every new project, external participants should be informed and encouraged to collaborate in the development of such improvement-minded environment, by sharing the benefits and responsibilities of the improvement outcomes mutually achieved. In this case, the preparation tends to be quicker and intense, but prone to generate limited impact in pilot experiences due to the lack of familiarity with the ultimate purposes and methods.

Recommendations in the implementation charter for the preparatory stage can be structured either as broad suggestions or narrow instructions to be followed. They can also be prescribed either in a succession of steps or irrespective of sequence, depending on the enterprise context and project openness for innovation. In the context of this investigation, the course of preparation below consists of guidelines which are irrespective of chronological sequence.

Diffuse the goals across all stakeholders

A major gap identified along the research was the need to address a comprehensive solution capable to integrate design and production process and technologies by involving all teams within and across the boundaries of the organization. Therefore, in the sensitization phase, a bi-directional approach to promote vertical and horizontal integration should initiate with the diffusion of roadmapping goals and improvement areas for implementation. Regardless of individual talents and influence power, awareness and educational programs should reach all players in order to develop the required skills, encourage collective participation, and warn about the potential changes at both project- and organizational-levels.

Match the innovation goals within suitable management orientations

The company had adopted principles and tools from lean production in alignment with their business goals. Lean initiatives (including research studies held in the partnership with NORIE) strive to orchestrate managerial efforts with new performance and innovation objectives. After years running Lean programs, the outcomes achieved so far ensured a positive mood concerning the promising linkages between the current Lean orientation with projected BIM efforts, also recommended in the literature and industry reports.

Associate current bottlenecks of practice with the technology improvement pledges

Problems related to failing information exchange and communication, poor understanding of documents and digital files, and the lack of collaboration between teams have led to an ever-growing adoption of IT tools capable to attenuate these issues. The literature has emphasized the benefits provided by object-oriented modelling tools (i.e. BIM) to recover and manage product information. The latest trends point out computer-integrated solutions which cover advanced parametric product modelling, process modelling and simulation, cyber-physical interactions, and data management applications. Moreover, the partial adoption of BIM in the multi-storey unit of this company has proved to be advantageous in relation to other internal units still working in a traditional way (non-BIM workflow). Despite of the challenges to implement and operate new systems, the benefits perceived from the integration between CAE, CAD/CAM and ERP, and more recently with BIM, unified database and mobile technologies have encouraged the development of more robust IT platforms capable to manage the huge amount of complex information in an interoperable and secure way.

Position the envisioned technological scenario with emerging trends in industry

Large manufacturing firms have put efforts on setting tools to establish and run a PLM platform. The company's decision was influenced by positive outcomes observed in other large organizations from the metal-mechanics industry, while internal endeavours for IT (implementation of ERP, gradual implementation of BIM, improvements in CAE software configurations, etc.) have driven to a similar direction. Up to this point, very few examples of PLM in construction have been reported, so that the development and implementation of PLM would put the company in an avant-garde position. In recent years, software developers and a few academics – exploring synergistic characteristics with BIM – presented ideas that seem to be suitable in the present panorama of the company.

Consider specific features of product typology and the taxonomy of production situations

Despite of the wide reach of the company's portfolio, this investigation has only focused in two building system typologies: the industrial facilities and the multi-storey buildings. This deployment plan was designed to the division of multi-storey steel structures, although some procedural aspects are applicable to other building typologies. The steps take in considerations the complexity of engineer-to-order operations, in which most components of the building system are developed in an ETO scheme, with some minor parts delivered as ATO or MTO. Features for design integration and the management of design information downstream is a major object of improvement for future system configurations.

Select the critical sections of the value chain to be the initial focus of development

Although the whole-lifecycle considerations are essential to a comprehensive management, in this investigation, the design and production phases have been selected to tackle issues related to the complexity of ETO operations in the delivery of prefabricated steel structures. At this organization, many of the identified process issues are related to poor integration between design and production phases, which became clearer with the challenges faced in the empirical studies. The introduction of innovations placed in the roadmap should contribute to enhance integration in these phases. After delivering improvements to these phases, future efforts could be dedicated to the fuzzy front-end or to the post-construction phases.

Comments

Although these guidelines may seem obvious to academics and managers, not all participants are familiar with the background associated to them. Without understanding the context and the company's position for improvements, teams struggle to propose feasible changes and to design larger reforms related to BIM implementation. The identification of bottlenecks and solutions related to the vision becomes clearer as far as players recognize the innovative and changing context in which they take part. Functional departments tend to focus on accomplishing their tasks associated to a specific product lifecycle phase. Thus, even though the staff know what comes just before and after their activities, they rarely understand the real impact in the entire value chain.

Once established a levelled awareness about the implementation program, advices to prepare the ground are organized and communicated to players, based on perceived challenges in the empirical studies (or pilot projects, from the company's perspective):

- P1. Define typical project gateways for intensifying the concentration of integration efforts
- P2. Encourage the early involvement of multidisciplinary stakeholders in new engagements
- P3. Forecast and manage the impacts of design and production downstream each phase
- P4. Feed the engineering teams with requirements and constrains of their downstream activities
- P5. Nurture a culture of collaborative planning – i.e. project scheduling synchronization with discipline's schedules

A breakdown of each advice is then further structured, defining the procedures as component projects of a major program for the development and implementation of integrated BIM workflow. These tasks can be carried out simultaneously to speed up the preparatory stage and are flexible to accept adjustments and refinements with the feedback of participants.

7.2.2 Development of the viewpoints

The comprehensiveness of the implementation plan arises from the need of a holistic proposition capable to stimulate constructive engagement in strategic areas for the development and implementation of selected viewpoints. Although there are several viewpoints to be analysed, this investigation focused on the “technology” perspective to devise a vision of a

computer-integrated schemes capable to address improvements for design and production integration in the context of the company involved in this research.

The company has required solutions to improve the delivery of project assignments and internal process productivity through innovative methods and technologies. Concerning the migration from traditional practice towards BIM, ongoing initiatives position the company as an “early majority pragmatist”, just after “the chasm”¹⁸, in the Brazilian context. On the other hand, the PLM endeavour place the company between an “innovator/technology enthusiast” and “early adopter visionary” categories, ahead of most competitors.

However, due to the characteristics of current organizational process and the audacious nature of the envisioned goals, the vision of high “governance, security, and cyber-physical integration through BLM” can only be achieved in lengthy horizons. Since the required changes that comes together with the implementation are difficult to handle, it is first necessary to setup an enabling environment in which players can deploy the action plans.

The first part of the plan introduces a series of general recommendations to be applied to those selected viewpoints. It provides sequential instructions for a specific context, considering the contextual analysis of the company held in the preparatory stage.

The example below aggregates the hints given by both the researcher and company’s staff. Yet, the script is supplemented with further recommendations based on literature and experiences from other case studies not debated along the empirical part of the research.

Viewpoints of the strategic development

Technology: Gradual introduction of integrated technology modules

1. Establish levelled BIM across the business units and functional departments.
2. Increase BIM capability and maturity level and develop a BIM knowledge repository.
3. Devise an integrated BIM-ERP scheme to multi-project planning and coordination.
4. Mature integrated BIM connections with PDM, cloud and mobile technologies.
5. Run fully integrated PLM with capabilities to incorporate upcoming technologies.

Process (ETO business chain): Enhancement of lifecycle phases integration

1. Perform a comprehensive process modelling with focus in phase interchanges.
2. Execute systemic improvements in the identified flaw interface between phases.

¹⁸ “Crossing the innovation chasm” presented by G. Moore (1991)

3. Streamline collaborative processes between in-house functional teams along the value chain.
4. Set parameters for process control and synchronization to facilitate continuous improvement.
5. Optimize work and information flow with “autonomation” abilities.

Process (construction project): Engagement of cross-organizational collaboration

1. Co-design the project process to align milestones, gateways, and exchange points.
2. Identify potential hindrances in project process and pre-set feasible alternatives to solve them.
3. Agree on the critical implementation routes and areas of prioritization in project development.
4. Establish tangible parameters for the coordinated delivery of design and production outputs.
5. Plan project conduction in view of optimizing the flow of information and materials.

Policies: Articulation of integrative policies at project- and enterprise-level

1. Pre-set Project Execution Plans based on previous experiences and most used contractual schemes.
2. Customize digital information exchange protocol templates to fit the project strategy.
3. Agree on the use of national standards for information exchange and project phase deliverables.
4. Encourage the inclusion of gain-gain contractual clauses leading to more committed teams.
5. Orchestrate working practices that enable all partners to reach individual IT governance objectives.

People: Foster people development

1. Understand, adapt and diffuse the concept of people development together with technical aspects.
2. Develop technical skills and the ability to collectively solve problems and deliver integrated solutions.
3. Encourage the sense of collective importance and multi-level hierarchy and multi-disciplinary exchange.
4. Perform mechanisms of feedback learning and knowledge creation and dissemination.
5. Boost enterprise continuous improvement and nurture leadership to innovation.

The propositions above elucidate the mainstream of each viewpoint to establish a common direction in the changing process. Concerning the technology perspective, the analysis at the beginning of the research identified distinct maturity levels associated to design teams using BIM. The company still employ different computer technologies due to technical requirements related to the characteristics of product typologies and production situations, requiring multiple software capabilities to respond to tricky interoperability issues and data management.

Prior to the empirical studies, the main IT targets reported by the company were: (a) full implementation of ERP for centralizing information across the distinct units; and (b) advancement of the PLM project, responsible to customize tools to the own engineering standards, provide training, run pilot projects, and lead the system implementation.

However, many of the challenges perceived in the PLM project showed that improvements in the use of BIM could be positive because not all functionalities could be directly migrated from traditional CAD to PLM in such short time, while BIM authoring tools offered a friendly interface to soften the transition. Moreover, skills and capabilities developed for operating BIM could be reused to run PLM in a future stage.

In the empirical study 1, the design team used to operate in a traditional workflow based on a mix of 2D/3D CAD tools for design, detailing and documentation with external linkages to CAD/CAM and ERP. Along the research process, several improvements enabled by software updates and the acquisitions of new applications allowed to re-think the project information flow and to introduce an alternative work flow which takes advantage of digital model information to increase data reliability and optimize product information exchange. The research interventions requested the use of IFC files to use in external BIM functions, even though disconnected from a BIM workflow.

The empirical studies 2 and 3 attempted to explore potentialities of a BIM-based workflow by mixing some hard-to-change traditional process with trials of introducing a BIM-oriented process through the utilization of BIM functionalities. Compared to the exploratory study, these studies benefited from the recovery of 3D models already developed by the design team instead of spending hours of re-work for remodelling redundant product information.

The study 4 (developed with the design team of the multi-storey unit) already featured some characteristics of a BIM process. The major challenges in the expansion of BIM uses were across planning and erection phases. Even though production tasks were supplied of design and production information, "BIM for production" was not performed at full potential, because the reach of intervention was very limited in the construction site compared to the better-implemented uses in design offices and in the plants, leading to volatile results.

Despite of transfer data mechanisms between CAD/CAM and MRP/ERP or BIM and MRP/ERP, solutions to improve such integration was not extensively debated in this research. However, inspired by BIM apps for mobile devices, the idea to integrate graphical information (retrieved from BIM models) with project status (maintained by ERP) was discussed for future research. Concerning the strategic plan for PLM, up to this point, the company did not communicate a clear strategy to deploy PLM associated with improvements in BIM. Instead, there was an apparent trend of replacing BIM tools by the new CAD tool for PLM platform.

The new business process to be established with PLM is likely to cause striking changes in the working methods and in the way project information flow. Therefore, the following steps suggest a gradual promotion of technology integration via BIM and PLM connections to attenuate the impacts resulting from such shift. Advices are supplemented with novel approaches retrieved from the academic literature and white papers of technology developers.

Technology: Gradual introduction of integrated technology platforms

Step 1: Establish levelled BIM across the business units and functional departments

Assuming BIM as a fundamental step towards the Building Lifecycle Management (BLM), the company should first diffuse and implement levelled BIM across different business units and functional teams. Since the ultimate computer-integrated platform should cover the entire lifecycle of the whole portfolio, all product design and production information should be jointly managed. Despite of different product development strategies, BIM is capable to support a range of product typologies. Based on the experiences from the multi-storey systems, other structural typologies (industrial facilities, civil structures, pre-engineered fast-buildings) can take advantage of BIM resources already available to increased performance and reliability to run a BIM-based workflow. Moreover, functional departments in charge of different phases of the product lifecycle presented varying levels of BIM awareness and capabilities. As demonstrated in the empirical studies, the challenges to expand the use of BIM from design to other lifecycle phases are not only technical, but essentially strategic and managerial. Although the purchase and adaptation of software extensions may be required – especially for projects whose processes are substantially different (e.g. infrastructure, complex architecture designs, etc.) – learning outcomes from prior BIM experiences contribute to make the future PLM implementation less dramatic.

Step 2: Increase BIM capability and maturity level and develop a BIM knowledge repository

Based on the premise that BIM knowledge and experience can contribute to a future PLM implementation, as the use of BIM becomes more advanced, the easier it will be to accommodate robust computer-integrated platforms and complex business process engines. There are several approaches to assess BIM capability maturity levels. The best known is the Interactive - Capability Maturity Model (I-CMM/NBIMS, 2007), which establishes a tool to determine the level of maturity of an individual BIM as measured against a set of weighted criteria agreed to be desirable in a BIM model. Afterwards, Succar (2010) proposed a more

comprehensive tool named BIM Maturity Matrix (BIm³), a performance measurement and improvement tool which identified the correlation between BIM stages, competency sets, maturity levels and organizational scales. From the industry side, one remarkable example is the Arup BIM Maturity Measure tool, a straightforward tool derivative of the BIM PEP Guide (CIC Research Council, Penn State) to help demonstrate current capabilities and future needs. At this point, the goal is not to reach high scores, but to understand the different levels and identify improvement priorities. The deployment of improvements generates new learning outcomes that enable the company to feed and manage a BIM knowledge repository to be consulted and refined alongside the implementation process.

Step 3: Devise an integrated BIM-ERP scheme to multi-project planning and coordination

Although the ERP consolidation, BIM expansion and PLM project share common challenges in terms of implementation, these are managed as independent initiatives. A major challenge is centred in the fact that BIM and ERP platforms do not have an interface solution by default. Although some degree of data exchange is possible, it lacks a smooth mechanism for automating status update from ERP to BIM models. On the one hand, production-oriented ERP enabled better control of information across the business chain, achieving a more reliable planning, material flow optimization and improvements in managing bunch of design data from engineer-to-order operations. Meanwhile, an expanded and mature use of BIM has enabling design teams to deliver thorough product information to be consulted downstream in a much friendlier visualization. If an interface between BIM and ERP systems is yet complex to setup, an external integration system could be applied to bridge product design and updated production information, and hence, provide more than an improved visualisation, but transparency for multiple project management.

Step 4: Mature integrated BIM connections with PDM, cloud and mobile technologies

The consolidation of the BIM-ERP exchangeability drives information management to a superior level of design and production integration. The complexity involved in the development process of ETO components requires abilities which can be attenuated by IT providing reliable platform to manage product essential information across the value chain. In this regard, PDM functionalities together with ERP can provide mechanisms to entail product data from CAD or BIM models and make them available for manufacturing management through integrated databases. An attracting factor for expanding BIM-ERP integration stems

from mobile applications that enable field workers to directly send updates on the status of the steel components to projects modelled in a compatible BIM modelling software. These apps allow users to update information by input or barcode scans effectively and very quickly. Such integration could be enhanced by bridging BIM models and status update information from the ERP system, in a way to generate friendly graphical visualizations of the multiple project progress simultaneously. Henceforth, an effective link of the just purchased PDM module with BIM and ERP would set the stage for a smoother PLM deployment. The integrated management of databases, business process and project workflows can potentially address major bottlenecks of poor communication and information exchange flaws while providing a positive environment for increased project and program performance.

Step 5: Run fully integrated PLM with capabilities to incorporate upcoming technologies

Aiming to reach the benefits from an integrated BLM scheme comprised of an integrated BIM-PLM, a few sub-implementations are required. Because PLM system is composed of several modules and holds numerous interfaces, a full integration of PLM occurs when packages are properly interfaced and are operating steadily. The addition of new packages over the core modules imply in solving interoperability challenges and business process side effects. Moreover, the fast development of new technologies enforces the openness to upcoming solutions possibly developed in different schemes to PLM. Yet, this propensity for conglomeration requires technology strategy to manage fragmentation-integration relations of technology development thinking on the company's goals. Finally, this plan acknowledges the tendency of this vision to be replaced by new conceptualizations, perhaps using totally different technologies.

7.2.3 Prioritization, implementation and feedback

The elaboration of the implementation plan should consider the high complexity of the implementation process. A recurrent approach is the use of urgent-important matrix, inspired by the Eisenhower Matrix which helps decision-makers prioritize tasks in time management. In addition, technical concerns must focus on the “do-ability” of the project or vision. Cooper (1990) explains that customer needs and “wish lists” must be translated into technically and economically feasible solutions.

By combining such approaches, a matrix evaluating “impact” vs “do-ability” or “importance” vs “urgency” is adapted to the context of technology strategy and roadmapping. The balance

between benefits and ease of implementation may generate layers of priorities and topics for future consideration (less feasible with the available resources and current degree of expertise). In fact, the fifth guideline is not exactly the last stage, since the vision is devised to set broad scenarios for strategic planning purposes (Figure 50).

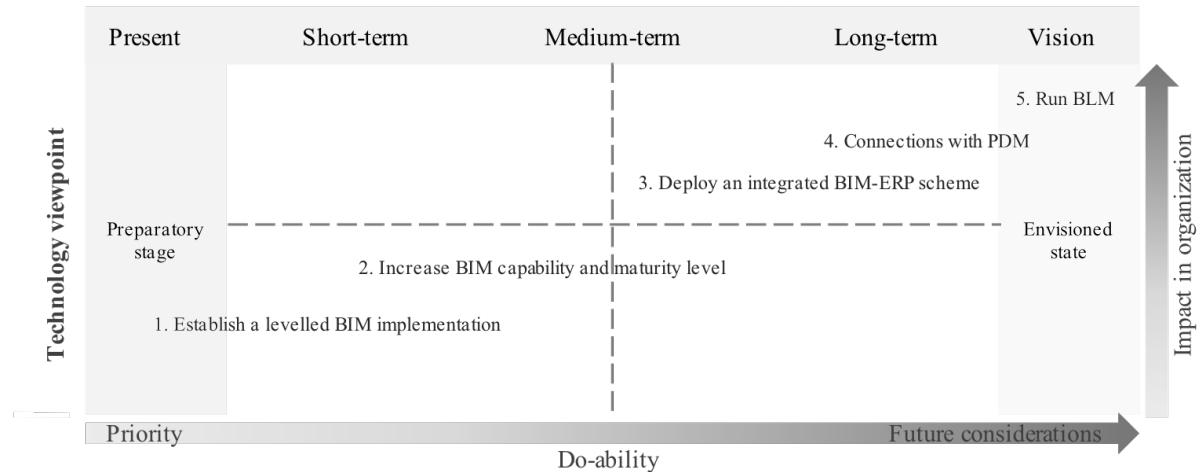


Figure 50: Prioritization of the stages

To some extent, the long-term vision resembles the predictions of governments, technology developers and academics, whose impacts reflect in policy-making, mass technology shift, and renovation of service offering in the market.

The elements discoursed along this vision lead to a notion similar with BIM Level 3 or “iBIM” blended with a robust platform encompassing PLM (more diffused in manufacturing, so far). Just to cite an example, the “BIM Level 2” has been pursuit (formally since 2011) by the UK Government and construction companies by 2016. For years, large efforts have been made to support the industry in transitioning from traditional approach to collaborative BIM practices, through the provision of technical and managerial guidance, and policy-making. For the next stage, strategies aiming “BIM Level 3 and beyond” have been articulated to shape the BIM picture by 2019, expecting to “change the way global construction industry operates (Digital Built Britain, 2016)”. As can be noted, there is an alignment between the fast-evolving technology developments and the high-level industry policies, creating opportunities to companies in the forefront of innovation.

Concerning the five stages here presented, the empirical studies corresponded to partial implementations related to stages 1 and 2. Although BIM expansion to other business units and

lifecycle phases were deployed in empirical studies, the continuity of BIM implementation without the researcher is not guaranteed within the expected time targets. In relation to BIM capability maturity level, the company has achieved improvements in some of the assessment topics, but they need to be managed in such manner to maintain, and then increase the levels.

7.3 IMPACTS OF DIGITAL INTEGRATION STRATEGIES

Looking back to the outcomes of the empirical studies in relation to the steps above, it was possible to identify: (a) benefits resulting from BIM application in the intervened projects; (b) gaps requiring further adaptations in the workflow and development of skills to manage available technologies to achieve the expected benefits; and (c) situations requiring drastic changes in the business process. This section describes the effects of implementation at project-level, organizational-level and implications in the long-term vision.

7.3.1 Impacts at project level

Concerning the steps 1 and 2, it could be observed improvements related to an extension of the use of BIM across lifecycle phases. Prior to the research interventions, design data stored in the CAD system was used for shop drawing generation and CAD/CAM fabrication orders, but project information was not employed in other BIM applications.

Excepting the exploratory study, there were opportunities in all other projects to recover information from digital models (available from early design phases) to use in downstream activities such as design coordination, 3D visualization, and 4D simulations of the site installation. In the empirical studies 1, 2, 3 and 4, product information was recovered from digital models developed in the engineering department (in IFC format) to support scheduling and logistics planning in addition to pre-established design and manufacturing orders.

In the multi-storey unit (more advanced in the use of BIM for design and engineering compared with the industrial facilities unit), the interoperability between BIM applications allowed the production of visualization and coordination models for external users and fast design changes capabilities. Major enabling factors were: (a) the availability of BIM applications configured with the engineering standards of the company, increasing information management capability and integration with other IT platforms used within the company; and (b) prior experience with digital workflows to exchange project information (CAE to BIM, via CIS/2).

As previously explained in the literature review, there are tools used to measure BIM performance. One of the most diffused is the I-CMM (Interactive Capability Maturity Model), developed as part of the National BIM Standard (NBIMS) of the National Institute for Building Science (NBIMS, 2015). The NBIMS CMM Chart determine 11 areas of interest measured against 10 levels of maturity, applicable for an individual project. The I-CMM excel spreadsheet provides an interactive tool that weigh the value according to specific requirements. The scoring system can generate different results according to the subjective evaluation of individuals about the project. Useful as an internal tool, it is not recommended to benchmark it with externals, displaying only a big picture of the capability maturity level.

The first assessment was held in the early weeks of the investigation, based on analysing a sample models of reference projects and non-structured interviews with a designer, a BIM staff and the design coordinator. The interviewees did not fulfil the form themselves, but their answers and accounts were later synthesized by the researcher in the spreadsheet. The values obtained in this application are limited projects of the multi-storey unit.

The second assessment was held after the empirical study 4 (healthcare facility) only by the researcher. There was an expectation to see improvements in the areas tackled by the research interventions. Major improvements have been perceived in the fields of interoperability, lifecycle views, and roles and disciplines (Figure 51).

Área	Nível 1	Nível 2	Nível 3	Nível 4	Nível 5	Nível 6	Nível 7	Nível 8	Nível 9	Nível 10
1. Interoperability/IFC support										
2. Life-cycle views										
3. Roles or disciplines										
4. Change management										
5. Business process										
6. Timeliness/response										
7. Delivery method										
8. Graphical information										
9. Spatial capability										
10. Information accuracy										

AVERAGE LEVEL IN ORDINARY PROJECTS
 ACHIEVEMENTS IN THE EMPIRICAL STUDY

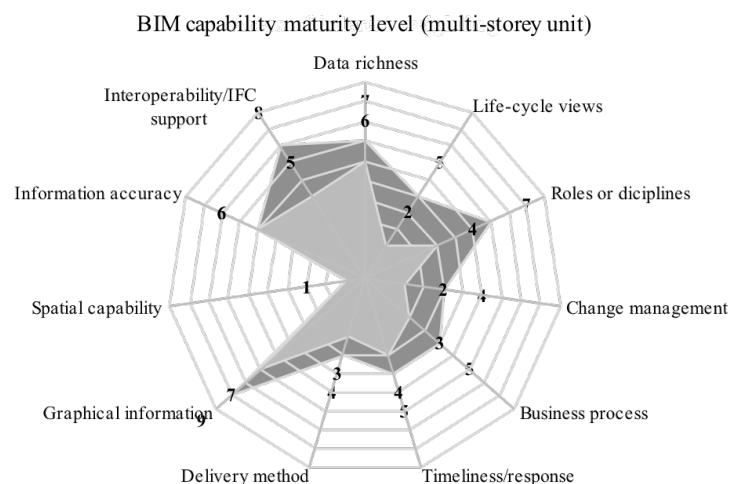


Figure 51: Perceived BIM capability maturity level after the research intervention

The drivers and barriers for such variations were discussed with design participants of the empirical study 4, attempting to highlight the achievements in the study and to guide a tactical preparation for next projects towards mature steps. A report to a company's director expressed the improvements and remaining opportunities perceived in BIM capability maturity levels after performing the empirical studies. The results may guide technology planning efforts regarding the identified barriers in the existing practice and availability of technological infrastructure and policies, and the priorities of improvement to consolidate improved practices in future projects.

7.3.2 Impacts at organizational level

In relation to step 3, the current system architecture does not provide interfaces between BIM and ERP. In meetings with a ERP key-user and the BIM officer, it was discussed alternatives to establish connections between BIM models and updated material status information retrieved from ERP. About that time, a software vendor made available a BIM add-in, in which smartphones could send status to the BIM modelling software in the office. However, there was not a scheme or process in which designers, manufacturers and assemblers could systematically update statuses to ERP modules and check them straight from BIM models.

An exchangeable platform of ERP and BIM would provide powerful connections not only to enhance the visualization of updated statuses, but to manage a range of project and routine operational issues related to the coordination of production batches supply due to improved capabilities in product configuration, change management and material resources management.

In this study, the researcher devised a scheme using web service to make information transactions between BIM and ERP. A new tool should be developed to link accurate BIM models (at fabrication level) and real-time updated ERP data sent from the manufacturing plant, material transportation hubs and the construction site.

Working in the cloud, a visual integration system display 3D or even 4D graphical interfaces to progress visualization of simultaneous projects (Figure 52). The shared understanding of project progress would support strategic decision-making to balance production capacity, procurement, and resource control of ETO operations.

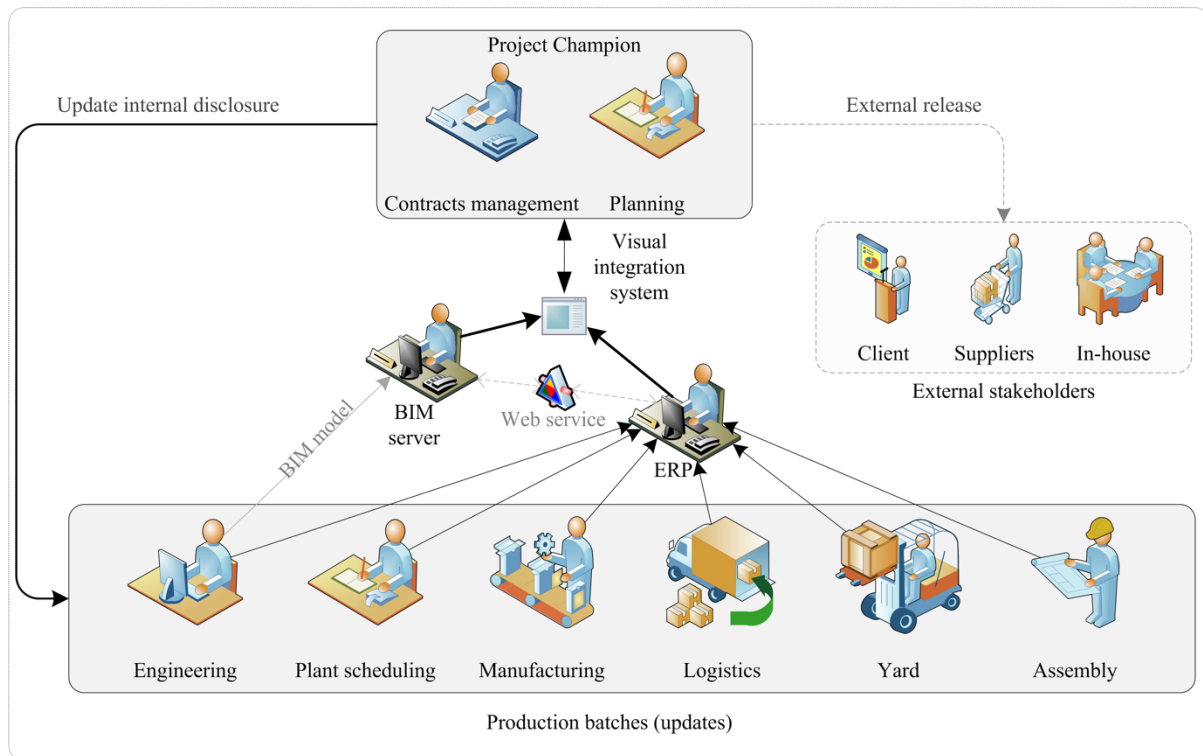


Figure 52: Scheme for BIM-ERP link through web service

The step 4 foresees BIM connections to the new CAD and PDM modules of PLM. Some of the PDM functions overlap with the scheme above. System-level integration enables different domains involved in the value chain to share and manage data created by several applications in a single source of product and process knowledge. Although PDM may boost internal operational control, construction suppliers and architecture firms are unlikely to access the company's systems. Thus, link to construction project partners require communication channels to out of the borders of the company, streamlined with the business process at organizational level. Since they use different databases and software platforms, BIM remains as a solution to exchange and collaborate in project level (Figure 53).

In a hypothetical scenario for step 5, the PLM platform interfaces with BIM, which is still an important exchange channel at project level. As technologies issues are being resolved, new procurement schemes and project delivery methods drive the major concerns of project teams. Collaboration and contractual issues for inter-organizational transactions needs to be agreed at each new engagement. Product and process information of internal operations, such as product and production models and simulations are managed from an integrated PLM platform.

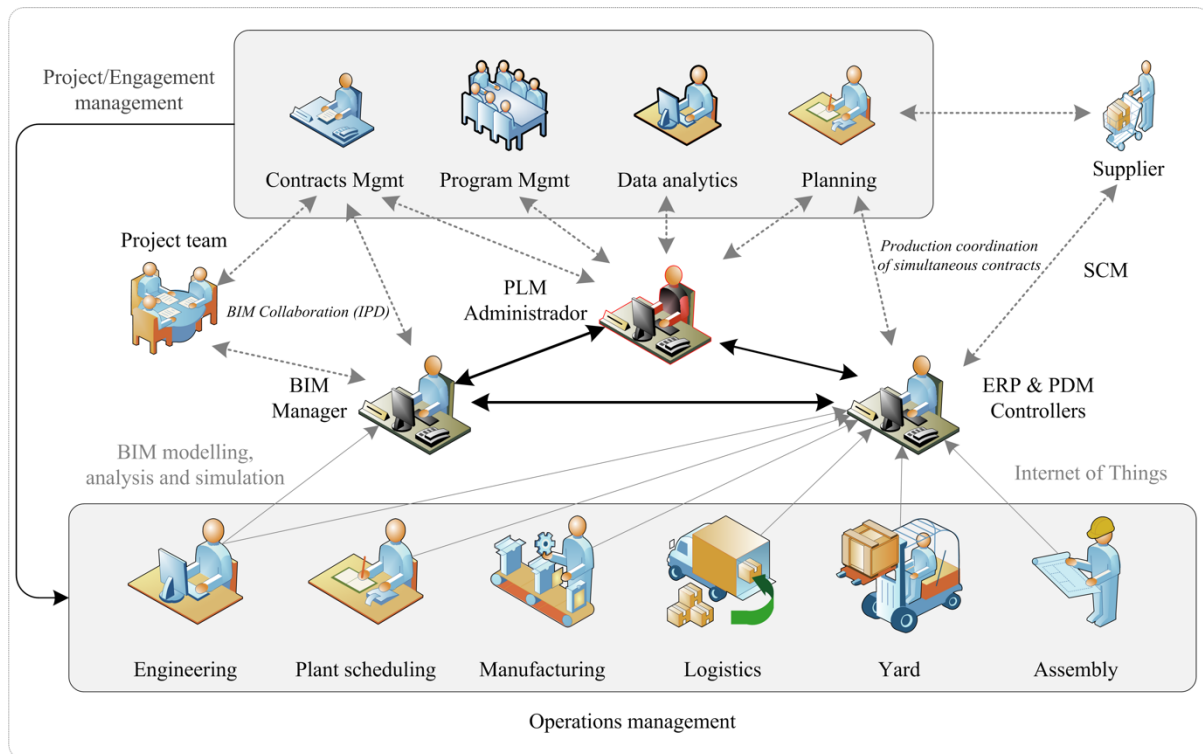


Figure 53: Scheme of a BIM-ERP-PLM integrated system

Automated commands for information flow between functional departments (in charge of a phase of project life) are set with an ever-increasing degree of artificial intelligence. Sophisticated engineering and simulation tools consider the variabilities in ETO production supply to optimize production design, and production and supply arrangements providing more flexible manufacturing lines and improved constructability on-site based on semi-automated product configuration functions in the engineering tools integrated with production simulation tools. These technologies will enable a more comprehensive program management by coordinating multiple contracts for internal operations improvements and increased transparency of project information with external suppliers and partners.

7.3.3 Impacts on the long-term vision

A central point of the conceptualization in step 5 is the rationale of a computer-integrated system supporting the management of sophisticated internal operations related to the development and delivery of ETO products and at the same time considering the complexity of construction project environment.

Striving for leaner operations, the interface between design and manufacturing processes of prefabricated systems remains a crucial gap for improvements. Major concerns relate to the

existence of a construction project flow simultaneous to an internal value flow of the fabricator's operations. The flows interact with each other along the project progress. Multiple information technologies giving support to the business process and operations need to be streamlined to orchestrate information across functional departments (Figure 54).

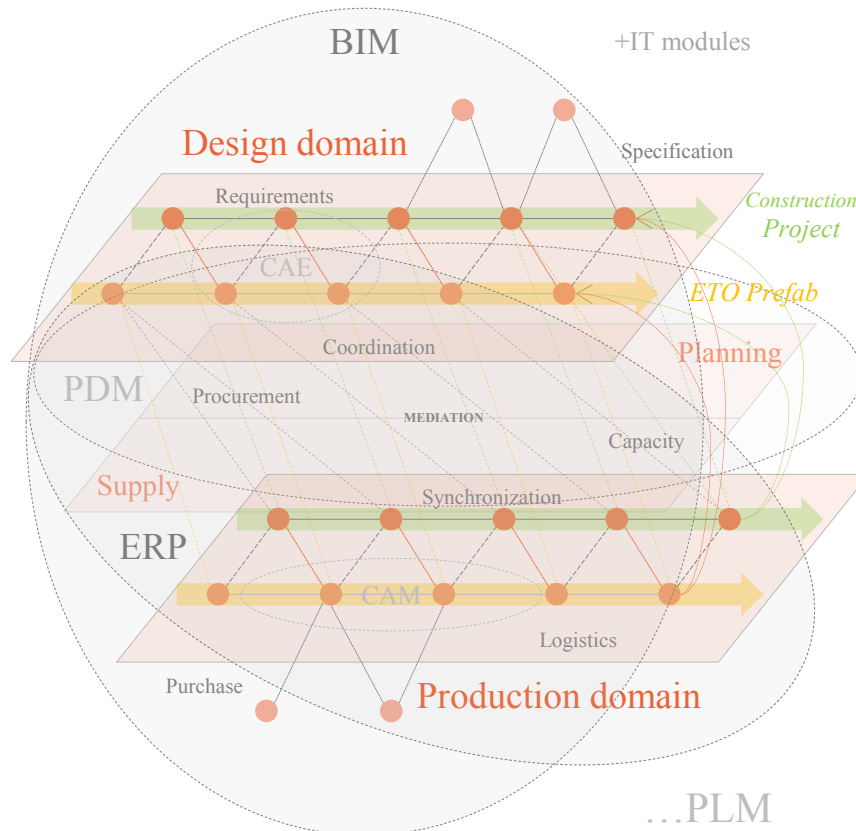


Figure 54: Conceptualization of a computer-integrated system for design and production

Although the concepts and toolkits of BIM and PLM aim to cover the whole project and product lifecycles, the domains of design and production require specific functions which are better addressed by one or another technological solution subject to the business and operational context of the company. According to the type of product and typology of production supply, complex product development demands advanced software (i.e. CAE and BIM) for sophisticated engineering of products such as steel structure components. The complexity of prefabrication manufacturing and logistics operations can be supported by MRP, SCM, ERP systems integrated with robots and control sensors. New trends towards integrated BIM in construction and PLM in manufacturing strive to reduce the gaps between information platforms and streamline digital assets from design and production.

Among the interventions foreseen for technology management, those understood as priorities for the company are to: (a) replace applications to newer and more complete software packages (e.g. discontinue some of the old CAD tools); (b) improve integration among systems in-use (e.g. as done with data exchange standards between CAE and BIM software); (c) introduce new modules to the computer-integrated system (e.g. sensors and tag systems, mobile device integration, cloud databases, etc.) before the full establishment of PLM.

The concurrent use of multiple technologies increases the role weight of interoperability. Besides, the propensity of releasing new system solutions demands flexible configurations of modular system architectures. New software add-ins, data analytics tools, cyber-physical interaction devices and new types of robots require friendly interfaces from the technology viewpoint, but also in terms of policies for working method implications.

Advancements in technology development may lead a shift from mere information recovery (achieved in early BIM stages) towards a scenario in which real knowledge can be shared among accredited stakeholders (BLM vision). In the empirical studies (step 1 and 2), efforts concerning information recovery to the co-creation of integrated solutions among design and production players, delivering solutions. In mature stages (from step 3 onwards), it is expected to foster effective and constructible designs and to improve the delivered performance aided by upcoming technologies and leaner working methods, with less change orders from the manufacturing plant and construction site, and thus, reduced time, cost and labour waste.

7.3.4 Discussion

As identified in the literature review, underperforming project resulting from lack of design and production integration has led organizations to pursue collaborative working practices and value chain integration with support of information technologies. Another issue was the need to approach the strategy and implementation of new technologies from a comprehensive socio-technical perspective, since technical viewpoint is insufficient to address all aspects of implementation. The potential of technology to improve business productivity and value creation can be expressed in future-oriented visions exposing the advantages to be achieved when fully implemented. Such visions have been called utopias or idealistic goals, because in some cases, the picture of future reality disregards many of the conditions and constrains which complicate and retard the realization of the vision (MIETTINEN; PAAVOLA, 2014).

Typical prefabricated building systems employ a mix of typologies of production situations to deliver a structural solution. Among these typologies, ETO operations is one to cope with complex processes from product development until site assembly and commissioning of construction projects. In this scene, BIM has been pointed as a potential supporter to an improved delivery of ETO products (EASTMAN *et al.*, 2011). Prefabrication firms have increasingly adopted BIM over the last years. Recent surveys indicate a trend of keep growing the adoption levels worldwide, as reported by NBS and McGraw Hill reports¹⁹. The expansion is not only in terms of number of companies, but also capabilities to manage asset information.

Despite of peculiarities in construction, other industries (e.g. aerospace, shipbuilding) have reached achievements to many common challenges through combined managerial and technological realizations. According to Ballard and Arbulu (2004), products manufactured by fabrication shops – including ETO prefabricated building products – are placed at the intersection of manufacturing and construction.

Technology developers and vendors have suggested the adaptation of information systems (e.g. ERP, PDM, etc.) employed in ETO manufacturing to be used by construction-related companies. As the prefabrication sector shares more characteristics in design and production with manufacturing (if compared to traditional construction), the adaptation of tools and its implementation process tends to demand less impactful changes in these firms.

The approach of looking at other industries meets the line of reasoning of Porter *et al.* (1999), who says that “a particular innovation might of course be a radically new idea or technological advancement, but in practice, innovation is usually the adaptation of a successful idea or technology from one manufacturing class that migrates or is transferred to another”. Thus, the adaptations of technologies must consider the peculiarities of construction context, as a separate type of industry with unique challenges to be addressed.

As in the move from CAD to BIM, there is recent discussion to amalgamate the well-diffused notion of BIM in construction with the infrastructure of the emergent PLM in manufacturing. The result is a visionary overlap between BIM and PLM to generate an elaborated Building Lifecycle [Information] Management (BLM) approach. This vision resembles to a yet unclear notion of iBIM assigned in the B/555 roadmap for BIM with front-line tool packages of PLM.

¹⁹McGraw Hill Construction. SmartMarket Report. Prefabrication and Modularization (2011)

Despite of the iBIM or BLM vision at industry level, when analysing it from an enterprise viewpoint, an understanding of the context of implementation of PLM or whichever new generation of technology is essential for any company setting the technology strategy. If outline visions are needed to guide implementations, these require a realistic understanding of the conditions for implementation (MIETTINEN; PAAVOLA, 2014). Further, the diffusion of BIM and other innovations have been influenced by the positive experiences of earlier adopters added to the ability of modifying them to suit individual organization requirements and goals (GU; LONDON, 2010).

Similarities found in key-objectives and core functions of BIM and PLM serve as strategic opportunities for the development of an integrated environment in ETO prefabrication firms, including data sharing mechanisms and coordination of teams around deliverables. However, their distinctions in data governance and portfolio management may require reforms in business process model and information management strategy, which are not necessarily straightforward.

In the context of construction firms, an implementation of PLM platform would be less traumatic, for instance, if BIM's ground concepts are well understood and sufficiently mature. Taking advantage of similar structures, the reforms sustained on expertise developed internally are tailored to meet the requirements of the company's operations and business problems, while concerned with the peculiarities of the construction projects and supply chain.

Concerning the raise of PLM in construction, Jupp and Singh (2014) notice that new processes, methods and ways of working have emerged together with new interfaces between design and production teams and PLM administrators. This is not dissonant of the impacts of BIM implementation in construction firms, but such scenario demands much higher degrees of implementation awareness and IT infrastructure.

However, there is still much to progress in terms of BIM from the earlier steps of the roadmap, before getting into the PLM preparation. Although BIM have been used to integrate information, unified solutions did not reach a stage in which real knowledge sharing give support to design and construction streams (OWEN, 2009). Moreover, the expected outcomes from synergic Lean and BIM are hardly obtained in totality because: (a) in many cases, the use of BIM is still limited to isolated activities; (b) lean management systems rely on manual information retrieval; (c) field BIM is now becoming accessible due to advanced hardware and

maturing software; and (d) current BIM coordination systems are not yet capable for detailed planning needed to support lean process (DAVE; BODDY; KOSKELA, 2011). Thus, a company must overcome remaining limitations still common to many enterprises.

The gradual introduction of IT modules shaping an advanced computer-integrated system is being driven by the realization of improvement opportunities relying on socio-technical competencies and business-oriented priorities in technology management strategies at organizational level, and not at project level. Oppositely to the experiences in BIM driven projects, the steps forward BLM vision imply in more radical changes in business process models and routine operations aligned with the company's ultimate goals, even with a gradual implementation approach in projects.

The difficulty to reach higher levels (of the technology viewpoint) of the strategic roadmap rely on excessive focus on project results disregarding the lasting effect of implementation at organizational level, as could be perceived in the empirical studies. The role weight of the awareness of human resource in implementation activities matters. The risk of discontinuity of the implemented improvements can be avoided if the interventions in project levels belonged to a wider and formal and enduring strategic implementation program with strong engagement of human resources of the company.

An integrated approach for BIM implementation with Program and Portfolio Management can possibly prevent misconnections of lessons learned in pilot projects interventions with the knowledge base for reforms of business process and workflow. A program management method instead of dealing with discrete projects (contracts or engagements) is key for aligning operations of the company with simultaneously projects by promoting learning cycles to cope with ETO variabilities and construction uncertainties.

Program management fits to mission-oriented enterprises dealing with multiple projects within programs. The operations of the value chain are coordinated in a way that outcomes of component projects constitute contributing parts towards a shared mission. The functions of PLM modules to coordinate design, production and supply of multiple projects combine vertical integration of the supply chain with program management advantages to tackle lifecycle operations of steel fabricators. It helps to organize the deliverables of each functional department corresponding to a section of the product value chain.

Once again, the increase of BIM capabilities in internal operations is the first step following the awareness of the implementation plan. In the case of the company of the empirical studies, these primary steps related to BIM should to be developed before the introduction of the new CAD and PDM modules foreseen in the PLM project. The achievement of BIM targets starts with the consolidation and refinement of the practices recommended in the empirical studies.

Apart from the vision creation process at strategic level, the deployment of the plan is usually tough. Structured implementation plans, as proposed in this investigation, can lead to smoother and more sustainable implementations. Implementation activities held in a balanced socio-technical system environment leads to faster, effective and more durable implementation outcomes. In order to generate lasting outcomes, implementation needs human resources development programs across many levels of the workplace. The intelligence and judgment capabilities required in human-machine interfaces – faced in socio-technical systems like these – to manage such complex information environment are foster with training and clear policies for the management of technology.

The complexity of ETO operations of simultaneous projects demand decision-making capabilities that challenge automation rulesets, especially in an environment plenty of uncertainties as construction projects. If PLM can enhance the operations of fabricators by optimizing engineering, production and supply solutions of ETO products, the enterprise needs first to setup an enabling environment to run such complex technology platform with improvements in project management, routine operations and people development, as experienced in early BIM implementation efforts.

8 CONCLUSIONS

Critical challenges in design and production activities caused by the lack of integration in the complex environment of ETO operations has led to an increased adoption of information technologies. Fabricators of building systems have strived to establish better connections between tools aiding the development of sophisticated engineered products together with planning strategies and methodologies to cope with the uncertainties in the production and supply of construction projects.

Since the operations of prefabricated building systems share characteristics of both manufacturing and construction, tools and management strategies adapted from different industries have been jointly thought in the development of innovations to improve construction productivity and delivery of value. If on the one hand, BIM has been established in construction industry for a while, not all firms had been able to fully implement and take advantages of BIM integrated workflow and project delivery methods. On the other hand, advanced technologies under development in the manufacturing sector, like PLM and other trends (e.g. IoT and AI), represent new opportunities to improve production operations and business strategies to the prefabrication sector.

Despite of fast release of new technologies, before introducing them in the company's operations, the first step was to understand the enterprise context. The socio-technical system approach discoursed along this study highlight that implementation process requires more than just making available powerful tools and technologies. The promotion of strategic shifts matters, and should be carried out together with organizational awareness, the development of human resources capabilities, and reviews in business process and working methods.

The roadmapping approach was used to capture ideas and organize the understanding about the enterprise context in order to steer BIM implementation. The structured steps towards the devised vision guided the gradual implementation considering not only the push of new technologies, but a comprehensive preparation of the ground for all changes required with the implementation activities from here on. The empirical studies showed that the use of product information contained in the BIM models could be reused downstream the value chain in analysis, simulations and co-development of integrated solutions involving team members of different functional departments.

The proposed starting point was the utilization of BIM functions for uses beyond engineering by taking advantage of the highly-detailed models delivered by the design team added to information from production and supply phases such as scheduling, manufacturing, expedition, inventory control and assembly on site. Despite of the vision predefined by the company to shortly utilize PLM tools, this research study made clear the need for preparatory steps to make the transition from current CAD, ERP and BIM systems to PLM modules less drastic. The development and discussion of the impacts of the roadmap contributed to understand the context of BIM implementation, from the current level of use passing through the introduction of BIM and PLM modules already in course to finally reach a future technology vision on behalf of the ultimate strategic goals of the company.

8.1 CRITICAL REFLECTION ABOUT THE RESEARCH OUTCOMES

This investigation provided a comprehensive understanding of the context of BIM implementation. The research outputs consisted of a conceptual framework for vision creation process following a roadmapping approach, an outline method for deploying of steps toward the envisioned scenario, and a discussion on the barriers and prospects based reflecting the effects of implementation.

From introducing BIM functions in pilot projects of the empirical studies to the conceptualization of schemes of system architectures integrating modules to expand the current uses BIM, the outcomes of this investigation had a practical impact in the intervened projects. However, this study essentially contributed to structure the understanding of the implementation environment, playing the role of as a first step for future systems design and implementation.

As a last reflection about the research outputs, the following aspects are examined: (a) utility, referring to the usefulness of the outputs in the context of technology management strategy and implementation within prefabrication firms; (b) applicability, from the perspectives of the staff operating the envisioned systems; and (c) generality or comprehensiveness, related to the applicability of the research outputs in similar companies or industrial sectors.

Utility

Dissemination of improvement opportunities

One prominent achievement of this research was the identification and dissemination of improvement opportunities in design and production process, as well as the proposition of mechanisms to achieve better integration between functional teams across the value chain. Although the main practical interventions have been limited to a narrow scope (predominantly related to the implementation of BIM functionalities in pilot projects) several applications which were unknown or unused by the staff of the company were instantiated in these projects.

Besides, mapping the company's product development process and the assessment of BIM capability maturity level provided an overview of their practices from a perspective of improvement opportunities concerning better integrated flows of work and information. The diagnosis of current practices at both project and organizational level followed by instantiations of BIM-related activities provided clearer notion of implementation impacts.

This study delivered a methodological approach to support firms in creating visions that meet their business objectives by designing a suitable environment to the implementation of managerial and technological innovations. The roadmap and implementation guidelines were designed to be adapted to the unique needs of companies. It intends to serve as a useful reference for organizations striving to improve design and production processes.

Support decision-making

In the empirical part of this research, the implementations and use of BIM applications allowed planners, designers, assemblers and managers to make more reliable decisions at different stages of projects (as well as in critical intersections between projects stages) based on intelligible information availability through from BIM.

Moreover, BIM functions tested in the empirical studies enabled better integrated decision-making by engaging people from different functional departments towards a shared implementation mission, which, in turn, would reward these teams with improvements in their routine operations. Besides, in order to make these functionalities actually work, the researcher endeavoured to put players together and facilitated a shared understanding of process issues before providing them digital visualisations or the construction simulations.

It was expected that roadmapping could be collectively designed and discussed in order to disseminate strategic improvement intentions within the organization. Increasing awareness across functional teams was a fundamental step to make key-stakeholders to contribute with their knowledge and experience aiming to set an adequate changing environment by understanding the context of implementation. As the research duration was shorter than the roadmap time length, the establishment of the approach proposed in this study might support lasting BIM implementation with more assertive decision-making from now on.

Applicability

Ease of use

The empirical studies attempted to implement and instruct first-time run applications of BIM functionalities in pilot projects. The demonstrations enhanced the level of confidence in performing such BIM uses in subsequent projects even though training have been offered only to a limited number of users. Some of the activities were easy-to-apply and could be quickly incorporated into operation routine with few training and effort. However, an impediment to proceed with these uses was the unavailability of all resources employed in this research (e.g. software and gadgets), as many were made available for testing by the University and the researcher only during the research study.

In view of disseminating BIM use across functional teams at further projects, structured implementation programs with a clear mission aligned with the roadmap and human resource development may embrace comprehensive training and resource acquisitions. Even if the vision creation is set with the engagement of multi-level hierarchy players, the actual deployment of the steps can be tough and slow, demanding structural changes in business process, capital investments in technology infrastructure and people education.

A sustainable implementation must not only settle achievements in empirical trials, but to establish lasting and ever-improving practices along future projects. A deficient program management for BIM implementation - unable to provide adequate conditions to run the implementation plan - may lead teams to waste lot of time and effort, discouraging people to advance in the roadmap steps.

Generality

Applicability in other contexts

Many of the concepts adopted along the research came from experiences reported with other typologies of building systems and even from other industries. The researcher believes that adaptations of the artefact can be applied in other similar contexts (beyond structural steel), such as the case of precast concrete and some types of facades and building envelopes. Moreover, the roadmapping approach and guidelines can be employed to comply with distinct group of products and building systems, such as joinery, HVAC ductworks or even piping works for infrastructure projects. Besides, this approach can also be replicated by firms adopting a mix of typologies of production situations like concept-to-order or configure-to-order (with strong design integration efforts) and fabricate-to-order or assembly-to-order (with strong supply chain coordination efforts) just as done at the company of this study.

8.2 CONTRIBUTIONS TO PRACTICE AND KNOWLEDGE

Implementation, in this context, is essentially a practical activity with strategic background. Despite of the need to promote changes regarding the introduction of new technologies and reforms in business process models, how to do it is tough and risky. The challenges to reach lasting implementation results start from understanding the company's needs and expectations, as well as the implementation context driving to a strategic goal.

This study does not detail technical procedures for BIM-based operations. According to the enterprise context, implementation may focus in some parts of the implementation plan (based on the roadmap) and select the most suitable recommendations in the guidelines. Finally, the company's activities become supported by BIM functionalities, but the most important point is how system architecture respond the needs of workflows of ETO operations, delivering building systems to complex construction projects.

The main contribution of this study is the elucidation of the contextual factors for BIM implementation for firms of the prefabrication sector running ETO operations. Although the company's main deliverables serve the construction market, internal operations share many challenges with other manufacturing industries using different planning methods and

supporting technologies. The adaptations of practices and tools from other contexts is enabled by understanding similarities to finally identify improvement opportunities.

This study revealed challenges faced by ETO fabricators to develop and implement computer-integration systems – by interfacing technologies in-place (i.e. CAD/CAM, CAE, ERP) with BIM (growing importance at industry level) and upcoming technologies (aiming to achieve higher performance by adapting them from manufacturing industries – capable to foster project and organizational performance in a smooth and sustainable way.

Outcomes of the empirical part are expected to be perceived with the realization of improvements related to the synchronization of the value chain. However, there is a need to go beyond the interventions of the study to achieve better benefits of program and portfolio management supported by an integrated system architecture comprised of BIM, PLM and other upcoming technologies.

Evidently, knowledge base from other sectors needs to consider the characteristics of the construction industry to incorporate those elements in designing a new framework. In this research, complex ETO operations run in a matrix-structure organization with a strong project orientation have to deal with variability and uncertainties related to the construction projects.

On this basis, the strategic shift could start from (1) improvements of flow interfaces between project phases orchestrated with the manufacturing and site requirements, evolving to (2) streamlined collaborative process along the business chain, to finally reach (3) semi-automated flows supported by easy configuration and change management functions integrated to the systems managing simultaneous projects and programs and the whole portfolio.

Concerning the challenges faced in the empirical studies, it was possible to perceive difficulties related to changes of working process and people awareness (dissemination across the whole organization) in addition to the mere pull of technology, corroborating the reports in the literature review for BIM. The need for a systemic view is about looking to the problem from a socio-technical system perspective. Innovation strategies aligned with the implementation of technologies can use the roadmapping approach to set future visions and implementation plans.

Emerging discussions from this research related with the following aspects:

- (a) The strategic roadmap definition is not static nor should be treated as a stand-alone approach. Here, roadmapping is about seeing the evolution of technologies and managerial trends towards the design of a vision which is strategically developed to meet long-term objectives through the gradual introduction of new or adapted solutions to meet new supply needs. As important as the vision (artefact), the vision creation process involving different parties is key in terms of building enterprise knowledge. In addition, it can set different criteria or maturity targets to balance the business intents within a time frame.
- (b) With due precautions, this research attempted to adapt features from other fields of application due to limited availability of ready-to-use tools and references in literature concerning the very specific scope. The results of the proposed interventions (inspired by other contexts and applied without proof of utility) have shown a mix of positive outcomes as well as inconvenient situations. Even though it has been argued that the prefabrication sector shares characteristics with traditional manufacturing (able to benefit from advancements reached in this field), when bringing ideas to the context of construction, principles of lean construction were fundamental to clarify the unique characteristics and implications of construction projects. Likewise, similarities and potential synergies were also explored in this investigation, looking at IT platforms already used in other industries to be adapted and incorporated by building system fabricators.
- (c) This research proposed a discussion for the management of mixed ETO/MTO/ATO components by a single fabricator, because this mix occurs in most building system. As most studies focus on a limited type of product, emphasis is usually given to one type of production situation, whereas a fabricator usually manages more than one simultaneously. The existence of more than one typology should not be ignored due to the impacts in portfolio management, and also in the coordination of manufacturing release and logistics. This study noticed that the mix of production situations also impact the way design and engineering software works, and considering the implementation of new tools and platforms, the peculiarities of each typology should be managed within new systems. More than this, IT should be used in a way to attenuate the impacts of the diversity of production situations with integrated systems

8.3 SUGGESTIONS FOR FURTHER RESEARCH

Despite of the trends towards a lifecycle management approach, a large share of fabricators and construction firms are not yet sufficiently mature in terms of IT integration to fully operate a PLM platform. By contrast, BIM has established an ever more consolidated stream, and has been adopted by both large companies and Small and Medium-Sized Enterprises. Besides, major owners are increasingly demanding the delivery of BIM assets, while governmental mandatories are contributing to the pull of BIM in capital projects, in some countries. Hence, BIM has gradually expanded the scope, range of functionalities and lifecycle span.

Although BIM efforts converge to similar objectives and characteristics with PLM, at least in short term, BIM seems to keep as a distinct paradigm, instead of being an enabling step towards the Building Lifecycle Management (BLM) concept. Current BIM initiatives seek to improve the integration of business process and stakeholders with the idea of establishing expanded enterprise and supply chain – covering different disciplines and lifecycle stages of the project, emphasizing the integration of design and production process. This brings attention to the impacts of early collaboration in downstream activities and the increased role weight of digital information flow.

A prominent effect of this changing environment undergoes social-technical issues – beyond technology. For instance, concerning critical issues such as procurement, project delivery methods and people education, they are still insufficiently resolved or are still immature in most organizations, especially when dealing with the interface between information systems which were not originally designed for construction enterprises.

If this study presented how to prepare the ground for change, further research should indicate how the company can manage themselves to become more resilient to the fast-changing environment and able to achieve implementations in a faster, responsive and sustainable way along with the deployment of steps here presented.

In examining the opportunities and remaining gaps, further research on the following topics are suggested:

- Instantiate and refine the roadmapping process and the implementation plan in similar companies interested to use TRM as part of the business innovation strategy.

- Evaluate the use of roadmaps and the implementation of guidelines in companies delivering other types of building systems, observing issues related to the management of operations of a different mix of production situations.
- Extend the investigation over companies that are less vertical integrated (with higher degrees of outsourcing), which are more influenced by the supply chain.
- Extend the scope of application beyond the integration of design and production to cover more lifecycle phases.
- Evaluate the use of roadmaps and the implementation of guidelines in companies using (and aiming to use) a different set of technologies, including BIM software from other vendors, gadgets and machineries not employed in the empirical studies.
- Consider the potential of PLM modules for an integrated management of multiple projects in a program management and portfolio management level.

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