Comparison of building information modeling and product lifecycle management approaches from the standpoint of engineering change management

by

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Comparaison des approches de modélisation des informations du bâtiment et de gestion du cycle de vie des produits du point de vue de la gestion des modifications d'ingénierie

Hamidreza POURZAREI

RÉSUMÉ

La modélisation des informations du bâtiment (*Building Information Modeling*, BIM) et la gestion du cycle de vie des produits (*Product Lifecycle Management*, PLM) sont deux approches holistiques basées sur les maquettes numériques qui visent à organiser et gérer les données relatives aux produits au cours de leur cycle de vie. Le BIM et le PLM sont assez similaires, malgré leurs différences, et sont mis en œuvre dans différentes industries, telles que l'industrie de la construction (soutenue par le BIM) et l'industrie aérospatiale (soutenue par le PLM). Selon la littérature, il semble que le niveau de maturité du PLM soit supérieur à celui du BIM.

Plusieurs études ont donc suggéré qu'une pollinisation croisée entre BIM et PLM serait bénéfique pour leur développement dans leurs industries respectives. Le PLM et le BIM doivent alors être comparés pour permettre une pollinisation croisée efficace. Cependant, mener une telle comparaison est difficile, en raison des différences importantes entre ces industries et les travaux de recherche sont souvent limités à une analyse comparative de très haut niveau. Selon la littérature, cette comparaison devrait être menée selon un point de vue spécifique. Les chercheurs ont proposé divers points de vue pour la comparaison, tels que *la structure du produit*, *l'ingénierie système* et *la vue de configuration*.

Ce projet de doctorat utilise les pratiques de gestion des modifications d'ingénierie (*Engineering Change Management*, ECM) comme perspective pour comparer le BIM et le PLM. En effet, les modifications d'ingénierie (*Engineering Change*, EC) sont inévitables pour les industries de la construction comme pour les autres industries. De plus, la gestion des modifications d'ingénierie est soutenue par l'utilisation de maquettes numériques dans le BIM et le PLM.

Il s'agit d'une recherche exploratoire ayant pour objectif principal de comparer le BIM et le PLM du point de vue ECM. L'objectif est d'identifier les caractéristiques et les fonctionnalités potentiellement candidates à une pollinisation croisée entre les deux. La recherche implique la description des pratiques de gestion des modifications de conception dans l'industrie soutenue par le BIM, ainsi que des pratiques de gestion des modifications d'ingénierie dans l'industrie soutenue par le PLM. De là, l'étude permet d'identifier et d'analyser les similitudes et les différences entre la gestion des modifications de conception (*Design Change Management*, DCM) dans l'industrie de la construction (soutenue par le BIM) et ECM dans l'industrie aérospatiale (soutenue par le PLM). En examinant ces variations, ce projet de doctorat cherche à identifier les caractéristiques et les fonctionnalités transférables qui peuvent permettre une pollinisation croisée entre le BIM et le PLM.

Le projet doctoral est basé sur une méthodologie en quatre phases : La Phase 1 impliquait une étude théorique de la DCM/ECM à travers une revue de littérature. La Phase 2 se concentrait sur des études de cas pratiques. La phase 3 consistait à réaliser la caractérisation des processus DCM/ECM. Enfin, la Phase 4 identifiait des candidats potentiels pour une pollinisation croisée entre le BIM et le PLM, en se basant sur les découvertes des phases précédentes. L'objectif du projet était de comprendre de manière systématique la DCM dans l'industrie soutenue par le BIM, ainsi que l'ECM dans l'industrie soutenue par le PLM, de répondre à des objectifs spécifiques et d'atteindre l'objectif global du projet.

Les contributions de la thèse peuvent être classées en trois catégories principales. Premièrement, elle améliore la description des pratiques de gestion des modifications de conception et des pratiques de gestion des modifications d'ingénierie dans les industries soutenues par le BIM et le PLM. Deuxièmement, elle caractérise les forces et les limites des pratiques actuelles de DCM/ECM dans les deux industries, dans le but de combiner les forces et de pallier les limites des deux approches. Troisièmement, elle ouvre de nouvelles perspectives pour identifier les candidats potentiels à la pollinisation croisée entre le BIM et le PLM afin d'améliorer la productivité des industries soutenues par le BIM et le PLM.

Mots-clés : Modélisation des informations du bâtiment, BIM, gestion du cycle de vie des produits, ECM, gestion des modifications d’ingénierie, gestion des modifications de conception, comparaison, pollinisation croisée

Comparison of building information modeling and product lifecycle management approaches from the standpoint of engineering change management

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ABSTRACT

Building information modeling (BIM) and product lifecycle management (PLM) are two holistic approaches that are based on digital models and aim to organize and manage product data over a product's lifecycle. BIM and PLM are quite similar despite their differences and are implemented in different industries, such as the construction industry (which is supported by BIM) and the aerospace industry (which is supported by PLM). According to the literature, it seems that PLM is more mature than BIM.

Several research studies have therefore suggested that cross-pollinating BIM and PLM would be beneficial for their respective development in their respective industries. PLM and BIM must therefore be compared to enable effective cross-pollination. However, they are difficult to compare due to the significant differences that exist between their industries and the fact that the studies presented in the literature are often limited to very high-level comparative analysis. According to the literature, these approaches should be compared from a specific point of view. Researchers have proposed a variety of different viewpoints for comparison, such as *product structure*, *system engineering*, and *configuration view*.

This doctoral project uses engineering change management (ECM) practices as the basis for comparing BIM and PLM. Engineering changes (ECs) are as inevitable for construction industries as they are for other industries. In addition, ECM is supported by the use of digital models in BIM and PLM.

This is an exploratory research endeavor whose primary objective is to compare BIM and PLM from the perspective of ECM in order to identify characteristics and functionalities that could potentially be used for cross-pollination between the two approaches. The research involves describing design change management (DCM) practices in BIM-supported industry and ECM practices in PLM-supported industry. Additionally, the study identifies and analyzes the similarities and differences between DCM in the construction industry (which is supported by BIM) and ECM in the aerospace industry (which is supported by PLM). By examining these variations, this doctoral project seeks to identify transferrable characteristics and functionalities that could enable cross-pollination between BIM and PLM.

The doctoral project's methodology consists of four phases. Phase 1 involved a theoretical study of DCM/ECM that took the form of a literature review. Phase 2 focused on practical case studies. Phase 3 involved conducting the characterization of DCM/ECM processes. And lastly, in Phase 4, potential candidate characteristics and functionalities for cross-pollination between BIM and PLM were identified based on the findings of the previous phases. The project aimed to systematically understand DCM in BIM-supported industry and ECM in PLM-supported industry, address specific objectives and achieve the project's overall goal.

This thesis offers a range of contributions that can be classified into three main categories. First, it improves the description of DCM and ECM practices in BIM- and PLM-supported industries. Second, it characterizes the strengths and limitations of current DCM/ECM practices in both industries in order to combine both approaches' strengths and mitigate their limitations. Third, it opens up new avenues for identifying characteristics and functionalities that could potentially be used to cross-pollinate BIM and PLM to enhance the productivity of BIM- and PLM-supported industries.

Keywords: Building Information Modeling, BIM, Product Lifecycle Management, PLM, Engineering Change Management, ECM, Design Change Management, Comparison, Cross-Pollination

TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

LIST OF ABBREVIATIONS

AEC	Architecture, Engineering and Construction
ATO	Assemble to Order
BIM	Building Information Modeling
BLM	Building Lifecycle Management
BOL	Beginning of Life
BOM	Bill of Materials
BPMN	Business Process Model and Notation
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CAM	Computer-Aided Manufacturing
CBR	Case Based Reasoning
CCD	Construction Change Directive
CCDC	Canadian Construction Documents Committee
CCS	Change Control System
CCT	Change Control Tool
CDCM	Construction Design Change Management
CDR	Critical Design Review
CECM	Collaborative Environment for Engineering Change Management

CI	Configuration Item
CII	Construction Industry Institute
CIS	Computer Information System
CM	Change Management
CM	Configuration Management
CMII	Configuration Management II
CO	Change Order
CPA	Change Propagation Analysis
CPLM	Construction Product Lifecycle Management
DAA	Designated Airworthiness Authority
DC	Design Change
DCM	Design Change Management
DCN	Design Change Notice
DCR	Design Change Request
DID	Design Intent Document
DMU	Digital Mock-Up
DSM	Design Structure Matrix
EC	Engineering Change
ECB	Engineering Change Board

ECM	Engineering Change Management
ECN	Engineering Change Notice
ECO	Engineering Change Order
ECP	Engineering Change Proposal
ECR	Engineering Change Request
EOL	End of Life
ERP	Enterprise Resource Planning
EV6	Enovia V6
FBS	Function Behavior Structure
FCM	Fuzzy Cognitive Map
FDR	Final Design Review
FM	Facility Management
FPA	Flower Pollination Algorithm
IAEA	International Atomic Energy Agency
IEC	International Electrotechnical Commission
INCOSE	International Council on Systems Engineering
IPT	Integrated Product Team
ISO	International Organization for Standardization
MBD	Model Based Definition

MBSE	Model-Based Systems Engineering
MCD	Managing Change Dependency
MCT	Maîtrise de la Configuration Technique
MEB	Model Element Breakdown
MET	Model Element Table
MOL	Middle of Life
NBIMS	National Building Information Modeling Standard
NFD	Nuclear Facility Decommissioning
NPP	Nuclear Power Plant
O&M	Operations and Maintenance
PBS	Product Breakdown Structure
PCO	Proposal Change Order
PDCA	Plan-Do-Check-Act
PDM	Product Data Management
PDR	Primarily Design Review
PIM	Product Information Modeling
PLM	Product Lifecycle Management
PMBOK	Project Management Body of Knowledge
PS	Product Structure

PSS	Product Service Systems
RFI	Request For Information
SDMP	Sequential Decision-Making Problem
SE	Systems Engineering
SEM	Systems Engineering Management
SLM	Service Lifecycle Management
TPD	Technical Product Documentation
V&V	Verification and Validation
WBS	Work Breakdown Structure

INTRODUCTION

Enabling collaboration and providing access to the right information, at the right time and in the right format, are crucial challenges in various industries, including the aerospace, automotive, construction and infrastructure industries. The product lifecycle management (PLM) approach has evolved to support manufacturing by providing a platform for product-related knowledge creation, organization and dissemination across different enterprises (Jupp and Singh, 2014). PLM is an engineering management principle that should tangibly improve production efficiency and quality when applied to any product from start to finish (Jupp, 2016).

Furthermore, being an innovative company in complex PLM-supported manufacturing industries, such as the aerospace and automotive industries, means not only designing innovative products, but also improving the processes used to design and produce products and making those processes better able to support the product lifecycle. PLM deployment has matured over the past decade from a set of engineering-oriented tools to enterprise-level integrated solutions. In other words, "PLM is serving as a central hub for product data so as to support collaborative design and production processes" (Jupp and Singh, 2016).

The construction industry, on the other hand, uses building information modeling (BIM) and has suffered from significant delays in increasing productivity compared to other industries, such as the aerospace and automotive industries (Boton et al., 2016). BIM appears to have the potential to solve some persistent construction difficulties (interoperability, information flow optimization, etc.) and improve productivity (Boton et al., 2018). Developing and operating buildings and infrastructure require that data and information about a facility's delivery and operational processes be accessible to stakeholders (including clients/developers, architects, engineers, contractors, suppliers, and facility/asset managers), and BIM often incorporates these levels of integration (Jupp and Singh, 2016). Interestingly, using BIM in design and construction has clear cost and time advantages (Chen and Jupp, 2019). In simple terms, BIM can be defined as "a 3D object-oriented approach to creating, managing and using the product and product-related knowledge" (Jupp, 2016; Jupp and Singh, 2016, 2014). It can therefore be said that BIM is an approach that promotes collaboration and information management among different project stakeholders (Jupp, 2013). It should be noted that BIM has only recently become the accepted term for the production and management of information about a built asset throughout the design, construction and operations phases, with recent expansion beyond design, engineering and construction activities to property valuation tasks (Jupp, 2016; Jupp and Singh, 2014).

BIM and PLM have recently begun to be compared in terms of their functionalities and capabilities, with most initial motivations for comparison being to transfer PLM functions and industry characteristics from PLM-supported industry to BIM-supported industry, specifically the construction industry (Jupp, 2016). Since the construction industry is comparable to some manufacturing industries despite some notable differences, BIM and PLM comparison seems to be an interesting option with good potential to enable BIM to develop into an information-centered management approach (Boton et al., 2018).

Hence, a deeper understanding of the similarities and differences that exist between PLM and BIM is required before the transfer of knowledge and lessons learned in their respective industries can lead to meaningful results (Jupp, 2016). Although the aim has traditionally been to transfer mature knowledge from PLM to BIM, several research studies (Boton et al., 2018; Chen and Jupp, 2019; Mangialardi et al., 2017) suggest that BIM and PLM cross-pollination would be more beneficial and provide an opportunity to improve efficiency and productivity in both BIM-[1] and PLM[2]-supported industries.

The first step to achieve effective cross-pollination between BIM and PLM is to compare them accurately and in-detail. Although the benefits of comparison are obvious (potential improvement on both sides), more information is needed about how to compare BIM and PLM from both a theoretical and a practical perspective. Comparison is challenging because BIM-

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[1] Using the term “BIM-supported industry” makes it possible to emphasize that our focus is on the support provided by BIM technologies and approaches when referring to industries that may not be dedicated to “buildings construction.”

[2] Similarly, using this term makes it possible to emphasize that our focus is on the support provided by PLM technologies and approaches when referring to industries that may not be dedicated to “manufacturing.”

and PLM-supported industries are dynamic by nature. The complexity of the objects that can be compared and the differences in culture and technology make comparison very difficult.

On the other hand, engineering change management (ECM) and its nearest equivalent in BIM—design change management (DCM)—are important practices in their respective BIM- or PLM-supported industries, ones that are highly reliant on digital models. Engineering change (EC) is inevitable and critical for all industrial sectors, and effectively managing EC is an important objective for both BIM- and PLM-supported industries. ECM is a management process that is used to ensure the effective execution and recording of engineering changes.

Furthermore, most of the works in the literature that address BIM and PLM comparison are limited to high-level comparative analysis. However, comparison needs to be from a more detailed, practical standpoint to take into account collaboration, IT tools and information within the processes/practices. This doctoral project therefore aims to compare BIM and PLM from the specific standpoint of ECM.

This thesis is divided into nine chapters. The first chapter introduces the research questions and objectives. The second chapter presents a review of relevant literature. The third chapter presents the research methodology. Chapters four to six present this research project’s journal articles. The seventh chapter proposes to use a PLM platform for DCM. The eighth chapter presents a discussion of the findings (candidate characteristics and functionalities for cross-pollination), research limitations, and contributions. Finally, the ninth chapter presents the conclusion.

Since this doctoral thesis is article-based, it contains journal articles that have been written as a result of the research conducted for it, which are as follows:

1. Comparing the descriptions of engineering vs. design change management in BIM- and PLM-supported industries from the literature—submitted to the Journal of Research to Engineering Design in July 2022 (Chapter 4).

2. Design change management in construction industry: Comparing theory and practice—submitted to the Journal of Information Technology in Construction (ITcon) in April 2023 (Chapter 5).

3. Engineering change management: Comparing theory to a case study from aerospace—submitted to the Journal of Product Lifecycle Management in June 2023 (Chapter 6).

In addition, the following conference articles have been written as a result of the research conducted for this thesis:

1. Cross-pollination as a comparative analysis approach to comparing BIM and PLM: A literature review (Pourzarei et al., 2020).

2. On Considering a PLM Platform for Design Change Management in Construction—submitted to the international conference on product lifecycle management in February 2023 (Chapter 7).

CHAPTER 1

RESEARCH QUESTIONS AND OBJECTIVES

1.1 Research Questions

This research project has the potential to have many different research questions. The following questions were chosen to guide the proposed research. The first one is:

- **RQ1:** *Is design/engineering change management (DCM/ECM) a suitable standpoint for comparing BIM and PLM?*

The first research question aims to determine whether DCM/ECM is an appropriate standpoint from which to compare BIM and PLM. Assuming the answer is yes, the second research question is:

- **RQ2:** *How can BIM and PLM be compared from a DCM/ECM standpoint?*

The second question aims to determine which approach to use to compare BIM and PLM from a DCM/ECM standpoint. This research question helped to identify which aspects of DCM/ECM (concepts, tools and processes) should be compared and how. Finally, to be more precise about the contributions of this research, the third research question is:

- **RQ3:** *How can the comparison of BIM and PLM from a DCM/ECM standpoint help cross-pollination between BIM and PLM in BIM- and PLM-supported industries?*

This question helped to narrow down and analyze the research project's contributions and determine how the results of this doctoral project would help cross-pollination by comparing BIM and PLM from a DCM/ECM standpoint.

These research questions guided the research by helping to establish appropriate research objectives, which are presented next.

1.2 Research Objectives

1.2.1 Overall Objective

With the research questions specified, now is the time to look at *what* we want to achieve. The overall objective of this doctoral project is to:

- *Compare building information modeling and product lifecycle management from the standpoint of engineering change management to identify potential characteristics and functionalities for cross-pollination between BIM and PLM.*

This overall objective is divided into four specific objectives.

1.2.2 Specific Objectives

The four specific objectives of this research are to:

i. *Describe design change management (concepts, IT tools, processes, methods, etc.) and relevant approaches in BIM-supported industry (the construction industry).*

ii. *Describe engineering change management (concepts, IT tools, processes, methods, etc.) and relevant approaches in PLM-supported industry (the aerospace industry).*

iii. *Identify and describe the similarities and differences between theory and practice when looking at the strengths and limitations of DCM in BIM-supported industry and ECM in PLM-supported industry.*

iv. *From the differences, identify the characteristics and functionalities that are transferrable between BIM and PLM from the standpoint of ECM.*

These specific objectives will enable us to achieve the overall objective of this doctoral project. This thesis continues with a literature review in the next chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter investigates the relevant scientific literature. It includes a review of the concepts of BIM and PLM, a comparison of BIM and PLM, and an overview of ECM in PLM-supported industry and DCM in BIM-supported industry.

2.2 Product Lifecycle Management (PLM)

Nowadays, complex product design and manufacturing call for large networks of specialists to work together. Product data must therefore be shared electronically between and within companies with a high level of information security (Saaksvuori and Immonen, 2008). On the other hand, companies always need to find novel solutions to their everyday problems. With market globalization, customers always expect products to have better and more advanced properties. These situations make products and their production processes more complex. Complex products have, in turn, forced companies to specialize and involve large groups of specialists in product design and planning. In addition, new technologies are needed to manage design networks of tens or hundreds of companies having facilities worldwide (Saaksvuori and Immonen, 2008; Stark, 2022).

Efficient network management requires advanced IT solutions because the network economy is massively increasing the need for data transfer and administration. One possible solution is to use a PLM system (Saaksvuori and Immonen, 2008; Stark, 2022). Companies that operate in a highly interconnected business environment must be able to change their products and find the information they need promptly. According to Immonen and Saaksvuori (Saaksvuori and Immonen, 2008), "PLM can be considered as a tool for collaboration in the supply network and for managing product creation and lifecycle processes in today's networked world, bringing new products to the market with less expenditure of time and effort" and "product lifecycle management (PLM) is a systematic, controlled concept for managing and developing products and product-related information.” In other words, PLM is the concept that has been defined to enable the integrated management of all product information and processes throughout the entire lifecycle (conception and design, production, distribution, maintenance, and retirement) (Liu et al., 2009).

In recent decades, increased focus has been put on PLM. The concept has been investigated by various authors from a variety of perspectives. It has been defined as a knowledge management solution for the product lifecycle as well as a strategic business approach that proposes a set of business solutions integrated with technologies that can interoperate with other solutions (Liu et al., 2009). A variety of definitions have been proposed for PLM by authors including Boton et al. (2018), Cheutet et al. (2018), Immonen and Saaksvuori (2008), Jupp and Singh (2016), Mangialardi et al. (2017), and Terzi et al. (2010). We provide Terzi et al.’s definition of PLM as an example (Terzi et al., 2010):

> [PLM is] “a business strategy for creating and sustaining such a product-centric knowledge environment. It is rooted not only in design tools and data warehouse systems, but also on product maintenance, repair and dismissal support systems. A PLM environment enables collaboration between – and informed decision making by – various stakeholders of a product over its lifecycle.”

PLM’s focus is to create, preserve and store information relating to a company’s products and activities to ensure that the data required for daily operations can be quickly, easily and painlessly refined, distributed and reused. PLM does not refer to any individual computer software program or method; it is an extensive functional totality, a concept and set of methods to control product information (Immonen and Saaksvuori, 2008).

Companies implement PLM for various reasons depending on the corporate branch in question, how products are produced and, in particular, what users want the systems to do (Immonen and Saaksvuori, 2008). PLM provides tools and methods that are extremely useful for solving day-to-day product information and product lifecycle management problems. In short, PLM can be considered a strategic approach that provides information throughout the lifecycle of a product. Modern PLM functions include workflows and program and project management features that standardize, automate and accelerate product management and make it possible for companies to more effectively control the product lifecycle so they can boost their income streams by speeding up the pace of commercialization of innovative products (Immonen and Saaksvuori, 2008).

2.3 Building Information Modeling (BIM)

Architects were the first to use electronic building models. Eventually, engineers, contractors and building owners began to dream of adding other useful information to the electronic building model, and the word “information” was inserted in the middle of “building model” to form the term “building information model” (Eastman et al., 2011; Sacks et al., 2018). Building information modeling changes the look and function of buildings and how they are constructed. The term “BIM” is used mostly to represent “building information modeling” rather than “building information model,” because, as Sacks et al. explain, “BIM is not a thing or a type of software but a socio-technical system that ultimately involves broad process changes in design, construction and facility management” (Sacks et al., 2018).

In recent decades, interest in focusing on and investigating BIM has grown. The BIM Handbook (Sacks et al., 2018) defines BIM as a modeling technology and associated set of processes for producing, communicating and analyzing building models. Although a number of researchers have investigated BIM and BIM-supported industry, including Azhar Salman (2011), Chen and Jupp (2019, 2018), Cheutet et al. (2018), Jupp and Singh (2016), Latiffi et al. (2016), and Sacks et al. (2018), one of the most widely accepted definitions of BIM is the one proposed by the National Building Information Modeling Standard (NBIMS) (Sacks et al., 2018):

> [BIM is] “an improved planning, design, construction, operation, and maintenance process using a standardized machine-readable information model for each facility, new or old, which contains all appropriate information created or gathered about that facility in a format useable by all throughout its lifecycle.”

According to Sacks et al. (Sacks et al., 2018), “BIM has become established as an invaluable process enabler for modern architecture, engineering, and construction (AEC).” With BIM technology, one or more precise virtual building models are digitally constructed so that they support all design phases to enable better analysis and control than with manual processes (Sacks et al., 2018). Once completed, these computer models contain accurate geometric information and the data needed to support the construction, fabrication and procurement activities through which a building is built, operated and maintained (Sacks et al., 2018). AEC as well as facility management (FM) use BIM in construction projects to implement collaborative construction project management among all stakeholders (Cheutet et al., 2018). BIM not only supports virtual design and construction but also provides a basis for deploying information and knowledge management systems in the operations and maintenance (O&M) phase (Jupp and Singh, 2016).

BIM is also considered a combination of processes and technologies that enhances the efficiency and effectiveness of project delivery from inception through operation and maintenance (Cheutet et al., 2018). Implementing BIM in the design and construction phases provides advantages in terms of carrying out performance-based simulation and analysis and having increased control over costs and schedules (Chen and Jupp, 2018). Interestingly, some authors thought that since construction can be viewed as a manufacturing process, then BIM could be widely considered as the basis of the fourth industrial revolution (Chen and Jupp, 2019; Whyte and Hartmann, 2017). Consequently, the implementation of BIM in construction projects is meant to simplify the flow of information throughout a building’s lifecycle by using highly reliable data from virtual construction components that represent their physical counterparts as faithfully as possible (Holzer, 2014). Therefore, BIM is an approach that facilitates multidisciplinary collaboration and information management among different project stakeholders (Jupp, 2013).

A building model, or building objective model, consists of a digital database that contains information about a building’s objects. Examples of building models include a Revit model and a Digital Project model (Sacks et al., 2018). “A building model can be considered the next-generation replacement for construction drawings or architectural drawings” according to

Sacks et al. (Sacks et al., 2018). The authors go on to explain building models are characterized by 1) “building components that are represented with digital representations (objects) that carry computable graphics and data attributes that identify them to software applications, as well as parametric rules that allow them to be manipulated in an intelligent fashion”; 2) “components that include data and describe how they behave, as needed for analyses and work processes, such as quantity takeoff, specification and energy analysis”; and 3) “consistent and nonredundant data such that changes to component data are represented in all views of the component and the assemblies of which it is a part” (Sacks et al., 2018).

2.4 Comparison of BIM and PLM

As previously mentioned, the construction industry has suffered great delays in increasing productivity compared to other industries like the aerospace and automotive industries (Boton et al., 2016). Comparing PLM and BIM seems to be an interesting avenue to address this issue and enhance collaboration, information exchange and traceability in the industries they support (Boton et al., 2018; Jupp, 2016). The terms BIM and PLM are cited contextually in many publications for different reasons, and sometimes assumed to be similar and have something in common and other times considered to be completely different concepts (Mangialardi et al., 2017).

Data governance and information management, storage and distribution are essential for both BIM- and PLM-supported industries, as are the new skills and digital expertise required throughout the building/product lifecycle (Mangialardi et al., 2017). Research by Mangialardi et al. (Mangialardi et al., 2017) indicates that the AEC industry could benefit from the manufacturing sector’s extensive use of PLM in sharing information at different phases of the lifecycle to compensate for its main missing features. In both industries, the strategic vision of information lifecycle management involves significant efficiency, time-saving and value-creation benefits (Di Biccari et al., 2018). The benefits of comparison, such as increasing productivity, making production more cost-effective and sustainable, optimizing design, minimizing production waste, managing the supply chain, standardizing product components, and managing product changes and adoptions, are generally similar (Mangialardi et al., 2017).

There has been increased focus in recent years on applying BIM to the entire building lifecycle (Jupp, 2013). The literature reviewed by Jupp (Jupp, 2013) revealed that an increasing number of studies consider a range of issues related to BIM.

It seems that BIM has the potential to solve several of the construction industry's persistent problems (interoperability, information flow optimization, etc.), which would lead to improved productivity (Boton et al., 2018). Although there have been many advancements in BIM application, there are still limitations in terms of management, technology and collaboration capabilities throughout a project and the operational phase of a facility's lifecycle. BIM's continued evolution therefore requires an integrated lifecycle approach to developing and adopting a new business model (Jupp and Singh, 2016). BIM is currently used at the project level and, as a result, the construction industry continues to lack a strategic business perspective for the whole building lifecycle. PLM, on the other hand, serves project, operational and business goals by consistently integrating a variety of information and communications technology systems (CAD, CAM, PDM [product data management], etc.) that contain data, information and product knowledge. PLM systems are therefore an enabling technology that serves as a central hub for product data to support collaborative design and production processes, whereas BIM applications are not viewed as a holistic business concept (Jupp and Singh, 2016). Hence, PLM and BIM both have the same objective, i.e., to increase collaboration, productivity and optimization, and deliver better value to the client. Moreover, Cheutet et al. (Cheutet et al., 2018) claim that "BIM is a subset of PLM, and a major part of any organization is based on the accurate management and the monitoring of assets."

The results of many research studies illustrate that BIM and PLM can be viewed as similar or different concepts. They are similar in that "to enable collaboration throughout the product lifecycle, they are approaches based on information tools and models" (Boton et al., 2018) and in terms of their "project information, integration and reuse; digital mock-up concept; and project management practices" (Cheutet et al., 2018). In addition, according to Cheutet et al. and Jupp and Singh (Cheutet et al., 2018; Jupp and Singh, 2016), they can be differentiated, as BIM is generally used in the design and construction of buildings, whereas PLM is typically used in the design and manufacturing of products. They differ also in relation to the tools, workflows and standards that are used to implement each approach (Boton et al., 2018). BIM has valuable features to manage the different building processes from design to construction but lacks monitoring and management mechanisms, and this is the main point that differentiates PLM and BIM (Cheutet et al., 2018). PLM provides strong management capabilities for any constructed project's lifecycle. Comparing BIM and PLM can help to improve the two worlds through cross-pollination (Boton et al., 2018).

Several researchers have investigated comparing BIM and PLM. Jupp and Nepal (Jupp and Nepal, 2014) explored how BIM and PLM have impacted professional practices in construction and manufacturing. They concluded that BIM is maturing in the construction industry and there is greater potential for it to achieve a common endpoint with manufacturing.

Jupp (Jupp, 2013) examined the implications of incomplete BIM implementation during design and construction. Their research detected three kinds of problems: process-based issues, technology-based issues and policy- or procedure-based issues. Their results indicate that PLM has the potential to efficiently expand existing applications of BIM. Additionally, Jupp and Singh (Jupp and Singh, 2016) provided a considerable research contribution to advancing BIM by mapping PLM capabilities. Their useful taxonomy is based on the fields in which BIM is being developed and encompasses managerial, technical and collaborative capabilities (Chen and Jupp, 2019).

The common idea for comparison is that the mature functionalities of PLM that are used in complex product manufacturing could be tailored to the specific context of the construction and infrastructure industry to effectively manipulate complex BIM models. However, as previously mentioned, many research studies suggest that the cross-pollination of BIM and PLM would be more beneficial (Boton et al., 2018; Chen and Jupp, 2019; Mangialardi et al., 2017) and that it is important to compare these approaches to achieve effective cross-pollination (Boton et al., 2018; Jupp, 2016). It is also important to note that this comparison is very challenging because the BIM-supported construction industry and PLM-supported industry are dynamic by nature. The complexity of the objects that can be compared and cultural and technological differences also complicate comparison. To summarize the importance of comparing BIM and PLM, comparison can benefit both industries, especially the construction industry (based on the incomplete implementation of BIM), but determining how to compare them should be further investigated and proven from both a theoretical and a practical perspective.

Several proposals and standpoints have been put forward to compare BIM and PLM. They are summarized below.

- *Combining PLM with BIM and ERP* – Holzer (Holzer, 2014) proposed to combine PLM with BIM and enterprise resource planning (ERP). In their research, they suggested that rather than using the construction-dedicated PLM approach, BIM should be developed in such a way as to make it possible to directly trace structured product data from the model to the existing information systems across the industry. Hence, Holzer (Holzer, 2014) shows that the bill of materials (BOM) is the missing link between BIM and existing feasibility, design, construction and operational processes.

- *Comparing BIM and PLM from a product structure standpoint* – A number of researchers have investigated comparing BIM and PLM from a *product structure* standpoint (Boton et al., 2018, 2016; Di Biccari et al., 2018). The idea of comparing BIM and PLM began with Boton et al. (Boton et al., 2016), who discussed why and how product structure (PS) is well known in manufacturing and less so in construction, and the potential of PS to be the missing link for comparison. The authors (Boton et al., 2016) explored how the BOM and PS are used in existing BIM practices and how they could be used as a standpoint for comparing BIM and PLM in discrete manufacturing industries. Later on, Boton et al. (Boton et al., 2018) indicated that the cross-pollination of BIM and PLM could benefit both the construction and shipbuilding industries in terms of knowledge transfer. They based this idea on Holzer's hypothesis that "BOM is the missing link between BIM and existing (and largely disconnected) feasibility, design, construction and operational processes" (Boton et al., 2018, 2016). The authors investigated further by conducting a practical study in the construction and shipbuilding industries to provide an in-depth understanding of this comparison. Interestingly, as they mention, the shipbuilding industry is pretty similar to the construction industry, among other discrete manufacturing industries, because of the unique requirements of the project, site conditions and final product (Boton et al., 2018).

Notwithstanding their differences, the study of the beginning-of-life (BOL) phase in shipbuilding and construction reveals that the two industries have quite similar and comparable project steps (Boton et al., 2018). Both products are first designed, based on the customer's specific requirements, before they are built (in construction) or manufactured (in shipbuilding). The product (building or ship) consists of various components, which justifies using a product breakdown structure (PBS) for different purposes in each industry. Although there are some concepts in the construction industry that are similar to BOM, such as the model element table (MET), the model element breakdown (MEB) and the PBS, they support different objectives (Boton et al., 2018). In other words, it is possible to generate a hierarchical list of model elements, and many concepts are used that could be similar to the PS, including the PBS and the MEB, but, unlike in PLM, they are all disconnected and aren't linked to associated product data or customized product families (Boton et al., 2016).

- *Mixing the functionalities of BIM and PLM* – In Cheutet et al. (Cheutet et al., 2018), PLM and BIM seem to be interesting options to support collaboration, information exchange and traceability throughout the nuclear facility decommissioning (NFD) process. The intrinsic characteristics of the NFD process make information management very complex and new approaches necessary (Cheutet et al., 2018). The authors (Cheutet et al., 2018) aimed to characterize the NFD process specifically to determine the key characteristics that should be gathered by a dedicated information system to successfully support NFD. Based on this analysis, their research proposed a digital roadmap for NFD information management that compares some promising approaches to information management and information systems. However, there are many works in the literature that investigate using PLM and/or BIM for the BOL or MOL phases of nuclear power plants (NPPs), all of which argue that PLM and BIM play an important role in the manufacturing and construction of innovative NPPs and industries (Cheutet et al., 2018).

The authors therefore propose to blend the functionalities of BIM and PLM for NFD (Cheutet et al., 2018). Their proposal contains a list indicating the functionalities that are required for NFD (Figure 2.1) and which are specific to PLM, specific to BIM, common to BIM and PLM, and specific to NFD and currently non-existent in either BIM or PLM (Cheutet et al., 2018). Interestingly, there are fewer BIM-related functionalities (five in total—one specific and four common) than PLM-related ones (nine in total—five specific and four common).

Legend for Figure 2.1:

- Green = PLM-specific functionalities
- Orange = BIM-specific functionalities
- Blue = Functionalities common to BIM and PLM
- White = NFD-specific functionality

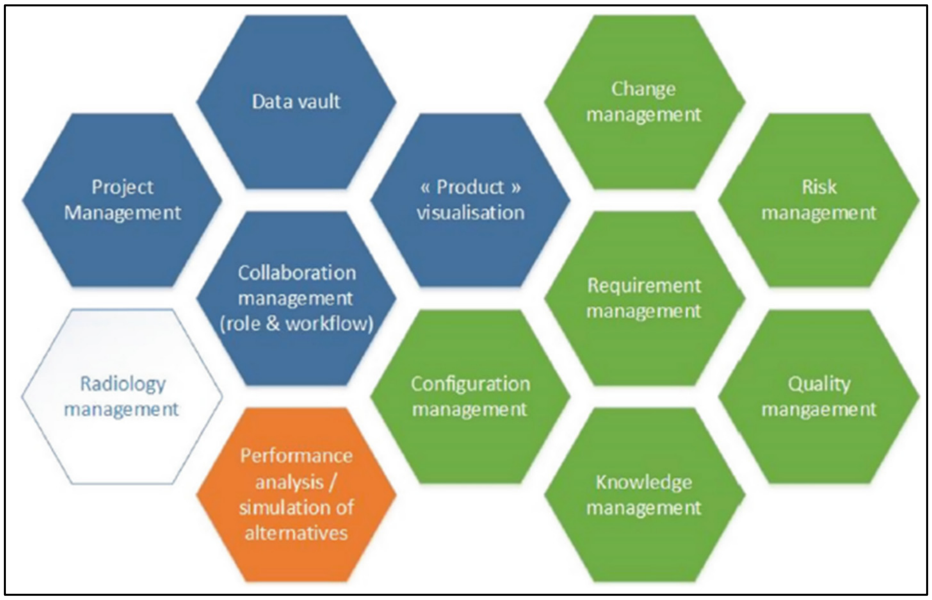

Figure 2.1 Functionalities required for nuclear facility decommissioning
Developed from Cheutet et al. (2018)

❖ *Incorporating the configuration view from PLM in BIM* – Di Biccari et al. (Di Biccari et al., 2018) assessed the “configuration” view concept, more specifically the “product structure configuration," from complex manufacturing and whether it had previously been applied to process or information management for different lifecycle phases in the AEC industry. Their purpose for presenting the configuration view concept was to identify gaps in BIM's existing technological process and recommend a customized product structure that is based on personalized configuration views in the construction world to implement building lifecycle management (BLM) (Di Biccari et al., 2018). The authors began their research by assuming that the PS is one of the most important features of BIM. They thought that BIM could be to BLM what product information modeling (PIM) is to PLM and that the PS is the link that is missing in the BIM approach to be able to cover the entire lifecycle, and called BLM the solution that the construction industry needs to manage the whole lifecycle (Di Biccari et al., 2018). Hence, in the AEC industry, configuration management provides a means of tracking how the customer's expectations generated at the beginning of a project are made a reality by the end of the project (Di Biccari et al., 2018). The PS supports a dynamic product information model that enriches the product model throughout its lifecycle. According to Di Biccari et al. (Di Biccari et al., 2018), "the configuration views of the PS can manage building/infrastructure data, updating and archiving information over time, in a suitable manner for each specific lifecycle phase."

- *Using a systems engineering approach* – The idea of using systems engineering (SE) to compare BIM and PLM has been investigated by Chen and Jupp (Chen and Jupp, 2019, 2018) in two steps. First, Chen and Jupp (Chen and Jupp, 2018) worked on the concept of model-based SE and through-life information management in complex construction to digitize complex construction delivery and the reuse of model-based information for operations and maintenance (O&M). They specifically reviewed related research and explored the V-model's role in the development process, discussing its importance in structuring a through-life information management approach (Chen and Jupp, 2018). In other words, they indicated how the application of SE activities in construction could inform the development of new methods and processes to improve a facility's lifecycle (Chen and Jupp, 2018). Nevertheless, there are still gaps in the holistic systems approaches when it comes to how data is structured, reused and managed throughout the lifecycle (Chen and Jupp, 2019). The core of Chen and Jupp's research involved examining the importance of SE activities in the construction industry, identifying the gaps in model progression methodologies and revealing where challenges lie for the construction industry in developing a system mindset to implement BIM in complex projects (Chen and Jupp, 2019). The results of their work (Chen and Jupp, 2019) compared SE and BIM in terms of their methods, tools and initiatives. The authors aimed to highlight a number of gaps and opportunities pertaining to implementing the SE approach and systems engineering management (SEM) activities in order to better integrate project design, project delivery and structured information management over the life of the project or facility (Chen and Jupp, 2019). Chen and Jupp (Chen and Jupp, 2019) mentioned that understanding the role of SE and SEM is the first step to supporting BIM over the entire lifecycle, whereas until now, the focus has been on explaining and comparing SE, SEM and BIM methods.

Hence, BIM and PLM are two approaches that are utilized in different industries. BIM is used extensively in the construction, architecture, engineering, and facilities management industries, which are localized and highly fragmented. In contrast, PLM is widely employed across a variety of industries (e.g., manufacturing and emerging sectors) that are more globalized and consolidated (Cheutet et al., 2018; Di Biccari et al., 2018; Holzer, 2014; Jupp, 2016).

While BIM emphasizes collaboration, productivity, optimization, and value delivery throughout the construction process, PLM focuses on delivering potential value based on through-life performance and managing the entire product lifecycle from ideation to disposal (Di Biccari et al., 2018; Jupp, 2016).

BIM relies on a 3D digital model as its central framework for integrating and managing project information, whereas PLM adopts an information-centric approach to lifecycle management. BIM captures and manages building-related data, including geometric data, material specifications, performance data, and project documentation, while PLM handles a broader range of product-related data, such as design data, bills of materials, manufacturing processes, quality data, and maintenance records (Boton et al., 2018; Cheutet et al., 2018; Di Biccari et al., 2018; Jupp, 2016; Mangialardi et al., 2017).

Both approaches require expertise in the relevant technologies, but BIM specifically relies on advanced information and communication technologies that are specific to the AEC industry. By leveraging their respective tools and frameworks, BIM and PLM make it possible for organizations to enhance their collaboration, decision-making, and project outcomes while optimizing their processes and delivering value to clients in their respective domains (Di Biccari et al., 2018; Jupp, 2016).

2.5 Design/Engineering Change Management

First and foremost, it should be mentioned that change is inevitable. As W.E. Deming, one of the initial researchers of quality management, said, “It is not necessary to change. Survival is not mandatory” (Armenakis and Harris, 2009). This quote implies the importance of change. Therefore, the best way to address changes is to manage them and have a plan for them. In complex industries like manufacturing and construction, change is an important issue that needs to be managed, especially throughout the engineering design and construction/manufacturing processes. It should be noted that since this doctoral project compares BIM and PLM from an ECM standpoint, it needs to understand engineering change (EC) and the engineering change management (ECM) process in the industries in question to be able to perform the comparison. Therefore, this section provides a concise overview of EC, and ECM in PLM-supported industries and explores design change (DC) and design change management (DCM) in BIM-supported industries. A more comprehensive comparative analysis of DCM and ECM in BIM- and PLM-supported industries is presented in Chapter 4.

2.5.1 ECM in PLM-supported industry

Jarratt et al. (Jarratt et al., 2011) have proposed one of the most fitting definitions of EC:

> “An engineering change is an alteration made to parts, drawings or software that have already been released during the product design process. The change

> can be of any size or type, involve any number of people and take any length of time."

Additionally, ECs can occur at any time in the product lifecycle, from the moment the concept is selected to when the product finally goes out of service (Jarratt et al., 2011). Jarratt et al. (Jarratt et al., 2011) identified two difference types of changes in PLM-supported industry: 1) emergent changes, which address errors, safety concerns, functional changes and product quality problems, and 2) initiated changes, which are requested by a customer, a supplier, sales and marketing, product support, production, product engineering or company management.

Engineering change management (ECM) is a management process that is used to ensure the effective execution and recording of a change, regardless of size, taking into account its technical, engineering and safety aspects. In other words, it can be said that "all change management procedures have a common purpose, which is to record, control and manage changes (including from the initial baseline) while taking into account the risks associated with the change" (Du Toit, 2014).

A number of authors, including Quintana et al. (Quintana et al., 2012), Jarratt et al. (Jarratt et al., 2011) and Maurino (Maurino, 1993), have proposed descriptions of ECM processes, all of which have followed the same basic structure despite including different steps. For instance, they all the processes described in the literature start with an engineering change request (ECR), which is followed by an engineering change proposal (ECP), an engineering change order (ECO) and an engineering change notice (ECN). Maurino (Maurino, 1993) proposed the following steps in particular:

i. *Request* – In this step, the change is requested (ECR).

ii. *Instruction* – The change request is analyzed to determine whether it is worthwhile to make the change (value engineering), and then the change management team (a team of professionals (e.g., engineers)) analyzes and proposes solutions for the requested change. Once the change is approved and solutions have been proposed, one solution is chosen for the change (ECP).

iii. *Execution* – The change management team works on the chosen solution and prepares the drawings, specifications, reports, standards, etc. documenting the chosen solution (ECO).

iv. *Application* – The chosen solution is carried out at the company level over the specified time frame (ECN). The ECN could be also considered as the formal release of the engineering change (AACEI, 2023).

The fundamental motivations for triggering an EC are to correct mistakes, make the product work properly or make improvements (Jarratt et al., 2011).

2.5.2 DCM in BIM-supported industry

Changes are very prevalent in construction projects and can be requested at any stage of a project by different sources for various reasons. A critical change can result in subsequent delays in the project schedule, a re-estimation-of-work statement, increased demand for equipment, and the need for additional materials and labor as well as overtime (Hao et al., 2008). While some changes may yield "benefits" for stakeholders, most changes, if not properly managed, will have "negative" impacts, most often in terms of time and cost overruns (Hao et al., 2008; Hwang and Low, 2012). It is important to note that the terms engineering change (EC) and engineering change management (ECM) are not commonly used in the construction industry; the similar terms that are commonly used instead are design change (DC) and design change management (DCM), which are briefly presented in Chapter 4 (Article 1). This section therefore aims to describe the concepts used in the construction industry—DC and DCM.

Hao et al. (Hao et al., 2008) thought that the "most frequent and costly changes are often related to design, such as design changes and design errors." A few research studies have been conducted on the concept of DC. For instance, Abdul-Rahman et al. (Abdul-Rahman et al., 2015) define design changes as:

> "Regular additions, omissions and adjustments to both the design and construction of work in a project that occur after the awarding of the contract

> and affect the contract provisions and work conditions that make construction dynamic and unstable" (Abdul-Rahman et al., 2015),

> and according to Alwi et al. and Suleiman and Valentine (Alwi et al., 2002; Suleiman and Valentine, 2016),

> "Design change is defined as any change to the scope of the work as defined by the contract documents following the creation of legal relations between the principal and the contractor. Design change may occur in architectural, structural, plumbing and drainage, site works or other aspects of construction" (Alwi et al., 2002; Suleiman and Valentine, 2016).

The interesting point in the above definitions of DC is that "change" refers to alterations that occur *after* the awarding of the contract. This is reminiscent of a similar aspect of EC in PLM-supported industry. Furthermore, most researchers recognize three kinds of changes in construction:

i. *Change orders,* which refer "to changes that are generated by unanticipated causes, for example, scope changes from the owner, design/technological changes from the architect, and cost/time changes arising from supplier problems or unsatisfactory site conditions" (Hao et al., 2008). This type of change needs to be negotiated on a case-by-case basis and requires common (documented) agreement among all parties involved. Furthermore, in construction projects, change orders can be from two sources (Riley David R. et al., 2005):

    - ➢ *Owner-generated change orders,* which are issued when an adjustment to the project scope, design or detailing is requested by the owner and a change to the original contract agreement is required.

    - ➢ *Field-generated change orders,* which arise when problems and conflicts detected in the field require a re-design or reconfiguration of the design.

ii. *Rework,* which refers to re-doing a process or activity that was incorrectly implemented in the first place and is generally caused by quality defects, variance, negligence, and poor design and on-site management (Motawa et al., 2007). Rework is usually pure waste and should be avoided in most cases.

iii. *Construction change directives (CCDs),* which are issued by an owner or its designate requesting a change in the contract scope when there has been no agreement on cost. CCDs originate from disputed change orders and can become change orders again once the dispute is settled (Hao et al., 2008).

On the other hand, one of the most important change-related issues in the construction industry is that changes can be either reactive or proactive (Motawa et al., 2007).

- ❖ *Reactive changes* represent the events when a change occurs and the project team starts to take actions to remedy the consequences of the change. In other words, reactive changes can be defined as actual changes that have already happened and must be controlled.

- ❖ *Proactive changes* represent the events when a change is likely to occur in a later stage and the project team plans to minimize its disruptive effect. In other words, proactive changes may be defined as potential changes that may occur later and must be preventively planned for.

Depending on whether changes are proactive or reactive, it is necessary to identify and predict them. Change prediction systems investigate the information available at the early stages of projects and use said information to predict change events (Motawa et al., 2007).

Prediction also helps to take appropriate action to minimize the disruptive effects of changes, which is why change management processes usually include prediction systems. Various authors have proposed different types of change management processes (CII, 1994; Hao et al., 2008; Hwang and Low, 2012; Ibbs et al., 2001; Motawa et al., 2007; Sun et al., 2006; Voropajev, 1998). As an example, Hao et al. (Hao et al., 2008) developed a generic change process model consisting of five sequential stages:

1. *Identify changes* – There are proactive rules defined to identify changes (including sources, causes, types and possible actions of changes) over the duration of a construction project.

2. *Evaluate and propose changes* – Based on criteria and options, determine all possible impacts that an identified change can have on other processes and team members in terms of time and cost. The outcome of evaluation is a proposal change order (PCO) that summarizes the change itself and its impacts—an updated action plan, the costs, the schedule, etc.

3. *Approve changes* – Each identified change needs to undergo a formal approval process. There are predefined approval processes for different types of changes and construction contracts. Furthermore, the change approval process must be approved by not only the professionals through the change process but also the client.

4. *Implement changes* – Change implementation mainly refers to the managing and coordinating the information, documents, designs/drawings and records containing the changes and their impacts. Unlike in previous stages, no major decision is expected during the change implementation phase.

5. *Analyze changes* – The change is analyzed and system performance is reviewed based on the data collected during the change implementation phase.

Interestingly, Hao et al. (Hao et al., 2008) thought that the ECM process in manufacturing was very similar to the general construction change model.

2.6 Literature Review Synthesis

This literature review took into consideration BIM, PLM, previous comparisons of BIM and PLM, as well as DCM and ECM in BIM- and PLM-supported industries, respectively. More specifically, it guided us to further investigate the current literature on BIM-PLM comparison when building our research proposal.

The literature review helped to identify the importance of comparatively analyzing BIM and PLM. Comparative analysis has the potential to benefit multiple industries, particularly the construction industry, which has encountered difficulty fully implementing BIM practices. However, while existing works in the scientific literature offer a valuable comparative analysis of BIM and PLM, they primarily stay at a high level without delving into the subject matter extensively. Consequently, there is a compelling need for additional investigation to thoroughly examine the topic from a theoretical and a practical perspective. Hence, the focus of this doctoral project is to address this need and comprehensively explore the topic in detail.

Furthermore, it could be seen that ECM is an important practice in both BIM- and PLM-supported industries and is increasingly supported digital models. We consider ECM to be an adequate standpoint from which to compare BIM and PLM because it is a compact version of the design process (evaluate change, document, approve, etc.) (Quintana, 2011). It is therefore more feasible and easier to replicate and document ECM in the lab than to document the design process of an entire project. Furthermore, engineering changes are omnipresent in the design process and involve concepts and collaborations of process tools and practices. This attests to the importance of ECM in both BIM- and PLM-supported industries and points to how its application can be extended to the lifecycle of a product. We now move on to design a research methodology for BIM and PLM comparison.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Introduction

As scholars such as Blessing and Chakrabarti (Blessing and Chakrabarti, 2009) and Hamraz (Hamraz, 2013) have highlighted, a research methodology serves as a guide for conducting research and gives a clear understanding of the approach, methods and tools that will be used throughout the project. The methodology explains how the objectives will be achieved by outlining the specific steps that will be taken, including theoretical and practical studies, case studies, data analysis and cross-pollination (Blessing and Chakrabarti, 2009). It ensures that research is conducted in a systematic and thorough manner and provides a clear path to achieving the project's objectives (Hamraz, 2013). Without a proper methodology, it is difficult to ensure that the research is conducted in an unbiased and systematic manner, which makes it challenging to draw meaningful conclusions from the data (Daragmeh et al., 2021; Heale and Twycross, 2015). Therefore, the research methodology building process is essential to ensure that the research is conducted in an effective and efficient way.

3.2 Research Methodology

The methodology for this doctoral project is divided into four distinct phases, which are:

Phase 1. Theoretical study of design/engineering change management.

Phase 2. Practical study of design/engineering change management.

Phase 3. Characterization of the design/engineering change management.

Phase 4. Cross-pollination candidate identification.

These phases are designed to ensure a systematic and thorough approach is taken to the research. The following sections explain each phase of this research methodology in detail.

3.2.1 Theoretical Study of DCM/ECM

The aim of this phase of the methodology was to thoroughly examine how ECM intersects with BIM and PLM through a comprehensive literature review. A variety of sources such as books, articles, standards, and reports were reviewed to gain a thorough understanding of the current state of ECM in the context of BIM and PLM.

A variety of scientific data collection tools such as Google Scholar and Scopus were utilized to find relevant reading material. To ensure accuracy and prevent duplicates, all resources were exported to Zotero. The data and information collected were then organized into two main categories: engineering change management within PLM-supported industry, and design change management within BIM-supported industry. Each category was further divided into subcategories such as glossaries and processes, which are discussed in detail in Chapter 4.

The data and information collected were analyzed to identify the similarities and differences between DCM and ECM in BIM- and PLM-supported industries, respectively. This comparison made it possible to identify unique characteristics, best practices, and challenges associated with implementing DCM/ECM in their respective industries. The theoretical study of ECM conducted in this phase of the methodology yielded three notable outcomes:

a. A description of DCM in BIM-supported industry from the literature.
b. A description of ECM in PLM-supported industry from the literature.
c. A comparison of the descriptions of DCM/ECM in BIM- and PLM-supported industries, respectively, that are provided in the literature.

These outcomes offer a comprehensive understanding of DCM's/ECM's function and significance in BIM- and PLM-supported industries, respectively, and reveal their similarities and differences.

3.2.2 Practical Study of DCM/ECM

The main goal of this phase of the methodology was to gather real-world data and information from actual industry scenarios. To achieve this, four case studies were conducted with a focus on collecting data and information.

It is worth mentioning that the three outcomes of Phase 1 of the methodology were used as inputs for the case studies conducted in this phase. More specifically, the results of the literature review, the similarities and differences between DCM/ECM in BIM- and PLM-supported industries, respectively, and the best practices and challenges associated with implementing DCM/ECM in these industries provided a foundation for data collection and case study analysis and interpretation. This ensured that the case studies conducted provided insights that were grounded in the existing literature and research.

We use *pure observation* (Blessing and Chakrabarti, 2009) for the case studies, which is defined as follows:

- "Pure observation means that the researcher is not involved in the process and does not interfere with the process while it is ongoing. The method used to gather data for this observation is '*retrospective data collection,*' such as studying the documents, analyzing the processes and interviewing experts without interrupting the process" (Blessing and Chakrabarti, 2009).

This phase of the methodology is divided into three distinct steps: data collection, data analysis, and comparison. The first step, data collection, involved a thorough examination of project documents, such as project descriptions, design changes, and engineering changes, and adherence to industry standards such as ISO 17599 (DMU), IEC 81346-1, and CCDC17. Additionally, we conducted interviews with the project teams to gather information and extract descriptions of DCM and ECM. We analyzed a total of 1,226 project documents, standards, and other relevant materials for the four case studies.

More precisely, this research involves two construction companies (one Canadian and one French) and an aerospace partner. The Canadian construction partner contributes case studies for projects A and B, while the French partner provides a case study for project C. These projects highlight differences in the size of the projects, documentation practices, and IT tools maturity. Notably, there are variations in the roles of the Canadian partner in the case studies; acting as the project manager in project A and as the construction manager in project B. Additionally, the aerospace partner offers insights into the ECM process and underscores the importance of IT tools in managing engineering changes.

The collaboration with the industrial partners was productive, and held a total of 22 meetings. These meetings were conducted efficiently and lasted an average of one and a half hours each. Due to the ongoing COVID-19 pandemic, all meetings were held online.

The second step, data analysis, began with documenting the DCM/ECM processes. Process modeling and validation were conducted in parallel. In process modeling, the authors mapped the DCM/ECM processes into the engineering process model using BPMN 2.0. The extracted models were presented to project team members and validated by them during various meetings. Then, we transferred the BPMN models to metamodels to organize the DCM/ECM descriptions. It is important to highlight that the metamodels utilized in this context served as a means of breaking down the DCM/ECM descriptions into different categories, such as terminology, activities, and IT tools. Utilizing the metamodels made it possible to structure the DCM/ECM descriptions and represent them in a consistent and standardized manner to ensure that they adhered to predefined rules and relationships set out in the metamodels. In other words, the metamodels acted as a guide to create well-structured and compliant DCM/ECM models for efficient utilization of the information contained in them.

In the third step of this phase of the methodology, the goal was to evaluate and compare how DCM and ECM are utilized in practice in different BIM- and PLM-supported industries. The examination of DCM/ECM use in practice yielded two key takeaways for this research phase:

a. A description of DCM use in practice in BIM-supported industry from case studies.

b. A description of ECM use in practice in PLM-supported industry from case study.

These contributions provide an understanding of and valuable insights into the potential benefits and challenges associated with DCM/ECM processes. It should be mentioned that by the end of this phase of the methodology, the first and second specific objectives will have been addressed.

3.2.3 Characterization of the DCM/ECM Process

In the first step of this phase, the primary aim was to recognize the differences that exist between DCM/ECM use in theory (as desired) and in reality (as practiced). The main intention was to verify some of the claims encountered in the literature and the case studies as well as compare the best DCM/ECM solution (best practices) from the literature and the case studies as documented.

The main tasks of this phase were to:

a. Compare DCM (*theory and practice*) in BIM-supported case studies.

b. Compare ECM (*theory and practice*) in PLM-supported case study.

By completing the above tasks once in each type of industry, the expected outcomes for this phase were:

a. A characterization of DCM best practices in BIM-supported case studies.

b. A characterization of ECM best practices in PLM-supported case study.

It is important to highlight that the aforementioned outcomes led this study to propose and implement a collaborative PLM platform (3DExperience) for the DCM process. Details about this platform can be found in Chapter 7. The outcomes of this phase of the research methodology address the third specific objective of this doctoral project.

3.2.4 Cross-Pollination Candidate Identification

In this phase of the methodology, we aimed to identify potential characteristics and functionalities for cross-pollination between BIM and PLM from the previous phases' findings.

A comprehensive comparison of DCM/ECM use in theory and in practice in BIM- and PLM-supported industries made it possible to discern the approaches' strengths and limitations. The outcomes and contributions derived from our analyses and the previous phases enabled us to determine which concepts, software functionalities, processes, and practices have the most potential for cross-pollination between BIM and PLM from an ECM standpoint. Therefore, the contribution of this phase was:

a. Concepts, software functionalities, processes and practices that have potential to support cross-pollination between BIM and PLM from an ECM standpoint.

By the end of this phase of the research methodology, the fourth specific objective of this doctoral project will have been addressed, which obviously points us to the overall objective of this doctoral project. The following figure provides an overview of the research methodology.

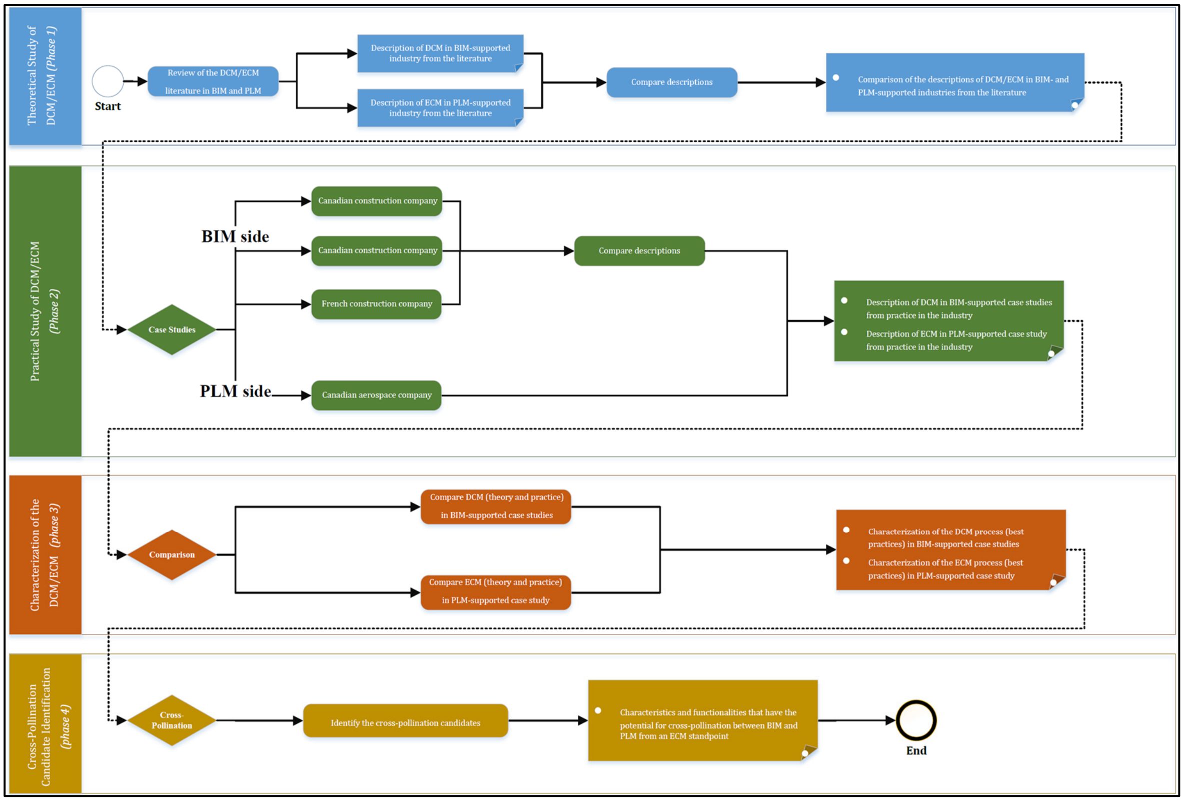

Figure 3.1 The research methodology

The extended format of the above research methodology is presented in Appendix II.

The chapters that follow, Chapters 4 to 7, present this doctoral project's articles and contributions. They offer comprehensive documentation and comparisons of DCM/ECM use in theory and in practice. Additionally, they include a comparative analysis of DCM/ECM in both theoretical and practical contexts, and propose a PLM platform for DCM.

CHAPTER 4

ARTICLE 1—COMPARING ENGINEERING/DESIGN CHANGE MANAGEMENT AND RELATED CONCEPTS IN BIM- AND PLM-SUPPORTED INDUSTRIES FROM THE LITERATURE

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4.1 Abstract

Several research studies have compared building information modeling (BIM) and product lifecycle management (PLM) from different perspectives. It is necessary to understanding the similarities and differences between BIM and PLM before transferring knowledge and lessons learned between them. This can be done by comparing BIM- and PLM-supported industries. This article aims to compare engineering/design change management (and similar approaches) in BIM- and PLM-supported industries. This article reviews and compares the definitions of engineering change management (ECM) and design change management (DCM), which are used in PLM- and BIM-supported industries, respectively. More specifically, this article compares the terminology, processes, tools, and methods used in ECM and DCM. It also proposes sample (best practice) ECM/DCM processes. Research findings of this comparison are evaluated to demonstrate the similarities and differences of ECM and DCM. This evaluation could help identify characteristics and functionalities that could potentially be transferred between BIM and PLM.

4.2 Introduction

Enabling collaboration and providing access to the right information, at the right time and in the right format, are crucial challenges in various industries, including the aerospace, automotive, construction, and infrastructure industries. The product lifecycle management

(PLM) approach has evolved to support organizations by providing a platform for product-related knowledge creation, organization, and dissemination across various non-construction enterprises (Jupp and Singh, 2014).

The construction industry, on the other hand, has suffered from significant delays in increasing productivity compared to other industries, such as the aerospace and automotive industries (Boton et al., 2016), and uses the building information modeling (BIM) approach instead. BIM is an approach that promotes collaboration and information management among different project stakeholders (Jupp, 2013). It appears to have the potential to solve some persistent construction difficulties (interoperability, information flow optimization, etc.), which would lead to improved productivity (Boton et al., 2018).

BIM and PLM have been compared in terms of their functionalities and capabilities, with most initial motivations for comparison being to transfer PLM functions and industry characteristics from PLM-supported ("non-construction") industries to the BIM-supported construction industry (Jupp, 2016). While the construction industry is comparable to some other industries (e.g., aerospace) despite some notable differences, BIM and PLM comparison seems to be an interesting option with good potential to develop an information-centered management approach for BIM (Boton et al., 2018).

The similarities and differences between PLM and BIM must be characterized before the transfer of knowledge and lessons learned in their respective industries can lead to meaningful results (Jupp, 2016). Although the aim has traditionally been to transfer mature knowledge from PLM to BIM, several research studies (Boton et al., 2018; Chen and Jupp, 2019; Mangialardi et al., 2017; Pourzarei et al., 2020) suggest that BIM and PLM cross-pollination would be more beneficial and provide an opportunity to improve efficiency and productivity in both the construction industry and non-construction industries.

Engineering change management (ECM), which is also referred to as *change order management* or *design change management*, is an important practice for both the construction and non-construction industries. ECM appears to be an adequate standpoint for comparing BIM and PLM since it is a compact version of the design process (evaluate change, document, approve, etc.) (Jarratt et al., 2011). It is therefore easier to document ECM practices and replicate them in the lab than to document the design process of the entire project. Moreover, ECM is key in managing the evolution of product definitions and is of significant importance in both BIM- and PLM-supported industries.

The intent of this article is to use ECM and design change management (DCM)—the latter of which is specific to the construction industry—as a standpoint for comparing BIM- and PLM-supported industries. Doing so implies the following three objectives:

1. To describe ECM and relevant approaches in a PLM-supported (non-construction) industry, such as aerospace.
2. To describe ECM and relevant approaches (e.g., DCM) in the BIM-supported (construction) industry.
3. To compare the descriptions of ECM and DCM used in BIM- and PLM-supported industries to describe the similarities and differences between BIM and PLM.

This article is broken down into nine sections as follows. Section 4.3 reviews related research. Section 4.4 presents the research methodology used in this article. Section 4.5 and Section 4.6 present ECM descriptions used in PLM-supported industry and DCM descriptions used in BIM-supported industry, respectively. Section 4.7 compares the descriptions of ECM and DCM. Section 4.8 presents a discussion on the research findings. Finally, Section 4.9 wraps up the article with the conclusion and future work.

4.3 Related Research

The construction industry has suffered great delays in increasing productivity compared to other industries like the aerospace and automotive industries (Boton et al., 2016). To address this issue and in the interest of collaboration, information exchange and traceability, comparing PLM and BIM approaches and the industries they support could reveal useful knowledge (Boton et al., 2018). Many publications compare the terms BIM and PLM, sometimes assuming they are similar and have something in common, and sometimes considering them to be completely distinct concepts (Mangialardi et al., 2017).

Data governance and information management, storage and distribution are essential for both BIM- and PLM-supported industries, as are the new skills and digital expertise required throughout the building and product lifecycle (Mangialardi et al., 2017). Research by Mangialardi et al. (Mangialardi et al., 2017) indicates that the construction industry could benefit from the manufacturing sector's extensive use of PLM in sharing information at different phases of the lifecycle to compensate for its main missing features. The comparison of BIM and PLM can bring various benefits, such as increasing productivity, making production more cost-effective and sustainable, optimizing design, minimizing production waste, managing the supply chain, standardizing product components, and managing product changes and adoptions (Mangialardi et al., 2017).

There has been increased focus in recent years on applying BIM to the entire building lifecycle (Jupp, 2013). The literature reviewed by Jupp (Jupp, 2013) revealed that an increasing number of studies consider a range of issues related to BIM. It seems that BIM can solve several of the construction industry's persisting problems (interoperability, information flow optimization, etc.), which would lead to improved productivity (Boton et al., 2018). Although there have been many advancements in BIM application, there are still limitations in terms of management, technology and collaboration capabilities throughout a project and the operational phase of a facility's lifecycle. BIM's continued evolution therefore requires an integrated lifecycle approach to developing and adopting a new business model (Jupp and Singh, 2016).

BIM is currently used at the project level and, as a result, the construction industry continues to lack a strategic business perspective for the whole building lifecycle. PLM, on the other hand, serves project, operational and business goals by consistently integrating a variety of information and communications technology systems (CAD, CAM, etc.) that contain data, information and product knowledge. PLM systems are therefore an enabling technology that serves as a central hub for product data to support collaborative design and production processes , whereas BIM applications are not viewed as a holistic business concept (Jupp and Singh, 2016). Interestingly, Cheutet et al. (Cheutet et al., 2018) claim that "BIM is a subset of

PLM, and a major part of any organization is based on the accurate management and monitoring of assets."

Many research studies illustrate that BIM and PLM can be viewed as similar or different concepts. They are similar in that, "to enable collaboration throughout the product lifecycle, they are approaches based on information tools and models" (Boton et al., 2018). They are also similar in terms of "project information, integration and reuse; digital mock-up concept; and project management practices" (Cheutet et al., 2018). In addition, according to Jupp and Singh (Jupp and Singh, 2016) and Cheutet et al. (Cheutet et al., 2018), they can be differentiated as BIM is generally used in the design and construction of buildings, whereas PLM is typically used in the design and manufacturing of products. They differ also in terms of the tools, workflows and standards that are used to implement each approach (Boton et al., 2018). "BIM has amazing features to manage the different building processes from design to construction but lacks monitoring and management mechanisms, and this is the main point that differentiates PLM and BIM" (Cheutet et al., 2018). PLM, on the other hand, provides strong management capabilities for any constructed project's lifecycle. Comparing BIM and PLM can help to improve the two worlds through cross-pollination (Boton et al., 2018).

Jupp and Nepal (Jupp and Nepal, 2014) explored how BIM and PLM have impacted professional practices in construction and non-construction industries. They concluded that BIM is maturing in the construction industry and there is now greater potential to achieve a common endpoint with non-construction industries.

Jupp (Jupp, 2013) examined the implications of incomplete BIM implementation during design and construction. Their research detected three kinds of problems: process-based issues, technology-based issues, and policy- or procedure-based issues. Their results indicate that PLM has the potential to efficiently expand existing applications of BIM. Additionally, Jupp and Singh (Jupp and Singh, 2016) provided a considerable research contribution to advancing BIM by mapping PLM capabilities. Their useful taxonomy is based on the fields in which BIM is being developed and encompasses managerial, technical and collaborative capabilities (Chen and Jupp, 2019).

The most common idea for comparison is that the mature functionalities of PLM that are used in complex product manufacturing could be tailored to the construction and infrastructure industry to effectively manipulate complex BIM models. However, many research studies suggest that the cross-pollination of BIM and PLM could help improve not only BIM, but also PLM ((Boton et al., 2018), (Chen and Jupp, 2019) and (Mangialardi et al., 2017)), and that it is therefore appropriate to compare these approaches to achieve effective cross-pollination ((Jupp, 2016) and (Boton et al., 2018)). It is also important to note that this comparison is very challenging because of the complexity of the objects that can be compared and cultural differences and the different technologies used in the construction industry and non-construction industries (e.g., aerospace).

Table 4.1 compares BIM- and PLM-supported industries from different perspectives. It was compiled from the results of three research studies: Boton et al. (Boton et al., 2018), Jupp (Jupp, 2016), and Mangialardi et al. (Mangialardi et al., 2017). In Boton et al. (Boton et al., 2018), the comparison of BIM use in construction and PLM use in shipbuilding from the viewpoint of product structure revealed different data structures are used in BIM and PLM. Jupp (Jupp, 2016) analyzed the similarities and differences between BIM and PLM in the construction and aerospace industries. These industries differ in terms of their technological intensity; for instance, aerospace is technologically intensive, whereas construction is not very technologically intensive by comparison (Jupp, 2016).

Table 4.1 Comparison of BIM- and PLM-supported industries

Comparison Perspectives		**PLM (Non-Construction Industries)**	**BIM (Construction Industry)**
Industry Structure and History	Industry structure (Jupp, 2016)	Globalized and consolidated.	Localized and highly fragmented.
	Stakeholders (Jupp, 2016)	Uniform and experienced, with long-standing collaborative relationships.	Diverse and less experienced, with short-term and more isolated relationships.

Table 4.1 Comparison of BIM- and PLM-supported industries (cont'd)

Comparison Perspectives		**PLM** **(Non-Construction Industries)**	**BIM** **(Construction Industry)**
	Approach to client and value delivery (Jupp, 2016)	Delivery of potential value based on through-life performance.	Delivery of optimal value based on project performance (time, cost, quality).
	Framework (Jupp, 2016)	Management methods based on information-centric approach to lifecycle management.	Process methods based on activity-centric approach to project management.
	Requirement management (Jupp, 2016)	Engineering methods support decision-making from a whole-lifecycle perspective.	No engineering methods to support a whole-lifecycle perspective.
Technological Aspects	Data requirement (Jupp, 2016)	Standardized data; some data interoperability; traceability of individual product information; data encryption and user authentication required.	No standardized data; some data interoperability; limited traceability of individual product information; little data quality verification, encryption and user authentication.
	Technological intensity and expertise (Mangialardi et al., 2017)	Medium to high.	Low to medium.
	Data management and tools (Jupp, 2016), (Mangialardi et al., 2017)	Higher levels of integration, PLM application modules, PDM, 3D CAD, CAM, CAE, information modeling architectures, development toolkits, business applications.	Largely separate application modules, 3D CAD, CAM, CAE, 4D-5D BIM.
	Data structure documents in information flow (Boton et al., 2018)	Bill of Materials, Product Structure, Work Breakdown Structure.	Product Breakdown Structure, Model Element Table, Model Element Breakdown, Work Breakdown Structure.

Mangialardi et al. (Mangialardi et al., 2017) used the literature to investigate industrial characteristics and categorize the characteristics of the Architectural Engineering and Construction (AEC) and complex manufacturing industries. Current BIM approaches lack support for through-life information management that covers the middle-of-life (MOL) and end-of-life (EOL) phases. According to Jupp (Jupp, 2016), “PLM is a management method supported by an information-centric approach to the whole product lifecycle; in contrast, BIM is a process method supported by an activity-based approach to construction project management” (Jupp, 2016).

Although several standpoints have been proposed for comparing BIM and PLM, this research project is the first to propose comparing BIM and PLM from the standpoint of ECM. It is important to mention that this article compares BIM and PLM by way of comparing BIM- and PLM-supported industries. In addition, ECM, regardless of which synonymous term is used, is an important practice for both the construction industry and non-construction industries.

4.4 Research Methodology

The research method used for this study is a selective literature review. Google Scholar and Scopus were selected as data collection sources. Various keywords were used for data collection. The keywords that were used on both the BIM and PLM sides are shown in Table 4.2.

Table 4.2 Summary of the keywords used for data collection

Data Collection Keywords	
PLM-Supported (Non-Construction) Industries	(“ECM” OR “Engineering Change Management” OR “Engineering Change” OR “Engineering Change Order” OR “Engineering Change Order Management” OR “ECO” OR “Engineering Change Request” OR “ECR” OR “Engineering Change Notice” OR “ECN” OR “Engineering Change Proposal” OR “ECP” OR “Engineering Change Control” OR “ECC” OR “Design Change” OR “Design Change Management” OR “Technical Change” OR “Technical Change Management”) AND (“Product Lifecycle Management” OR “PLM”)
BIM-Supported (Construction) Industry	(“ECM” OR “Engineering Change Management” OR “Engineering Change” OR “Engineering Change Order” OR “Engineering Change Order Management” OR “ECO” OR “Engineering Change Request” OR “ECR” OR “Engineering Change Notice” OR “ECN” OR “Engineering Change Proposal” OR “ECP” OR “Engineering Change Control” OR “ECC” OR “Design Change” OR “Design Change Management” OR “Technical Change” OR “Technical Change Management” OR “Construction Change” OR “Construction Change Management”) AND (“Building Information Modeling” OR “Building Information Model” OR “BIM” OR “Building Lifecycle Management” OR “BLM”)

As mentioned, the ECM that is used in PLM-supported industries is not the same as the one used in BIM-supported industry (not the same terminology). To have more research material, other resources such as PhD and master's theses, and books (e.g., the Project Management Body of Knowledge (PMBOK)) were also investigated. Furthermore, the authors decided to include some French-language reading materials (e.g., master's theses) to complete the review. All the aforementioned resources were exported to Zotero to avoid duplicates.

The extracted data and information were classified into two categories: ECM in PLM-supported industries and DCM in the BIM-supported industry. Each category was further broken down into sub-categories:

a) Engineering change (EC) and design change (DC)
    1) Definitions of EC and DC
    2) Associated synonyms of EC and DC from the literature
    3) Causes and impacts of EC and DC
b) ECM and DCM
    1) Definitions of ECM and DCM (or similar approaches)
    2) ECM and DCM glossary
    3) ECM and DCM processes (activities)
    4) ECM and DCM tools and methods

The authors then compared the definitions of EC and DC based on the type of change made and the moment it happens. In addition, the authors defined five phases of the ECM and DCM processes to facilitate process comparison. Moreover, four categories were defined to compare ECM and DCM tools and methods. They are: manage propagation/impact analysis, assist in decision-making, provide a new framework/model/interface, and develop a prediction tool.

Following this methodology resulted in a comprehensive review of ECM and DCM descriptions used in PLM- and BIM-supported industries, respectively, with the former being discussed in Section 4.5, and the latter, in Section 4.6.

4.5 Engineering Change Management in PLM-Supported Industry

ECM is an important practice in non-construction industries (e.g., aerospace) that typically involves 3D product models. This section aims to investigate ECM in PLM-supported industries.

This section has two parts, the first of which reviews definitions of EC, associated synonyms, and causes and impacts of ECs. The second one reviews the definitions of ECM, the ECM glossary, the ECM process, and ECM tools and methods.

4.5.1 Engineering Change (EC)

An EC can be as simple as a documentary shift or as challenging as a full restructuring (Wright, 1997). Generally, changes are made for one of two reasons: to correct errors (rework), or to improve, enhance or adapt the project (Rouibah and Caskey, 2003).

4.5.1.1 Definitions of Engineering Change

A variety of research studies propose different definitions for EC. Table 4.3 below summarizes some of these definitions.

Table 4.3 Definitions of engineering change

Definitions	**Author(s)**
"Engineering Changes (ECs) are changes and/or modifications to released structure (fits, forms and dimensions, surfaces, materials, etc.), behaviour (stability, strength, corrosion, etc.), function (speed, performance, efficiency, etc.), or the relations between functions and behaviour (design principles), or behaviour and structure (physical laws) of a technical artefact."	Hamraz (Hamraz, 2013)
"[…] are defined as modifications in form, fit, function, materials or dimensions in design parameters, constituting the design, are referred to as Engineering Changes."	Rouibah and Caskey (Rouibah and Caskey, 2003)
"An engineering change (EC) is a modification to a component of a product, after that product has entered production."	Wright (Wright, 1997)
"Changes and modifications in forms, fits, materials, dimensions, functions, etc. of a product or part are referred as to product design changes before the design is released, or engineering changes (ECs) after the design is released."	Huang and Mak (Huang and Mak, 1998)
"An engineering change is an alteration made to parts, drawings or software that have already been released during the product design process. The change can be of any size or type; the change can involve any number of people and take any length of time."	Jarratt et al. (Jarratt et al., 2005, 2011)
"EC is modification of a products component after the product has entered in production."	Shivankar et al. (Shivankar et al., 2015)
"Engineering changes (ECs) are the changes and/or modifications in dimensions, fits, forms, functions, materials, etc. of products or constituent components after the product design is released."	Huang et al. (Huang et al., 2003)
• "Change to the current approved configuration documentation of a configuration item (CI)." • "Any alteration to a product or its released configuration documentation. Effecting an engineering change may involve modification of the product, product information, and associated interfacing products."	Department of Defense handbook (Department of Defence, 2020)

ECs have an important role to play in product development and result in product improvement (Rouibah and Caskey, 2003). Hundreds or thousands of ECs are carried out every year, varying in scope from changes in color to changes in engine materials (Wu et al., 2014).

According to Jarratt et al.'s definition of EC (Jarratt et al., 2005, 2011), an EC can be initiated at any phase of the product lifecycle, and once the design concept has been released to design teams, suppliers, potential customers, etc., all changes to the data should be considered engineering changes (Jarratt et al., 2011). The authors consider Jarratt et al.'s definition (Jarratt et al., 2005, 2011) of EC to be the reference definition in this article.

Now that the term EC has been defined, the next section reviews various terms that are synonymous with EC.

4.5.1.2 Synonyms of Engineering Change from the Literature

Although "engineering change" is the most widely used term in the literature, some authors used other terms to refer to it (Hamraz, 2013). Beside of the different terms (e.g., product change) that have been proposed by different research studies, all the proposed terms addressing the same concept and phenomenon (Jarratt et al., 2005, 2011).

Table 4.4 Synonyms of engineering change found in the literature

Terms Used	Author(s)
Design change	Ollinger and Stahovich (Ollinger and Stahovich, 2004); Earl et al. (Earl et al., 2005)
Product change	Inness (Inness, 1994); Ulrich (Ulrich, 1995)
Product design change	Huang and Johnstone (Huang and Johnstone, 1995); Morris et al. (Morris et al., 2016)
Engineering design change	Kidd and Thompson (Kidd and Thompson, 2000); Fei et al. (Fei et al., 2011)
Change	Fricke et al. (Fricke et al., 2000)

Although different terms are used as synonyms for “engineering change,” as indicated in Table 4.4, “engineering change” is the reference term used in this article. The next section reviews the causes and impacts of ECs found in the literature.

4.5.1.3 Cause and Impacts of Engineering Change

In the competitive environment of manufacturing, ECs are inevitable and can affect to quality, cost, and delivery time of products (Huang et al., 2003). Some research studies indicate that managing ECs is costly and time-consuming in most manufacturing industries (Huang et al., 2003).

A research study of German engineering companies found that ECs account for about 30% of all work depending on their scope (Fricke et al., 2000) (Jarratt et al., 2005). The research of Quintana et al. (Quintana et al., 2012) mentioned that Bombardier Aerospace recorded 13,967 engineering changes in 2001. Terwiesch and Loch (Terwiesch and Loch, 1999) estimated that ECs consumed a third and a half of engineering capacity in the companies they analyzed (Jarratt et al., 2005). ECs are viewed negatively because they can overrun the budget and change the time plan; however, they can also be seen as an opportunity for organized companies (Jarratt et al., 2005).

Rivière et al. (Rivière et al., 2003) consider three kinds of ECs in their research. An EC is considered a *modification* when it affects product characteristics, an *amendment* when it has no repercussions on users' use of the amended product, and a *correction* if it affects only the presentation information and not the description of the component (Rivière et al., 2003).

Table 4.5 summarizes the causes of ECs.

Table 4.5 Causes of engineering changes according to the literature

Causes of Engineering Changes	**Author(s)**
• Emergent changes: error correction, safety, change of function, or product quality problems. • Initiated changes: from customers, the Sales and Marketing team, the Product Support team, the Production team, suppliers, the Product Engineering team, company management, or legislators.	Jarratt et al. (Jarratt et al., 2011)
• Changes in needs and requirements. • Program or project interactions. • The need to fix deficiencies. • Technological changes. • Legislation changes. • Project scheduling changes.	Riviere et al. (Rivière et al., 2003)
• Careless mistakes (correction of errors). • Poor communication (change in customer specifications). • Change snowballing (change of a part based on product requirements). • Cost savings. • Ease of manufacturing. • Product performance improvement (quality problems).	Lee et al. (Lee et al., 2006)

Jarratt et al. (Jarratt et al., 2011) classified the causes of ECs into two categories: emergent changes and initiated changes. They (Jarratt et al., 2011) also classified ECs according to their urgency: immediate, mandatory, or convenience. Another basis of classification is the timing of changes in the product development phase: early (low-impact) ECs, mid-production ECs, and late (expedited) ECs (Jarratt et al., 2011).

The propagation of changes can spread to components, systems, etc. Hence, Terwiesch and Loch (Terwiesch and Loch, 1999) identified three types of propagation in their research (Jarratt et al., 2005):

1. Propagation between components and manufacturing
2. Propagation between components within the same subsystem
3. Propagation between components in different subsystems

On the other hand, the authors of (El Hani et al., 2007) thought that ECs are usually communicated through modifications on engineering drawings depending on their impacts. ECs, like other kinds of changes, have some impacts and consequences. Hamraz (Hamraz, 2013) classified the consequences of ECs into three main categories in their research:

1. Total costs of EC
    a. Direct costs (e.g., design costs and prototyping costs)
    b. Indirect costs (e.g., fines)
2. Consequences of ECs on quality
3. Consequences of ECs on time-to-market

Riviere et al. (Rivière et al., 2003) also identified potential consequences of ECs: cost impacts, impacts on the program schedule, impacts on product performance, impacts on suppliers and work partners, impacts on other projects and programs, additional ECs related to the same problem, and impact on the phases of the lifecycle.

It is important to assess the impacts of ECs. In most cases, this evaluation is done by actors with appropriate expertise (Ouertani et al., 2004). Three factors control the effect of ECs on a product: the complexity of the product, the architecture of the product, and the level of product innovation (Jarratt et al., 2011).

4.5.2 Engineering Change Management (ECM)

ECs are inevitable (Du Toit, 2014; Pikosz and Malmqvist, 1998; Shivankar et al., 2015), and efficient ECM is an essential competency (Maurino, 1993). For instance, the authors of (Stojanovic and Stojanovic, 2002) reveal in their work that a large engineering company could potentially save $100 million a year jut by saving ten minutes of engineering time with quicker access to information. The recent research study (Shivankar et al., 2015) reported that Ford, General Motors and DaimlerChrysler recorded 350,000 ECs per year, with each EC costs approximately $50,000, which reminds us of the importance of ECM. Therefore, ECM is an essential process in industrial companies and plays an important role in product development (Ouertani et al., 2004), (Wu et al., 2014), (Kocar and Akgunduz, 2010; Tavcar and Duhovnik, 2006).

Wright (Wright, 1997) conducted one of the first literature reviews on ECM and proposed a tree-structured ECM model that included two different domains: the computer tools that are used to analyze and synthesize EC problems and solutions, and the methods that are used to reduce the impacts of ECs (Wright, 1997). In addition, various research studies have proposed valuable ECM methods and tools that are used in PLM-supported industries (Schuh et al., 2018; Tavcar and Duhovnik, 2006; Wu et al., 2014).

Tavcar and Duhovnik (Tavcar and Duhovnik, 2006) proposed in their research five criteria for evaluating efficiency in ECM:

1. Communication: The most common reason for ECM problems is poor communication.
2. Decision-making: Decision-making is the bottleneck stage in the ECM process.
3. Organization: The ECM and design processes should be supported by the organization to shorten response times.
4. Process definition: All participants should clearly understand the ECM process.
5. Information system: The information system is the foundation needed for efficient ECM.

ECM has its origins in several management systems, including configuration management (Jarratt et al., 2011). Unmanaged changes can affect a product’s performance as well as its functional and physical attributes (Jarratt et al., 2011). However, despite the interrelationship between configuration management and ECM, they are not one and the same (Jarratt et al., 2005).

ECM is typically supported by commercial PDM/PLM or ERP software (Tavcar and Duhovnik, 2006), and it can be noted that ECM is an essential PLM process (Holler, 2018). While web-based ECM systems offer better information sharing, simultaneous data access and smooth communication, ECM is quite often article-based, particularly in smaller companies (Huang et al., 2001; Tavcar and Duhovnik, 2006).

4.5.2.1 Definitions of Engineering Change Management

ECM is at the center of many research studies aiming to process ECs after the original design was implemented (Du Toit, 2014; Huang et al., 2003; Jarratt et al., 2011; Quintana et al., 2012; Wright, 1997). ECM applies to organizing, controlling and executing ECs and therefore covers the whole product lifecycle (Hamraz, 2013; Jarratt et al., 2011; Ouertani et al., 2004). A variety of research studies propose different definitions for ECM. Table 4.6 below summarizes some of these definitions.

Table 4.6 Definitions of engineering change management from the literature

Definitions	**Author(s)**
"ECM can be summarized according to its goals: to (1) avoid or reduce the number of engineering change requests (ECRs) before they occur, (2) detect them early when they occur, (3) address them effectively, (4) implement them efficiently, and (5) learn continuously for the future."	Hamraz (Hamraz, 2013)
"Engineering Change Management (ECM) is the process of organizing, controlling and managing the workflow and information flow for ECs. The ECM process involves three main phases: Request, Approval, and Notification and Execution."	Kocar and Akgunduz (Kocar and Akgunduz, 2010)
"Engineering change management is an effective management tool to ensure that a change, regardless of size, is properly executed and recorded taking into account the technical, engineering and safety aspect."	Du Toit (Du Toit, 2014)
[…] "Define ECM as the process of making ECs to a product in a planned or systematic fashion."	Rouibah and Caskey (Rouibah and Caskey, 2003)
"Engineering change management (ECM), which is the process of organizing, controlling and managing the workflow and information flow for engineering change (EC). The EC procedure is divided into two parts; in the first one, decisions are passed, and in the second emphasis are on rapid implementation."	Shivankar et al. (Shivankar et al., 2015)

The assessment of ECs is one of the main parts of the ECM process (Jarratt et al., 2005). The ECM process is often associated with long lead times due to several factors. Comprehensive document management is the first requirement. The process also involves meetings with all stakeholders in the various departments affected to assess possible options to satisfy all parties (Pikosz and Malmqvist, 1998). Du Toit's definition (Du Toit, 2014) of ECM is used as the reference definition in this article.

4.5.2.2 Engineering Change Management Glossary

The ECM process relies on various terms and concepts. Some of the most important terms and concepts that are used in ECM in PLM-supported industries are presented in this section, in Table 4.7.

Table 4.7 Engineering change management glossary

Term	Author(s)	Description
Engineering Change Request (ECR)	Jarratt et al. (Jarratt et al., 2005)	• "A form available to any employee used to describe a proposed change or problem which may exist in a given product."
Engineering Change Proposal (ECP)	Department of Defense handbook (Department of Defence, 2020)	• "A proposed engineering change to the product and its configuration documentation, by which the change is described, justified, and submitted to a Configuration Approval Authority for approval/disapproval or deferral."
Engineering Change Order (ECO)	Jarratt et al. (Jarratt et al., 2011)	• "A document which describes an approved engineering change to a product and is the authority or directive to implement the change into the product and its documentation."
Engineering Change Notice (ECN)	N/A; web document[3]	• "An Engineering Change Notice (ECN) is a document authorizing and recording design changes throughout the prototyping and life-cycle phases of a product."
Change Propagation	Hamraz (Hamraz, 2013)	• "Change propagation is the chain reaction that occurs when one change causes another change nearby, which then causes further changes, and so on, leading to a spread of changes."
Engineering Release	Department of Defense handbook (Department of Defence, 2020)	• "Engineering release is an action that makes configuration documentation available for its intended use and subject to configuration control procedures."

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[3] https://mae.ufl.edu/designlab/Lab%20Assignments/EML2322L-Engineering%20Change%20Notice.pdf

It is important to mention that some research studies (Ullman, 2003) consider ECN and ECO to be one and the same; however, it seems they are two different documents.

4.5.2.3 The Engineering Change Management Process

The ECM process focuses on identifying, analyzing, modifying, updating, verifying and approving ECs (Pikosz and Malmqvist, 1998; Quintana et al., 2012). Physical or electronic drawings are marked up and used to demonstrate the suggested modifications to stakeholders (Quintana et al., 2012). EC approval follows a formal process that involve a set of well-defined phases (Hamraz, 2013; Huang and Mak, 1998; Lee et al., 2006; Quintana et al., 2012).

There are two types of ECM processes: official ones and unofficial ones (Jarratt et al., 2011). The majority of the ECM processes that are proposed in the literature should be considered official processes (Jarratt et al., 2011). Although various ECM processes are proposed, the official ones typically include four phases (Huang et al., 2001; Lee et al., 2006; Pikosz and Malmqvist, 1998; Terwiesch and Loch, 1999).

Table 4.8 summarizes the ECM processes described in the literature. The processes have different numbers of phases, varying from two (Dale, 1982) to six (Jarratt et al., 2005).

Table 4.8 The engineering change management process according to the literature

Author(s)	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6
Dale (Dale, 1982)	**Procedure for approval of ECs** - Product engineering department prepares a package containing the reasons for EC and all documentation necessary for the action of an approved EC.	**Procedure on approval** - At this phase the EC package assumes the status of action. The package is forwarded to the product engineering department in order that the EC can be actioned.	-	-	-	-

Table 4.8 The engineering change management process according to the literature (cont'd)

Author(s)	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6
Maurino (Maurino, 1993)	**Request (ECR)** - The EC is requested (ECR).	**Proposal (ECP) or Instruction** - The request is analyzed to determine whether it is worthwhile to make the change. - The change management team analyzes and proposes solutions. - One solution is chosen.	**Engineering Change Order (ECO) or Execution** - The change management team prepares the documents (drawings, specifications, etc.) for the chosen solution.	**Notification (ECN) or Application** - The solution for the change is carried out at the company level over the specified time frame (ECN).	-	-
Riviere et al. (Rivière et al., 2003)	**EC proposal** - Collecting or initializing the ECR. - Pre-feasibility study of the proposed EC. - An accepted request proceeds to the ECP phase.	**EC investigation (ECP)** - EC impact analysis and feasibility studies. - Define a set of potential solutions for the proposed EC. - EC committee selects the best solution based on the costs, schedules, product performance, activities, systems impacted, and date of implementation.	**EC embodiment** - Physically implement the solution. - Update the documentation (e.g., drawings). - Inform the people who are concerned about the change.	-	-	-

Table 4.8 The engineering change management process according to the literature (cont'd)

Author(s)	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6
Lee et al. (Lee et al., 2006)	**Initiating an engineering change request (ECR)** - Detect or identify the problem. - Discuss and evaluate the problem detected/identified. - Submit a formal ECR form.	**Evaluating the ECR** - The engineering team reviews the change request. - Decide to accept or reject it. - Generate alternative solutions to the EC (usually relying on past experience and knowledge).	**Issuing engineering change orders (ECOs) to relevant participants** - The engineer in charge issues an ECO that contains the information from the ECR, including changes in weights and production costs, when the EC will become effective, and the plans to handle obsolete parts. - After administrative approval, ECOs are sent to the technology management team to validate the consistency of the product design and to check for possible errors and inconsistencies.	**Storing and analyzing ECOs for management purposes** - ECOs and associated product data are released and stored in the company's intranet system.	-	-

Table 4.8 The engineering change management process according to the literature (cont'd)

Author(s)	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6
Tavcar and Duhovnik (Tavcar and Duhovnik, 2006)	**Change request** - Collect change requests. - Properly document them. - Propose a change.	**Change preparation** - Analyze and test the proposed change	**Change approval** - Calculate the consequences of the change from all perspectives (e.g., in terms of cost and technical feasibility).	**Change of documentation** - Provide the documents for the proposed change. - Distribute the documents provided.	**Implementation in production** - Implement the proposed change in the production process, servicing, etc.	-
Kocar and Akgunduz (Kocar and Akgunduz, 2010)	**Request** - The need for a change emerges. - A department or an engineering team member initiates an engineering change request (ECR) in the ECM system. - An ECR indicates which component to change, which attributes to change, and the reason for the change, and includes a technical drawing representing the change.	**Approval** - The Engineering Change Board (ECB), whose members are from various functional departments, reviews and accepts the change. - This phase also includes the identification of components that are affected by the change and the resolution of propagated changes.	**Notification and execution** - The coordinator distributes an Engineering Change Notification (ECN) involving textual and graphical information regarding the change for execution.	-	-	-

Table 4.8 The engineering change management process according to the literature (cont'd)

Author(s)	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6
Jarratt et al. (Jarratt et al., 2011)	- A request for an engineering change must be made (either electronically or on paper). - The person making the request must outline the reason for the change, the priority of the change, the type of change, which components or systems are likely to be affected, etc. - The change controller must enter the form into an engineering database.	- Potential solutions for the proposed change must be identified, but often only a single one is examined.	- The impact or risk of implementing each solution must then be assessed. - Various factors must be considered: e.g., the impact upon design and production schedules, how relationships with suppliers will be affected; and whether a budget overrun will occur.	- The Engineering Change Board or Committee must review each change, conducting a cost-benefit analysis for the company as a whole, and then grants approval for implementation.	- Implementation of the engineering change can either occur immediately or be phased in. - Which option is followed will depend upon various factors, such as the nature of the change (e.g., if it is a safety issue, then the immediate implementation must occur) and when during the product lifecycle the change will occur. - Paperwork must be updated.	- After a period, the change should be reviewed to see if it achieved what was initially intended and what lessons can be learned for future changes. - The review should examine whether the product and associated processes (e.g., manufacturing) are functioning as expected. - Often, surprises can be discovered, such as more obsolete stock than was originally accounted for. - Not all companies carry out this review process properly.

Table 4.8 The engineering change management process according to the literature (cont'd)

Author(s)	**Phase 1**	**Phase 2**	**Phase 3**	**Phase 4**	**Phase 5**	**Phase 6**
Wu et al. (Wu et al., 2014)	**Identify the issue** - Describe, identify, clarify the issue. Propose the Problem Report. - Have the change administration evaluate the Problem Report to be able to create a change request.	**Conduct the analysis** - Create an engineering change request. - Conduct a technical review (identify and collect affected data). - Conduct an impact analysis (manufacturing, stock, and cost analysis). - Have the Change Review Board (CRB) review the analysis and decision-making.	**Plan the change** - Create an Engineering Change Notice (ECN). - Analyze the ECN to plan delegation: ✓ Fast Track (create change notice and implementation plan). ✓ Full Track (create change notice and implementation plan, and review implementation plan). - Update documents and data.	**Release the change** - Have the updated documents and data validated by: ✓ User ✓ Change administration ✓ Change notice audit - Release the change.	**Change the product configuration** - Document the engineering change history.	-

Table 4.8 The engineering change management process according to the literature (cont'd)

Author(s)	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6
Shivankar et al. (Shivankar et al., 2015)	**The change request (estimation/validation)** - Initiate the engineering change request (ECR). - The engineering change board (ECB) must review and accept the change. - The coordinator determines the departments to be informed and distributes an engineering change notification (ECN) involving textual and graphical information regarding the change for execution.	**The change implementation (schedule/drawing notification/execution/closing)** - The change implementation supervisor initiates the implementation, refers to the customer for approval, defines the production start dates, funding, and nominates the local change implementation supervisor and the purchasing coordinator. - The purchasing coordinator reviews the supplier requirements defined for each impacted production site. - The change implementation supervisor reviews the local CIS (computer information system) and the purchasing coordinator's preparation, and launches the execution. - This triggers the production release of the change (drawing, BOM). - The production site contacts and the suppliers execute the implementation of the change. - The change request is closed.	-	-	-	-

Table 4.8 The engineering change management process according to the literature (cont'd)

Author(s)	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6
Ouertani et al. (Ouertani et al., 2004)	**Engineering Change Request (ECR)** - Change requests are collected with the necessary information go ahead with treatment.	**EC treatment** - A feasibility study is undertaken to evaluate the economic and technical feasibility of the requested changes. - The impacts of ECs are analyzed to detect the consequences for the product and the organization. - Then, a decision is made whether to continue the process (abort or implement the change).	**Solution embodiment** - The solution is physically implemented, documents are updated, and concerned actors are informed.	-	-	-

Despite the fact that the proposed ECM processes involve different phases, they follow the same logic, and most of them use the same tasks (Du Toit, 2014). They all begin by identifying or raising an ECR, then, evaluate the ECR and propose a solution (ECP). Afterwards, once a solution has been chosen/approved, the documentation is prepared (ECO), and finally, the change is implemented (ECN).

Some difficulties can develop during the ECM process. For instance, an ECR that was previously analyzed can be raised again. This can happen for two reasons: different product families and ECR rejection (Kocar and Akgunduz, 2010).

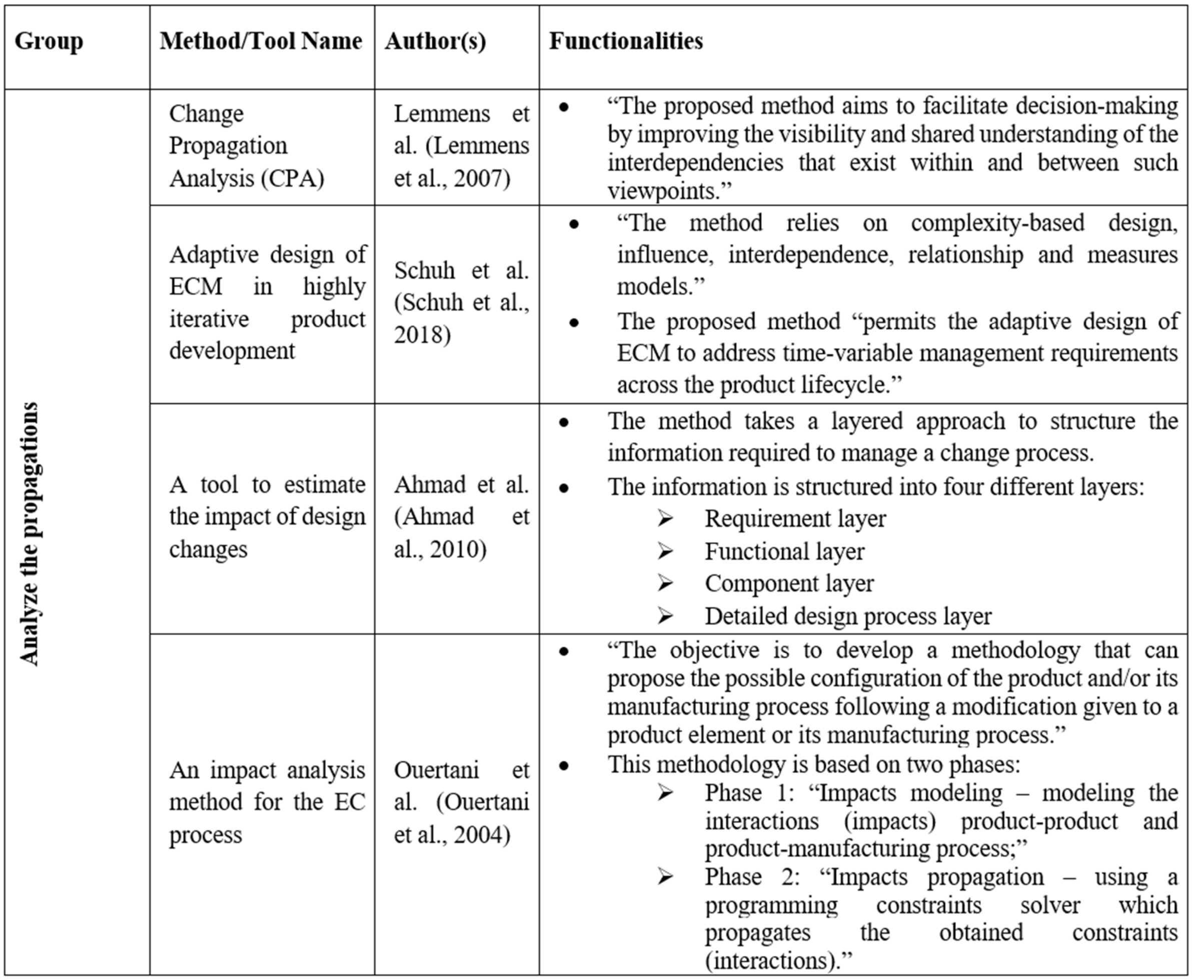
Various documents are utilized in the ECM process. Huang et al. (Huang et al., 2003) classified these documents into three groups based on their special functions related to ECM: those that are used to signal the need for an EC in the initial phases, those that are used to evaluate the impacts and effects of an EC, and those that are used to notify others of an approved EC.

4.5.2.4 Engineering Change Management Tools and Methods

Various methods and tools have been proposed to support ECM processes, some of which are computer-aided ECM systems (Huang et al., 2001; Wright, 1997). Knowledge management is also proposed in various research studies (Lee et al., 2006). Hamraz (Hamraz, 2013) evaluated different methods and tools that have been proposed for ECM in their research.

Table 4.9 summarizes some of the ECM methods and tools proposed in the literature.

Table 4.9 Engineering change management tools and methods from the literature



Group	**Method/Tool Name**	**Author(s)**	**Functionalities**
Analyze the propagations	Change Propagation Analysis (CPA)	Lemmens et al. (Lemmens et al., 2007)	• "The proposed method aims to facilitate decision-making by improving the visibility and shared understanding of the interdependencies that exist within and between such viewpoints."
	Adaptive design of ECM in highly iterative product development	Schuh et al. (Schuh et al., 2018)	• "The method relies on complexity-based design, influence, interdependence, relationship and measures models." • The proposed method "permits the adaptive design of ECM to address time-variable management requirements across the product lifecycle."
	A tool to estimate the impact of design changes	Ahmad et al. (Ahmad et al., 2010)	• The method takes a layered approach to structure the information required to manage a change process. • The information is structured into four different layers: ➢ Requirement layer ➢ Functional layer ➢ Component layer ➢ Detailed design process layer
	An impact analysis method for the EC process	Ouertani et al. (Ouertani et al., 2004)	• "The objective is to develop a methodology that can propose the possible configuration of the product and/or its manufacturing process following a modification given to a product element or its manufacturing process." • This methodology is based on two phases: ➢ Phase 1: "Impacts modeling – modeling the interactions (impacts) product-product and product-manufacturing process;" ➢ Phase 2: "Impacts propagation – using a programming constraints solver which propagates the obtained constraints (interactions)."

Table 4.9 Engineering change management tools and methods from the literature (cont'd)

Group	Method/Tool Name	Author(s)	Functionalities
Assist with decision-making	Capturing and reusing knowledge in ECM	Lee et al. (Lee et al., 2006)	• Using Semantic Web language to be able to accumulate knowledge items in the ECM process. • Using the case-based reasoning (CBR) technique to efficiently retrieve and reuse past engineering change cases. • Proposing a prototype system called Collaborative Environment for Engineering Change Management (CECM) that consists of three subsystems: the engineering change process support system, the knowledge repository, and ontology management.
	Automatic (DSM-based) ECM	Zheng et al. (Zheng et al., 2019)	• "Propose an occurrence-based design structure matrix (DSM) approach for automatic ECM in smart product-service systems (Smart PSS)." • "DSMs enable manufacturers to analyze both single and multiple domain architectures of ECs in a virtualized manner."
	EchoMag – decision-making assistance in the ECM process	Habhouba et al. (Habhouba et al., 2010)	• "EchoMag assists designers and experts during the change-management process." • "The proposed system ensures the coherence of data between the various disciplines involved in the change process." • "EchoMag assists experts in making decisions by proposing alternative solutions when change requests are not agreed upon."
	EC modeling using a function-behavior structure (FBS) scheme	Hamraz (Hamraz, 2013)	• "Develop a method to support engineering change propagation analysis, termed FBS Linkage."
Assist with decision-making	ADVICE – A virtual environment for ECM	Kocar and Akgunduz (Kocar and Akgunduz, 2010)	• "ADVICE, as a Virtual Collaborative Design Environment, provides smart user support for predicting Engineering Changes to be triggered due to a specific change and for offering priorities to Engineering Change Requests." • "ADVICE aims to improve the ECM process by providing both textual and graphical information. The proposed ECM solution is based on past experiences. For the cases where no similar past experience is available, companies still need to look into the functional dependencies of system components and use expert options."
	Applying PDCA to the ECM process	Shivankar et al. (Shivankar et al., 2015)	Plan-Do-Check-Act (PDCA) can be applied to the ECM process. • "In 'plan' stage, objectives are being established in accordance with expected results." • "Implementation of process is being done in 'Do' stage." • "Process is being monitored and results are reported against objectives in 'Check' stage." • "In 'Act' stage, actions are being done for continual improvement of process."

Table 4.9 Engineering change management tools and methods from the literature (cont'd)

Group	Method/Tool Name	Author(s)	Functionalities
	Using model-based definition for optimization in the ECM process	Quintana et al. (Quintana et al., 2012)	• Proposing a model-based definition (MBD) approach that can replace engineering drawings.
	An advanced CMII-based ECM framework	Wu et al. (Wu et al., 2014)	• "An advance CMII-based ECM framework integrates the PLM and ERP perspectives." • "The framework contains five phases: identify issue, conduct the analysis, plan the change, release the change, change product configuration."

The aforementioned methods and tools can be categorized into three groups: those that want to manage the propagations of ECs, such as analyze the propagations (Lemmens et al., 2007) or estimate the impacts of ECs (Ahmad et al., 2010); those that aim to assist with decision-making processes, such as using a DSM matrix (Zheng et al., 2019) or using knowledge management systems (Lee et al., 2006); and those that want to create a new interface, such as a virtual interface (Kocar and Akgunduz, 2010).

This section analyzed the ECM process by investigating ECM terminology, the ECM process, ECM tools and methods. These aspects will be compared latter with their corresponding aspects of the DCM process, which is briefly described in the next section.

4.6 Design Change Management in BIM-Support Industry

Changes are very prevalent in construction projects and are likely to be requested at any phase of a project by different sources and for different reasons. A change can result in subsequent delays in the project schedule, a re-estimation-of-work statement, and increased demand for equipment, and the need for additional materials and labor as well as overtime (Hao et al., 2008). While some changes may yield "benefits" for stakeholders, most, if not properly managed, will have “negative” impacts, most often in terms of time and cost overruns (Hao et al., 2008; Hwang and Low, 2012).

It is important to note that although the terms EC and ECM have been used in the construction industry (Huang and Mak, 1998; Jarratt et al., 2005), they are not the terms usually used in construction. The BIM-supported industry does not use the same terminology as PLM-supported industries. This section, therefore, aims to present the terms and concepts used in the construction industry that are similar to EC and ECM.

4.6.1 Design Change (DC)

Construction projects differ considerably in scale, nature, and complexity, but change is a common feature that all construction projects deal with (Chen and Jupp, 2019). While changes are inevitable in construction projects (Hwang and Low, 2012), Hao et al. (Hao et al., 2008) mentioned that most of the common and costly changes are those related to design, for instance, design changes and design errors.

4.6.1.1 Definitions of Design Change

In construction projects, any additions, deletions, or modifications to the scope of the project are considered changes (Hwang and Low, 2012). Since the term EC is not usually used in the construction industry, most of the research studies used a general definition of change that refers also to the EC definition (Department of Defence, 2020; Earl et al., 2005; Huang et al., 2003; Huang and Johnstone, 1995; Huang and Mak, 1998; Inness, 1994; Jarratt et al., 2005; Ollinger and Stahovich, 2004; Rouibah and Caskey, 2003; Shivankar et al., 2015; Ulrich, 1995; Wright, 1997; Wu et al., 2014).

The term “design change” is the most fitting term used in construction to map to the term EC. Table 4.10 below presents various definitions of design change.

Table 4.10 Definitions of design change from the literature

Definitions	**Author(s)**
“Design changes are regular additions, omissions, and adjustments to both design and construction of work in a construction project that occurs after the award of contract which affects the contract provisions and work conditions that make construction dynamic and unstable.”	Abdul-Rahman et al. (Abdul-Rahman et al., 2015)
“Design change is defined as any change to the scope of the work as defined by the contract documents following the creation of legal relations between the principal and the contractor. Design change may occur in architectural, structural, plumbing and drainage, site works or other aspects of construction.”	Suleiman and Luvara (Suleiman and Luvara, 2016)
[…] “Refers to an alteration to design, building work, project program or other project aspects caused by modifications to preexisting conditions, assumptions or requirements.”	Sun and Meng (Sun and Meng, 2009)
“A design change is a change initiated by the client, which can have a cost and schedule impact. The client can also come up with new requests or there can be changes to what the client already has requested in the scope of work.”	Mejlænder-Larsen (Mejlænder-Larsen, 2017)
“Design Change occurs when changes are made in the project design or requirement.”	Burati et al. (Burati Jr et al., 1992)
“A design change is defined as any change in the design or construction of a project after the contract is awarded and signed.”	Mohamad et al. (Mohamad et al., 2012)

An interesting point in the above DC definitions from (Abdul-Rahman et al., 2015; Mohamad et al., 2012) is that DC refers to those types of alterations that occur after the awarding of a contract. Similarly, EC in PLM-supported industries applies to released documents.

4.6.1.2 Synonyms of Design Change from the Literature

The DC concept is mostly referred to by the general term “change” in the construction industry. However, some research studies have used different terms to reference this type of change. Table 4.11 below reviews the various terms and concepts used.

Table 4.11 Synonyms of design change found in the literature

Terms Used	Author(s)
Engineering change	Fleurent (Fleurent, 2013); Pan and Chen (Mejlænder-Larsen, 2017); Erdogan et al. (Erdogan et al., 2005)
Construction change	Hwang and Low (Hwang and Low, 2012); Hao et al. (Hao et al., 2008); Motawa et al. (Motawa et al., 2007)
Project change	Mejlænder-Larsen (Mejlænder-Larsen, 2017); Okada et al. (Okada et al., 2017)
Design deviation	Burati et al. (Burati Jr et al., 1992)
Engineering design change	Mohamad et al. (Mohamad et al., 2012)
Change	Ibbs (Ibbs, 2005); Sun et al. (Sun et al., 2006); Ibbs et al. (Ibbs et al., 2001)

Although different terms are used as synonyms for DC, as indicated in Table 4-11, “design change” is the reference term used in this article. The next section presents the causes and impacts of DCs found in the literature.

4.6.1.3 Cause and Impacts of Design Change

A design change request can be raised in any phase of a project (Abdul-Rahman et al., 2015; Bröchner and Badenfelt, 2011; Moayeri, 2019; Suleiman and Luvara, 2016). DCs usually lead to rework, which increases the cost of the project (Sun et al., 2006; Sun and Meng, 2009). In construction projects, rework can cost 10 –15% of the contract value (Burati Jr et al., 1992; Sun et al., 2006; Sun and Meng, 2009). Burati et al. (Burati Jr et al., 1992) identified in their research that DCs can increase design costs 2.1–21.5%, and equate to 8.5% of construction change costs on average.

Recognizing the sources and causes of DCs could help to better manage them properly. A variety of research studies have proposed different categories of change causes (Bröchner and Badenfelt, 2011; Burati Jr et al., 1992; Hwang and Low, 2012; Moayeri, 2019; Riley David R. et al., 2005). Table 4.12 below summarizes the causes of DCs.

Table 4.12 Causes of design changes according to the literature

Causes of Design Changes	**Author(s)**
• Internal factors ➢ Owner's factors (e.g., incorrect information given by owner). ➢ Design consultant's factors (e.g., an unrealistic design period). ➢ Contractor's factors (e.g., lack of contractor involvement in design). ➢ Managing consultant's factors (e.g., lack of precise decisions). • External factors ➢ Environmental factors (e.g., changes in weather conditions). ➢ Third parties' factors (e.g., a request made by an end-user). ➢ Political and economic factors (e.g., inflation and price fluctuation).	Suleiman and Luvara (Suleiman and Luvara, 2016)
• External causes ➢ Environmental factors (e.g., weather conditions). ➢ Political factors (e.g., delay in planning permission approval). ➢ Social factors (e.g., skilled-worker shortage in certain trades). ➢ Economic factors (e.g., market competition). ➢ Technological factors (e.g., new construction method). • Organizational causes ➢ Process-related (e.g., organization business strategy). ➢ People-related (e.g., competence and skills). ➢ Technology-related (e.g., technical supports). • Internal project causes ➢ Client-generated (e.g., requirement change or variation). ➢ Design consultant-generated (e.g., poor or incomplete drawings). ➢ Contractor/subcontractor-generated (e.g., poor project plan/schedule). ➢ Other (e.g., poor interdisciplinary communication).	Sun and Meng (Sun and Meng, 2009)

Table 4.12 Causes of design changes according to the literature (cont’d)

Causes of Design Changes	**Author(s)**
• Owner request. • Incomplete design consideration. • Unclear design. • Inconsistent design and site. • Construction conflict. • Contractor suggestion. • People petition. • Actual needs.	Chang et al. (Chang et al., 2011)
• Due to clients o Addition of work/scope (not part of the original scope). o Omission of work/scope (reduction of the original scope). o Modifications to the original design (changes to the original scope). o Unclear initial design brief (e.g., the extent of the scope, requirements, details). o Desire to use alternative materials / new technology (may require different details and coordination with suppliers). o Desire to use better specifications (e.g., to extend the life of the structure, for better performance). o Insufficient background of the proposed site (e.g., possibility of underground facilities, previous structures, previous site conditions). • Due to consultants o Improper design / as part of design improvement (e.g., to rectify design mistakes, to adopt better detailing, to simplify the design for easy construction). o “Inconsistent information in drawings (e.g., a structural detail does not match an architectural detail).” o “Discrepancy between contract documents (e.g., drawings, specifications, Bill of Quantities).” o “Insufficient geotechnical investigation or wrong interpretation of the findings (e.g., unexpected rock layers, loose soil, high water table).” o “Insufficient detail of existing site condition (e.g., clashes with underground facilities, clashes with adjacent structures, flooding condition at site, etc.).” • Due to contractors o “To use available material.” o “To use alternative construction methods to save time.” o “To use alternative construction methods to save money.” o “To rectify construction mistakes.” o “To improve the quality of works at the site.”	Mohamad et al. (Mohamad et al., 2012)

Table 4.12 Causes of design changes according to the literature (cont'd)

Causes of Design Changes	**Author(s)**
• Changed employer requirements. • Design errors such as quantity estimate mistakes, planning mistakes, inadequate arrangement of contract interfaces, inconsistency between drawings and site conditions, and citation of inadequate specifications. • Unforeseen conditions regarding the site or administrative aspects such as a change of work rules / regulations, a change of decision-making authority, special requirements for project commissioning and ownership transfer, neighborhood pleading.	Erdogan et al. (Erdogan et al., 2005)

As can be seen in Table 4.12, DCs can be instigated by different predictable and unpredictable sources. Causes can be project-related, client-related, design-related, contractosr-related, or based on external factors (e.g., unforeseen site condition) and other considerations (e.g., claims and disputes) (Sun and Meng, 2009). However, some research studies claim that clients are the most common cause of ECs (Abdul-Rahman et al., 2015). Also, as the construction project is contract-based, most DCs require an original contract agreement (Riley David R. et al., 2005).

On the other hand, construction and design changes have impacts on construction projects that can be significant or trivial (Hwang and Low, 2012). Table 4.13 below presents some of these impacts.

Table 4.13 Impacts and consequences of design changes according to the literature

Design Change Impacts	**Author(s)**
• Increase in project costs. • Recruitment of new professionals. • Increase in overhead expenses. • Quality degradation. • Decrease in labor productivity. • Delay in the procurement process. • Rework and demolition. • Altered safety conditions. • Delay in completion schedule.	Hwang and Low (Hwang and Low, 2012)

Table 4.13 Impacts and consequences of design changes according to the literature (cont'd)

Design Change Impacts	**Author(s)**
• Time effect ➢ Time extension (e.g., rework/redesign). ➢ Loss of productivity (e.g., productivity degradation). ➢ Increased risk (e.g., acceleration measures). • Cost effect ➢ Direct cost increase (e.g., demolition costs). ➢ Indirect cost increase (e.g., overtime costs). • Relationship and people effect ➢ Relationship-related (e.g., claims and disputes). ➢ Working conditions (e.g., revision of work methods). ➢ Staff-related (e.g., loss of learning curve). ➢ Quality (e.g., quality degradation).	Sun and Meng (Sun and Meng, 2009)
• Project delays. • Change of project costs. • Abandonment of the project. • Wastage of materials. • Conflicts between the parties.	Suleiman and Luvara (Suleiman and Luvara, 2016)

According to Hwang and Low's research (Hwang and Low, 2012), cost overrun is the most common impact, and rework and demolition has the greatest potential impacts on construction projects.

4.6.2 Design Change Management (DCM)

Changes are inevitable in the construction industry, so there is a need to manage them properly to avoid cost overruns and delays (Erdogan et al., 2005). Indeed, the construction industry requires effective design change management that can predict possible changes and identify and plan to manage changes throughout an entire project (Hao et al., 2008). Riley et al.'s research (Riley David R. et al., 2005) indicates that over 50% of construction projects suffer from delays, and more than 30% of them have quality defects. Moreover, changes can increase client dissatisfaction. On the other hand, construction projects are contract-based and having different types of contracts can affect the number of changes required. For instance, Riley et al. (Riley David R. et al., 2005) show in their research that the average number of unforeseen changes is different in design-build and design-bid-build projects.

Hwang and Low's research (Hwang and Low, 2012) reveals that controlling project costs and statutory requirements are the two main factors that encourage companies to implement DCM in their projects (Hwang and Low, 2012).

4.6.2.1 Definitions of Design Change Management

It is important to note that while various research studies indicate that change management is an integral part of project management (Hwang and Low, 2012; Motawa et al., 2007) and propose different management processes to manage changes in construction (Hwang and Low, 2012), (Sun et al., 2006), (Voropajev, 1998), (Al-Sedairy, 2001), the literature lacks a precise definition of DCM. This is because all types of changes are managed with a general change management process.

We take inspiration from DCM processes (and activities) and the general definition of change management used in BIM-supported industry to propose the following definition of DCM:

- ✓ *Design change management is a management process that seeks to forecast potential design changes and recognize and manage changes throughout an entire project.*

The effectiveness of DCM can vary from one project to the next depending on the nature, type, complexity, and size of the project, and the types of contracts it involves (Hwang and Low, 2012).

4.6.2.2 Design Change Management Glossary

The process to manage design (and other similar) changes involves different terms and concepts. Some of the most important terms and concepts that are used in DCM in the BIM-supported industry are presented in this section, in Table 4.14.

Table 4.14 Design change management glossary

Term	**Author(s)**	**Description**
Design Change Notice (DCN)	Mejlænder-Larsen (Mejlænder-Larsen, 2017)	• “A design change notice or DCN is an instruction for implementation.”
Design Change Request (DCR)	Mejlænder-Larsen (Mejlænder-Larsen, 2017)	• “A DCR corresponds with ‘change order,’ which can be defined as a change to original plans, specifications or other contract documents, as well as a change in cost.”
Proposal Change Order (PCO)	Hao et al. (Hao et al., 2008)	• “PCO summarizes the change itself and the impacts of the change – a new updated action plan, cost, schedule, etc.”
Change order (CO)	Hao et al. (Hao et al., 2008); Riley et al. (Riley David R. et al., 2005)	• “Refers to changes that are generated by unanticipated causes, for example, scope changes from the owner, design/technological changes from the architect, and cost/time changes arising from supplier problems or unsatisfactory site conditions.” • Construction projects have two sources of change orders: ➢ Owner-generated change orders – “Are issued when an adjustment to the project scope, design or detailing is requested by the owner and a change to the original contract agreement is required.” ➢ Field-generated change orders – “Arise when problems and conflicts detected in the field require a re-design or reconfiguration of the design.”
Rework	Hao et al. (Hao et al., 2008)	• “Refers to re-doing a process or activity that was incorrectly implemented in the first place and is generally caused by quality defects, variance, negligence, and poor design and on-site management.”
Construction Change Directive (CCD)	Hao et al. (Hao et al., 2008)	• […] “Is issued by an owner or its designate requesting a change in the contract scope when there has been no agreement on cost. CCDs originate from disputed change orders and can become change orders again once the dispute is settled.”

Table 4.14 Design change management glossary (cont'd)

Term	Author(s)	Description
Reactive Change	Motawa et al. (Motawa et al., 2007)	• "Reactive changes represent the events when a change occurs and the project team starts to take actions to remedy the consequences of the change."
Proactive Change	Motawa et al. (Motawa et al., 2007)	• "Proactive changes represent the events when a change is likely to occur in a later stage and the project team plans to minimize its disruptive effect."
Stability	Motawa et al. (Motawa et al., 2007)	• "Stability indicates the degree to which the given work scope would be performed without a request for change. High stability means that only a small number of changes would be expected during the execution of a particular activity, while low stability represents the possibility that a great number of changes would be requested."

4.6.2.3 The Design Change Management Process

Depending on the characteristics of DCs (whether they are proactive or reactive), it may be necessary to identify and predict potential changes. A change prediction system relies investigating the information available in the early phases of projects and using said information to predict change events (Motawa et al., 2007).

Prediction also helps in terms of taking appropriate action to minimize the disruptive effects of changes, which is why a change management process usually includes a change prediction system. Various authors have proposed different types of DCM processes (Al-Sedairy, 2001; Erdogan et al., 2005; Mejlænder-Larsen, 2017; Park and Peña-Mora, 2003), as can be seen in Table 4.15.

Table 4.15 The design change management process according to the literature

Author(s)	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Fleurent (Fleurent, 2013)	**Source of change** - Receive change (from internal or external sources).	**Preliminary assessment** - The engineering group analyzes the change.	**Documentation** - Conduct impact assessment.	**Final evaluation** - The change management team decides to accept, reject or archive the change.	**Updating of management system information** - Update deliverables that are affected by the change.
Hao et al.(Hao et al., 2008)	**Identify changes** - Identify a change based on a set of proactive rules (including sources, causes and types of changes, and possible actions).	**Evaluate and propose changes** - Evaluate the change (based on criteria and options) for decision-making. - Submit a Proposal Change Order (PCO).	**Approve changes** - Review the change through a formal approval process (approve or reject). - Client approval is also required for the PCO to be finalized.	**Implement changes** - Finalize change decisions. - Update and release design and project baseline. - Notify the team. - Record decisions and management information.	**Analyze changes** - Resolve any disputes (if applicable). - Review performance and analyze the change (criteria and traceability).
Hwang et al. (Hwang and Low, 2012)	**Identify changes** - Identify a potential change.	**Evaluate changes** - Evaluate the proposed change.	**Implement changes** - Approve and implement the proposed change.	**Learn from past experiences** - Identify lessons learned.	-

Table 4.15 The design change management process according to the literature (cont'd)

Author(s)	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Motawa et al. (Motawa et al., 2007)	**Start-Up** - Define a set of proactive requirements for effective change management.	**Identification and evaluation** - Identify change causes, types, and effects. - Evaluate the change (based on criteria and options) for decision-making.	**Approval and propagation** - Have process approved by the client and the change management team. - Propose the final change and confirm instructions. - Update and issue the design and project baseline. - Notify the team. - Record the decisions reached.	**Post-Change** - Resolve any disputes (if applicable).	-
CII (CII., 1994)	**Promote a balanced change culture** - Encourage beneficial change. - Discourage detrimental change.	**Recognize change** - Education. - Communication. - Documentation. - Trends.	**Evaluate change** - Elective. - Required. - Decide quickly.	**Implement change** - Authorization. - Documentation. - Tracking.	**Continuously improve from the lessons learned** - Share lessons learned. - Be prepared to improve.
Sun et al. (Sun et al., 2006)	**Start-Up** Prepare project team (team building, clarification of roles and responsibilities, agreeing on change management processes and procedures) to increase readiness.	**Identification and evaluation** - Seek to identify potential changes. Assess changes (impacts and options).	**Approval** Go through the approval process.	**Implementation and review** - Inform the team members who are affected by the change. Review the change and the lessons learned from it.	-

Table 4.15 The design change management process according to the literature (cont'd)

Author(s)	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Mejlænder-Larsen (Mejlænder-Larsen, 2017)	**Identification** - Identify a potential change in the detailed design. - Raise a Design Change Request (DCR).	**Filtration** - If the DCR is approved by the discipline lead, it is presented to the change board. - The change board decides whether the DCR should be approved for evaluation.	**Evaluation** - The DCR's consequences and impacts are evaluated by the change board in the Change Control System (CCS).	**Approval** - The change board decides whether the DCR should be approved for implementation.	**Implementation** - A Design Change Notice (instruction for implementation) is created in the CCS.
Voropajev (Voropajev, 1998)	**Change forecast and detection** - Project context changes. - Project parent organization changes. - Project changes. - Project process changes.	**Project protection, plan development** - Current status and tendency monitoring. - Preventive measures. - Internal protection measures. - Project change plan.	**Plan execution** - Change procedures (requirements, discussion, approval, and responsibilities). - Change introduction system. - Change informational support system. - Corrective actions.	**Change control and result estimation** - Change monitoring. - Current change and result estimation. - Correction proposals. - Change database. - Archive forming. - Post-project analysis, change, and result evaluation. - Lessons learned and strategy correction.	-

Table 4.15 The design change management process according to the literature (cont'd)

Author(s)	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Ibbs et al. (Ibbs et al., 2001)	**Promote a balanced change culture** - Encourage beneficial change and discourage detrimental change. - Communicate and document the critical project success factors. - Establish a contract strategy (beneficial or detrimental changes). - Identify areas where changes are likely.	**Recognize change** - Identify potential changes. - Identify potential impacts (positive or negative).	**Evaluate change** - Classify changes as required or elective for decision-making. - Analyze the cost, schedule, quality, etc. - Elective changes should be removed.	**Implement change** - Obtain final approval. - Document authorizations. - Monitor and track implementation.	**Continuously improve from the lessons learned** - Perform a root causes evaluation. - Identify the lessons learned throughout the project lifecycle and share them. - Update databases.

The DCM process can be conducted in up to five phases (Hao et al., 2008). It begins with identifying potential changes based on proactive rules. Evaluating and analyzing the proposed change is the second phase depending on the criteria and options. The outcome of that phase of the process is a PCO (Hao et al., 2008). Based on the evaluation conducted in the previous phase, the change board (project team and clients) decide whether or not to approve the proposed change. Changes can be rejected permanently or be considered as latent changes (Motawa et al., 2007). Once a change has been approved, a DCN (instruction for implementation) is created in the CCS (Mejlænder-Larsen, 2017). The last phase involves continuously improving from the lessons learned (Ibbs et al., 2001).

4.6.2.4 Design Change Management Tools and Methods

Many research studies have discussed managing changes and design changes in the BIM-supported industry and have proposed various methods and tools to do so. Some have proposed systems (Liu et al., 2014; Mejlænder-Larsen, 2017; Motawa et al., 2007; Zhao et al., 2010) to manage changes, while others recommend using modeling approaches (Koch and Firmenich, 2011; Lee et al., 2004; Moselhi et al., 2005; Taghi Zadeh, 2016) or computer tools (Isaac and Navon, 2008; Mokhtar et al., 2000).

Table 4.16 summarizes some of the DCM tools and methods proposed in the literature.

Table 4.16 Design change management tools and methods from the literature

Method/Tool Name	**Author(s)**	**Functionalities**
Managing Change Dependency (MCD) Toolkit	Sun et al. (Lee, 2006)	• The MCD Toolkit addresses two aspects of project change management: predicting change and reacting to change by rescheduling workflows. ➢ "The change prediction tool aims to predict change events and to enable appropriate actions to be taken in order to minimize disruptive effects." ➢ "A work schedule, also known as workflow, of a construction project contains all the tasks and the relationships between these tasks. It sets out not only what needs to be done but also the correct sequence of doing these tasks."
Integrated Change Management System	Motawa et al. (Motawa et al., 2007)	• An IT system is proposed to help manage the change process effectively: ➢ Predict the level of stability, by predicting the likelihood of change occurrence. ➢ Simulate potential iterations that may occur during change implementation. • The integrated system leads to the Dynamic Planning and Controlling Methodology that evaluates the negative impacts of errors and changes on construction performance.

Table 4.16 Design change management tools and methods from the literature (cont'd)

Method/Tool Name	**Author(s)**	**Functionalities**
Construction Design Change Management (CDCM)	Hindmarch et al. (Hindmarch et al., 2010)	• "The CDCM model incorporates a Design Structure Matrix (DSM) and process map generation to create a checklist of rework; it also records the reason for deviation if the true impact is different to the assessed impact."
Dynamic Planning and Control Methodology	Lee (Lee, 2006)	• The proposed methodology is composed of: ➢ "An error and change management framework that enables understanding of the construction processes associated with errors and changes and how they affect construction performance." ➢ "A proactive buffering strategy for reducing sensitivity to iterative error and change cycles." ➢ "A System Dynamics based construction project model which provides policy guidelines for the planning and control of projects." ➢ "A web-based error and change management system, which supports coordination of errors and changes among contractors and design professionals without hardware and software compatibility issues."
Fuzzy Cognitive Map (FCM) Approach	Khanzadi et al. (Khanzadi et al., 2018)	• "Analyze and prioritize the causes of change orders in construction projects considering their entire causal interactions." • "The major limitation of the proposed approach is that construction and performance of the fuzzy cognitive map model are highly dependent on expert knowledge."
Change Control Tool (CCT)	Isaac and Navon (Isaac and Navon, 2008)	• CCT is a computer-based tool that aims to automate the construction change management process. • It uses the building program as a link between client requirements and the building design, and traces the different relationships that exist between the requirements in the project.
Prediction System for Change Management	Zhao et al. (Zhao et al., 2010)	• A prediction method is proposed that uses an activity-based dependency structure matrix (DSM). • A DSM is used to model the process that may occur as a result of changes. • The system predicts changes by setting the change criteria for each activity in the form of a rework scope. • A Monte Carlo simulation is used to analyze the change probability of activities involved in construction projects.
Computer-Assisted Methodology	Mokhtar et al. (Mokhtar et al., 2000)	• The proposed methodology overcomes the difficulties associated with planning and scheduling interrelated DCs. • It uses linking knowledge to collect and organize the data related to DCs.

Table 4.16 Design change management tools and methods from the literature (cont'd)

Method/Tool Name	Author(s)	Functionalities
Decision Tree Approach	Lee et al. (Lee et al., 2004)	• The proposed approach aims to classify and quantify labor productivity losses based on the cumulative impact of changes. • The approach helps to understand how change orders affect labor efficiency.
A Neural Network Model	Moselhi et al. (Moselhi et al., 2005)	• A neural network model is proposed to quantify the impact of change orders on labor productivity. • The model incorporates four other models in order to analyze the loss of labor productivity due to changes.
Predictive Model	Taghi Zadeh (Taghi Zadeh, 2016)	• A predictive model is proposed to identify the impacts of design changes on the cost and schedule of projects. • The model uses various quantitative techniques such as Pearson correlation and multiple regression analysis methods.
A New Modeling Approach	Koch and Firmenich (Koch and Firmenich, 2011)	• The proposed approach combines existing version-oriented information with change-oriented information, such as moving a wall or modifying a wall's thickness and material, using processing-oriented modeling. • "The proposed model contains both the design states and the design changes." • "Design changes are automatically recorded using a new operative modeling language."
An Integrated Framework for Integrating CM with BIM	Liu et al. (Liu et al., 2014)	• "The proposed framework aims to integrate change management with BIM." • "The framework contributes to an automated model updating workflow, a better method for information collection, and a more effective coordination process among team members." • "It also helps to reduce the negative impacts of the changes on energy efficiency."
Change Control System (CCS)	Mejlænder-Larsen (Mejlænder-Larsen, 2017)	• A change control system is proposed to manage changes to the detailed design and evaluate how to use BIM to identify the impacts of changes.

The functionalities set out in Table 4.16 illustrate that the authors had three goals in mind when proposing their methods/tools: propose a framework or model for managing changes properly, analyze and evaluate the impact of changes, and develop a change prediction method or tool.

The next section compares the characteristics and functionalities of ECM in PLM-supported industries and DCM in the BIM-supported industry.

4.7 Comparing the Descriptions of ECM and DCM Used in BIM- and PLM-Supported Industries

This section aims to compare the descriptions of ECM used in PLM-supported industries and of DCM used in the BIM-supported industry.

The comparison is performed along three axes: the definitions of EC and DC, the functionalities of the ECM and DCM processes, and the characteristics of the methods and tools proposed in the literature for ECM and DCM.

4.7.1 Comparing the Definitions of Engineering Change and Design Change

According to the definitions of EC used in PLM-supported industries and of DC used in the BIM-supported industry, the two terms have some similarities. In this section, their similarities are classified and compared based on two criteria: the type of change made and the timing of the change—in other words, when a change is considered an EC or a DC.

The comparison is presented in Table 4.17 below.

Table 4.17 Comparison of the similarities in the definitions of EC and DC

Type of Industry	Type of Change	Timing of Change
Engineering Change (PLM-Supported Industries)	• Changes/modifications to the released fits, forms, function, performance, design principles, etc., of a product (Hamraz, 2013). • Modifications to the forms, fits, function, materials or dimensions in the design parameters (Rouibah and Caskey, 2003). • Modifications to a component of a product (Wright, 1997). • Modifications to the forms, fits, materials, dimensions, functions, etc., of a product or part are referred as to product design change (Huang and Mak, 1998). • Alterations made to parts, drawings or software (Jarratt et al., 2005, 2011). • Modifications to a product component (Shivankar et al., 2015). • Changes/modifications to the dimensions, fits, forms, functions, materials, etc., of products or constituent components (Huang et al., 2003). • Changes to the current approved configuration documentation of a configuration item (Department of Defence, 2020).	• After product design is released (Huang et al., 2003; Huang and Mak, 1998; Jarratt et al., 2005, 2011). • After product has entered production (Shivankar et al., 2015; Wright, 1997). • After released configuration documentation (Department of Defence, 2020).
Design Change (BIM-Supported Industry)	• Regular additions, omissions, and adjustments to both the design and construction (Abdul-Rahman et al., 2015). • Changes to the scope of the work (Suleiman and Luvara, 2016). • An alteration to the design, building work, or project program (Sun and Meng, 2009). • A change initiated by a client that can have a cost and schedule impact (Mejlænder-Larsen, 2017). • Changes made to the project design or requirements (Burati Jr et al., 1992). • Changes made to the design or construction of a project (Mohamad et al., 2012).	• After awarding and signing the contract (Abdul-Rahman et al., 2015; Mejlænder-Larsen, 2017; Mohamad et al., 2012). • After releasing contract documents (Suleiman and Luvara, 2016).

Table 4.17 illustrates that there are two main similarities between the definitions of ECs and DCs from the literature. First, in terms of the type of change, changes are design-related in both BIM- and PLM-supported industries. Second, in terms of the timing of the change, a change is considered an EC after the product design is released in PLM-supported industries and a DC after the contract has been awarded and signed in BIM-supported industry.

4.7.2 Comparing the ECM and DCM Processes

As seen above, various research studies have proposed different processes for managing ECs and DCs. We propose in this section to compare these processes by first extracting two unique processes, one for DCM and one for ECM. It is important to mention that we extracted two processes from the literature to be able to compare the ECM and DCM processes. The extracted processes each have five phases. Starting by receiving the change request and processes and followed by evaluating the proposed change, approving the proposed change as well as preparing the required documents, implementing the proposed change, and finally reviewing and analyzing the executed changes. Table 4.18 below summarizes the extracted processes.

Table 4.18 Comparison of the ECM and DCM processes

Type of Process	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Engineering Change Management (PLM-Supported Industries)	**Request or initiation (ECR)** - An engineering change request is collected or initialized (either electronically or on paper) (Isaac and Navon, 2008). - The ECR should address the reason for the change, the priority, the type of change, and which components and products are likely to be affected (Bröchner and Badenfelt, 2011; Sun and Meng, 2009).	**Instruction or proposal (ECP)** - The ECR impact analysis and feasibility studies are conducted (Burati Jr et al., 1992; Isaac and Navon, 2008). - A set of potential solutions for the ECR is defined (Bröchner and Badenfelt, 2011; Burati Jr et al., 1992).	**Execution (ECO) or document issuing** - The change management team prepares the documents (drawings, specifications, etc.) for the chosen solution (ECO) (Isaac and Navon, 2008).	**Notification (ECN) or application** - The documented solution is carried out at the company level over the specified time frame (ECN) (Isaac and Navon, 2008; Mokhtar et al., 2000).	**Review and analyze** - Review the change to see if it achieved the initial intent, and identify lessons learned for future changes (Bröchner and Badenfelt, 2011).

Table 4.18 Comparison of the ECM and DCM processes (cont'd)

Type of Process	**Phase 1**	**Phase 2**	**Phase 3**	**Phase 4**	**Phase 5**
Engineering Change Management (PLM-Supported Industries)	-	- Once the change has been approved, the EC committee selects the best solution based on the costs, schedules, product performance, activities, systems impacted, and date of implementation (ECP) (Burati Jr et al., 1992).	-	- The ECN includes the information required to execute the change (Ibbs, 1997).	-
Design Change Management (BIM-Supported Industry)	**Initiate** - Identify and receive a change based on a set of proactive rules (including internal and external sources, causes and types of changes, and possible actions) (Fleurent, 2013; Hao et al., 2008), (Sun et al., 2006).	**Evaluate** - Evaluate the impacts and consequences of the proposed change (based on criteria and options) (Fleurent, 2013; Hao et al., 2008; Mejlænder-Larsen, 2017; Motawa et al., 2007).	**Document/ Negotiate/ Approve** - Based on the evaluation of the proposed change, the change board (the change management team and client) decide whether to approve or reject the change (Fleurent, 2013; Hao et al., 2008; Hwang and Low, 2012; Mejlænder-Larsen, 2017). - The change board prepares the documents (drawings, specifications, etc.) required for the chosen solution (Okada et al., 2017).	**Implement** - Create a design change notice (instruction for implementation) and release it to inform teams (Hao et al., 2008; Mejlænder-Larsen, 2017).	**Review and analyze** - Perform a root causes evaluation. - Identify lessons learned throughout the project lifecycle and share them. - Update databases (CII., 1994; Fleurent, 2013; Hao et al., 2008; Hwang and Low, 2012; Institute, 2000).

The ECM and DCM processes follow similar phases to manage ECs and DCs, respectively. However, they also have some differences.

Before comparing the processes, it is worth mentioning that a phase for team preparation is mentioned in the literature for the BIM-supported industry. Team building, the clarification of roles and responsibilities, and agreeing on DCM processes and procedures are some of the tasks identified to increase readiness. Although this type of preparation is not mentioned in the literature for PLM-supported industries, various standards exist that describe how to manage ECs and how to increase readiness on the PLM side.

The main objective of the first phase of both the ECM and DCM processes is to collect and initialize change requests. Change requests can be initialized in either electronic or paper format. In both types of industries, a change can be requested by anyone at any time. Change requests should describe the reason for the change, the priority, and the type of change. Although there are similarities in Phase 1 of both processes, there is one additional task in Phase 1 of the DCM process. Not only is the change request received in the first phase of the DCM process, but potential changes are also identified based on a set of predefined rules. This distinction might stem from differences in the nature of BIM- and PLM-supported industries.

The second phase of the ECM and DCM processes aims to evaluate the proposed change (analyze the impacts and consequences). The change committee proposes solutions for the proposed change and then chooses one of the solutions based on different criteria such as how the solution will address the proposed change. The proposed solution is approved in this phase on the PLM side, whereas it receives only preliminary approval on the BIM side. In the BIM-supported industry, final approval is granted in the third phase because it involves different stakeholders.

The principal objective of the third phase in both processes is to issue an ECO/CO. The change management team prepares the documents (drawing, specifications, etc.) required for the chosen solution. As mentioned above, in the BIM-supported industry, final approval is granted in this phase. The change management team and client decide whether to accept, reject, or negotiate the proposed solution.

In the fourth phase of the ECM and DCM processes, the documents (drawings, contract, etc.) impacted by the proposed change are updated based on the proposed solution. Then, an ECN/DCN is created and released to inform the departments involved. The ECN/DCN includes the latest version of the documents that are needed to execute the proposed change.

On the PLM side, the fifth phase includes reviewing the executed change to determine whether the chosen solution achieved the initial intent and identify lessons learned. On the BIM side, it involves performing various analyses such as a root causes evaluation, identifying lessons learned, and updating databases. Although some research studies use the 'review and analyze' phase in the ECM process, it seems that it is more commonly used in the DCM process. One reason why this phase is used more in construction may be because the construction industry is project-based and it can increase the efficiency of the DCM process.

4.7.3 Comparing ECM and DCM Tools and Methods

This section aims to compare the ECM and DCM tools and methods proposed in the literature. Accurately comparing the tools and methods proposed actually proved to be quite difficult for two reasons: the brief descriptions of the proposed tool and methods were not publicly available, and the differences in the nature of the companies (BIM- and PLM-side) did not permit us to precisely compare the characteristics of the proposed tools and methods. We therefore organized the tools and methods into four categories:

1. Manage propagations / impact analysis: to analyze the impacts of the proposed change.
2. Assist with decision-making: to help the change committee better evaluate the change.
3. Propose a new framework/model/interface: to optimize the ECM/DCM process.
4. Develop a prediction tool: to predict potential changes based on the criteria.

Table 4.19 below categorizes the proposed tools and methods based on these categories.

Table 4.19 Comparison of ECM and DCM tools and methods

Author(s)	Type of Industry	Manage Propagations / Impact Analysis	Assist with Decision-Making	Propose a New Framework/ Model/Interface	Develop a Prediction Tool
Zheng et al. (Zheng et al., 2019)	PLM-supported industry	X	X		
Schuh et al. (Schuh et al., 2018)	PLM-supported industry		X	X	
Shivankar et al. (Shivankar et al., 2015)	PLM-supported industry			X	
Hamraz (Hamraz, 2013)	PLM-supported industry	X	X		
Quintana (Quintana et al., 2012)	PLM-supported industry		X	X	
Kocar and Akgunduz (Kocar and Akgunduz, 2010)	PLM-supported industry	X	X	X	X
Wu et al. (Wu et al., 2014)	PLM-supported industry			X	
Ahmad et al. (Ahmad et al., 2010)	PLM-supported industry	X			
Habhouba et al. (Habhouba et al., 2010)	PLM-supported industry		X	X	
Lemmens et al. (Lemmens et al., 2007)	PLM-supported industry		X		
Ouertani et al. (Ouertani et al., 2004)	PLM-supported industry	X	X		
Lee et al. (Lee et al., 2006)	PLM-supported industry		X	X	
Sun et al. (Sun et al., 2006)	BIM-supported industry			X	X
Motawa et al. (Motawa et al., 2007)	BIM-supported industry	X		X	X
Hindmarch et al. (Hindmarch et al., 2010)	BIM-supported industry	X		X	
Lee. (Lee, 2006)	BIM-supported industry		X	X	

Table 4.19 Comparison of ECM and DCM tools and methods (cont'd)

Author(s)	**Type of Industry**	**Manage Propagations / Impact Analysis**	**Assist with Decision-Making**	**Propose a New Framework/ Model/Interface**	**Develop a Prediction Tool**
Khanzadi et al. (Khanzadi et al., 2018)	BIM-supported industry	X	X	X	
Isaac and Navon (Isaac and Navon, 2008)	BIM-supported industry		X	X	
Zhao et al. (Zhao et al., 2010)	BIM-supported industry	X	X	X	X
Mokhtar et al. (Mokhtar et al., 2000)	BIM-supported industry		X	X	
Lee et al. (Lee et al., 2004)	BIM-supported industry	X	X	X	
Moselhi et al. (Moselhi et al., 2005)	BIM-supported industry	X		X	
Taghi Zadeh (Taghi Zadeh, 2016)	BIM-supported industry	X	X		X
Koch and Firmenich (Koch and Firmenich, 2011)	BIM-supported industry		X	X	
Liu et al. (Liu et al., 2014)	BIM-supported industry	X	X	X	
Mejlænder-Larsen (Mejlænder-Larsen, 2017)	BIM-supported industry			X	

It is important to mention that Table 4.19 does not consider commercial applications or include all the tools and methods proposed in the literature. It includes only those that are relevant to this research study. The table illustrates that the methods and tools proposed are almost the same in BIM- and PLM-supported industries. There is a difference in the "Propose a New Framework/Model/Interface" category between the BIM and PLM sides, with more attention being paid on the BIM side to proposing a new framework for DCM. This may be because some commercial applications already exist on the PLM side. However, more attention is paid to identifying and predicting potential changes in the construction industry, as was mentioned before and is shown in Table 4.19.

4.8 Discussion

ECM and its similar approach DCM are important practices in PLM- and BIM- supported industries, respectively, that can cause cost overruns and delays according to the literature. The literature indicates that ECM is more widely known and better implemented on the PLM side than DCM is on the BIM side. Despite the importance of ECs and DCs, most of the research studies identified were done at a high level, particularly on the BIM side.

It is important to mention that this article has three categories of limitations. The first is in identifying the BIM- and PLM-supported industries. This was the first step to identify relevant research studies because the authors did not want to investigate hybrid industries (that use both BIM and PLM). On the other hand, as mentioned earlier, BIM- and PLM-supported industries do not use the same terminology for engineering change management. Although the term most commonly used in the BIM-supported industry is “design change,” the general term “change” incorporates the concept of “design change” in some research studies. In addition, this type of change is managed mostly through the general change management process rather than a specific DCM process. It was therefore quite difficult to distinguish the research studies that aimed to manage DCs. Lastly, most of the tools and methods that were proposed in the literature were not commercially available, and the authors therefore relied on the proposals.

Although this research study aimed to investigate the ECM and DCM processes proposed in the literature, it could not investigate commercial applications on both sides. Doing so could help the authors identify different functionalities of the tools that are used in ECM and DCM processes.

One of the most surprising findings of this research was that despite the importance of ECM and DCM, a lack of attention is paid to them. This is especially apparent on the BIM side and may be because of the differences in the nature of the two types of industries. In addition, the ECM and DCM processes investigated follow almost the same structure (similar phases). However, the proposed ECM and DCM processes are described at quite a high level and it is not possible to investigate them in more depth to identify precise differences. Moreover, the literature lacks precise information on some parts of the ECM and DCM processes, such as documentation and versioning.

The hope of this article is that this research would be a first step toward cross-pollination between BIM and PLM.

4.9 Conclusion and Future Work

BIM and PLM have been compared in terms of their functionalities and capabilities. However, a deeper understanding of the similarities and differences between them is required before knowledge and lessons learned can be transferred between them. This article is part of a more comprehensive research study that aims to compare BIM and PLM from the standpoint of engineering change management or design change management. “Engineering change management” is the term generally used in PLM-supported industries, whereas “design change management” is the term more commonly used in the BIM-supported industry. This article thus compares ECM in PLM-supported industries and DCM in BIM-supported industry as they are described in the literature.

This article offers three contributions. First, we collected engineering change and engineering change management definitions and related vocabulary used in PLM-supported industries. Second, we collected design change and design change management definitions and related vocabulary used in the BIM-supported industry. And third, we compared the descriptions of engineering change management and design change management that are used in BIM- and PLM-supported industries. The comparison revealed three points. The first finding is about the terminology used in ECM and DCM. Although the two types of change management use different terminology, they follow almost the same logic. For instance, the terms “engineering change” and “design change” (or their synonyms) refer to the same types of changes with similar characteristics. On the other hand, we extracted and compared two sample processes, one for ECM and one for DCM. The two processes were found to be quite similar but have some differences, such as in the approval phase, which may be because of the nature of BIM- and PLM-supported industries. It is important to mention that the literature lacks information on some parts of the processes such as documentation and versioning. Lastly, the proposed

ECM and DCM methods and tools investigated illustrate that considerable attention is paid to automating ECM and DCM processes by offering various tools and methods. Needless to say, most of the methods and tools investigated remained proposals and never became commercial applications.

However, these similarities and differences could be a starting point for identifying potential characteristics and functionalities for cross-pollination between BIM and PLM.

The next step of this research project is to investigate and compare ECM and DCM processes in a practical study in BIM- and PLM-supported industries. This future work will enable us compare the differences between the theoretical study and the real practice of ECM and DCM.

CHAPTER 5

ARTICLE 2—DESIGN CHANGE MANAGEMENT IN CONSTRUCTION INDUSTRY: COMPARING THEORY AND PRACTICE

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5.1 Abstract

Design change (DC) refers to any type of design or construction alteration made after a contract is awarded. DCs are dynamic in nature and omnipresent in a project, and can be requested by any stakeholder. DCs are usually managed in accordance with a change management process. A variety of research studies propose different design change management (DCM) processes. However, there are differences between the DCM processes proposed in the literature and those used in practice. This article aims to compare the DCM processes and tools that are used in theory and in practice. The DCM process descriptions provided in this research study were extracted from DCM processes used in practice. In this research study, we examine three case studies and extract the DCM processes followed, including the terminology and tools used, and the activities performed. These case studies are compared with the findings of theoretical studies of DCM in the construction industry from the literature. The comparison considers three aspects (1) DCM terminology, (2) DCM processes and activities, and (3) DCM tools and their functionalities. Identifying similarities and differences between theoretical and practical DCM processes contributes to improve DCM in the construction industry and to provide a better understanding of construction practice in literature.

5.2 Introduction

The construction industry continues to grow by adopting new technologies, one of the most important of which is building information modeling (BIM). In recent decades, BIM has proven itself to be invaluable in the construction industry (Sacks et al., 2018). It offers virtual support for design and construction as well as the management systems needed for operations and maintenance (Jupp and Singh, 2016). Implementing BIM in design and construction can help to improve cost control and time management (Cheutet et al., 2018).

BIM is implemented in construction projects to improve the flow of information throughout a building’s lifecycle by using highly reliable data from virtual construction components that represent their physical counterparts as faithfully as possible (Holzer, 2014). Therefore, BIM is an approach that facilitates multidisciplinary collaboration and information management among project stakeholders (Jupp, 2013).

Changes are inevitable in the construction industry, and they can be requested in any phase of a project by any stakeholder for any reason. Changes can have impacts on various elements of a project and in turn increase the cost and the time frame of the project. Therefore, changes are a very significant uncertainty that should be managed using an effective management process.

A design change (DC) is a type of technical change that is encountered in the construction industry (Abdul-Rahman et al., 2015; Alwi et al., 2002; Burati Jr et al., 1992; Mejlænder-Larsen, 2017; Mohamad et al., 2012; Suleiman and Luvara, 2016). It has been defined as “any change in the design or construction of a project after the contract is awarded” (Mohamad et al., 2012). It is also known as an engineering change (Erdogan et al., 2005; Fleurent, 2013; Pan and Chen, 2015), construction change (Hao et al., 2008; Hwang and Low, 2012; Motawa et al., 2007), design deviation (Burati Jr et al., 1992) or engineering design change (Mohamad et al., 2012).

It is worth highlighting that while there are similarities between design change in the construction industry and engineering change (Jarratt et al., 2011) in manufacturing (Pourzarei et al., 2022), this article will specifically address how to manage design change in the context of the construction industry.

A DC is disruptive (Hao et al., 2008; Pourzarei et al., 2022) and usually leads to rework, which increases the cost of a project (Sun et al., 2006; Sun and Meng, 2009). This increase can sometimes be around 10% to 15% of the value of the contract (Burati Jr et al., 1992; Sun et al., 2006; Sun and Meng, 2009); however, having an effective design change management (DCM) process in place can help to reduce this amount (Pourzarei et al., 2022). A variety of research studies propose different DCM processes (CII., 1994; Fleurent, 2013; Hao et al., 2008; Hwang and Low, 2012; Ibbs et al., 2001; Mejlænder-Larsen, 2017; Motawa et al., 2007; Pourzarei et al., 2022; Sun et al., 2006; Voropajev, 1998). In (Pourzarei et al., 2022), DCM methods and tools are classified into four categories: 1) manage propagations / impact analysis; 2) assist with decision-making; 3) propose a new framework/model/interface, and 4) develop a prediction tool. In addition, some research studies analyze the visualization of commercially available BIM-based DCM tools (Juszczyk et al., 2016) such as BIMestiMate.

However, there are differences between what is proposed in the scientific literature and what is used in the industry. Therefore, this article focuses on the following research question: to what extent do the design change management practices implemented in the construction industry align with or differ from theoretical descriptions from literature? This article investigates the practice of the construction industry through three case studies to identify similarities and differences between what is used in theory and in practice that could lead to increasing productivity.

The analysis will identify which characteristics and functionalities are currently being utilized in real-world project. The comparison between theory and practice will reveal both their similarities and differences. The differences may provide insights to improving real-world practices and highlight limitations in theoretical descriptions of these practices.

It should be noted that we use the DCM process descriptions proposed in our previous research study (Pourzarei et al., 2022) for the processes used in theory. The DCM processes used in practice were extracted from three case studies of projects carried out by two construction companies that use BIM. The results of our investigation and documentation of DCM terminology, processes, and software functionalities are presented for all three case studies. Finally, we compare the descriptions of the DCM processes used in theory and in practice. Hence, this research study achieves the following objectives:

1. Explore, document, and compare three DCM processes and their tools used in practice in the construction industry.
2. Identify similarities and differences between these DCM processes and tools that are used in practice in the construction industry with those said to be used in theory.

This article is broken down into seven sections. Section 5.3 presents the research methodology. Section 5.4 presents the results of the case studies. Section 5.5 presents the comparison of the DCM processes used in theory and in practice in the construction industry. Section 5.6 discusses the findings. Section 5.7 concludes the article and outlines future work.

5.3 Research Methodology

This article aims to compare the DCM processes and tools that are used in theory and in practice in the construction industry. In our previous research (Pourzarei et al., 2022), DCM processes were investigated by means of a theoretical study. Now, we investigate and document the DCM processes that are used in practice in the construction industry. To do this, we examined and extracted a description of the DCM processes used in three case studies. We documented, analyzed, and compared the extracted processes. Finally, we compared the DCM processes from the case studies with those used in theory.

The first step was to identify construction companies that have a formalized DCM process in place. We identified some local and international companies as potential construction partners and then filtered them based on various criteria. The main criteria were the company's interest in collaborating with the university, our ability to contact the top-level management, and the availability of their person responsible for DCM. After evaluating the potential partners we identified, we chose two construction companies, one based in Canada and the other based in France, to be our industrial partners and provide us with case studies.

Next, since the DCM process can vary from one project to another, we asked each partner to describe the DCM process used in a project of theirs that was representative of their usual practice. Three projects, project A and project B with the Canadian partner and project C with the French partner, were selected as case studies from among a variety of projects proposed by our partners. Two projects (A and B) belonging to the Canadian partner were documented because a change in role, project manager in project A vs. construction manager in project B, resulted in different DCM processes being followed.

We collaborated with our partners strictly through online meetings because of the COVID-19 pandemic. In total, we had 7 meetings with our Canadian industrial partner and 6 meetings with our French industrial partner to document and analyze the three projects studied. The average length of each meeting was about one hour and thirty minutes. The meeting included interviewing the experts to both document and validate the DCM processes we extracted.

To complement the information obtained during these meetings, we studied and analyzed different project documents, including written communications (emails), contracts, project descriptions, change orders, change requests, and Canadian Construction Documents Committee (CCDC) standards[4].

We used Business Process Model and Notation (BPMN) to model a process for each project that includes the following elements:

1. The activities involved.
2. The flow and types of documents.
3. The tools used.
4. The roles and titles of the participants.

Our BPMN models were presented to the members of the relevant industrial partner's project team for validation.

Next, we created a "metamodel" to organize the information and be able to compare the processes. That metamodel enabled us to organize the elements of the DCM process descriptions into the following three categories:

1. The DCM process stages and activities.

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[4] https://www.ccdc.org/

2. The tools used and their functionalities.
3. The terminology used.

In the final step, we compared the information from the metamodel with the findings of our previously conducted theoretical study (Pourzarei et al., 2022) on the basis of the above three categories.

The three case studies are presented in the following section.

5.4 The Case Studies

This section presents the case studies. It begins by describing our industrial partners, continues by presenting the terminology and IT tools used in the projects examined, and wraps up by outlining the processes used in the cases studied.

5.4.1 The Industrial Partners

Our first industrial partner is a Canadian company located in Montreal, Quebec. It provides various services including project management. Two of its building projects (projects A and B) were selected to be used as case studies for our research. Both projects are private projects and in the final stages of completion. One of the main differences between these two projects is that project B is much bigger than project A, and its documentation is similar to the documentation used in public projects.

Due to confidentiality concerns, some information about the projects cannot be disclosed. However, it is worth mentioning that projects A and B were selected because the company held different roles in them (project manager in project A vs. construction manager in project B), which led to different DCM processes being followed. The project manager and the construction manager have different responsibilities, with the latter having broader oversight of the project. Our partner fulfilled a client consultation role as project manager in project A, whereas it had more responsibilities as construction manager in project B.

Our second industrial partner is a French construction company located in France that provides building, infrastructure, and construction services. Project C was proposed by our French partner in response to our request for a project that has a general DCM process. In project C, our industrial partner's role was the general contractor.

5.4.2 Terminology

All three case studies used similar terminology, with the exception of a few words that were different. In addition, our industrial partners used French terminology, which we have mapped to English terminology in this article. Table 5.1 presents the terminology.

Table 5.1 Terminology used in the case studies

Term used	**Description**	**Project A**	**Project B**	**Project C**
Design Change Request (DCR)	"[A] change to original plans, specifications or other contract documents, as well as a change in cost" (Mejlænder-Larsen, 2017).	DCR	DCR	DCR
Request For Information (RFI)	"A request for information (RFI) is a formal written procedure initiated by contractor seeking additional information or clarification for issues related to design, construction, and other contract documents" (Hanna et al., 2012).	RFI	RFI	-
Construction Change Directive (CCD)	"Construction change directive is a written order prepared by the Architect and signed by the Owner and the Architect, directing a change in the Work prior to agreement on adjustment, if any, in the contract sum or contract time, both" (Yayla and Tas, 2010).	CCD	CCD	Instruction List
Amendment	"Amendments are official changes made to the contents of an agreement. Such changes can take the form of addition, subtraction, omission, and renewal of the contents of the contract and agreed by both parties" (Fertilia and Ayuningtias, 2020).	Contract Modification	Amendment	Service/Work Order

A problem or issue is a technical problem or need that can be raised by anyone involved in the project and most often results in either a Design Change Request (DCR) or a Request For Information (RFI). In projects A and B, an issue is submitted as a DCR if it is raised by the client, the construction manager, or the project manager, and an RFI if it is raised by the general contractor or a sub-contractor. However, in project C, all requests are submitted as DCRs.

In addition, a request for information (RFI) is a formal process that is used to ask and address technical questions and can lead to the initiation of a DC. In other words, the need for a DC can emerge from the responses to / clarification of an RFI, in which case a DCR is issued.

A construction change directive (CCD) is the instructions/solution proposed by professionals for a requested DC when no agreement has been reached on cost (Hao et al., 2008). In project C the term “instruction list” was used for this. Both terms, however, refer to the same concept, which is proposing instructions / a solution. To facilitate the reader’s understanding of the DCM process descriptions, the term “CCD” is used throughout the remainder of this article.

The terms “contract modification”, “amendment”, and “service/work order” refer to similar concepts. The main reason why different terms are used in projects A and B is that project B is more complex than project A and quite similar to a public project, and it therefore uses the terms (e.g., amendment) that are proposed by the standards (e.g., those of the CCDC). Contract modifications and amendments are called “change orders” in some construction projects though (De Silva et al., 2017). Moreover, project C used yet another term: “service/work order”. In the remainder of this article, the term “amendment” is used for all projects to facilitate the reader’s understanding of the DCM process descriptions.

Although the terms used in projects A, B, and C were initially French, we mapped them to corresponding English terms. It should be noted that these terms can vary by country, language, etc. It is also important to note that the aforementioned terms from projects A, B, and C are not *all* the terms and vocabulary used. We chose to review these terms here because they are key elements in the DCM processes described.

5.4.3 IT Tools

IT tools play an important role in DCM processes. In this section, we present the IT tools that were used in the aforementioned projects as well as their functionalities/characteristics. They are summarized in Table 5.2.

Table 5.2 The IT tools used in the case studies and their functionalities

Tool used	**Project A**	**Project B**	**Project C**
MS suite tools (e.g., Word, Excel)	✓ Mainly submitting forms (RFIs, CCDs, and amendments). ✓ Updating the status of CCDs. ✓ Updating the status of amendments.	✓ Mainly submitting forms (RFIs, CCDs, and amendments). ✓ Updating the status of CCDs. ✓ Updating the status of amendments.	✓ Mainly submitting forms (CCDs and amendments).
Adobe Acrobat	✓ Finalizing forms that were initially created in Word. ✓ Adding mark-up to drawings. ✓ Modifying CCDs and amendments. ✓ Archiving communications (emails).	✓ Finalizing forms that were initially created in Word. ✓ Adding mark-up to drawings. ✓ Modifying CCDs and amendments. ✓ Archiving communications (emails).	✓ Finalizing forms that were initially created in Word. ✓ Adding mark-up to drawings. ✓ Modifying CCDs and amendments. ✓ Archiving communications (emails).
Email applications	✓ Transferring documents. ✓ Collaboration and communication between project team members, stakeholders, etc.	✓ Transferring documents. ✓ Collaboration and communication between project team members, stakeholders, etc.	✓ Transferring documents. ✓ Collaboration and communication between project team members, stakeholders, etc.
Cloud database	-	-	✓ Organizing, storing, modifying, sharing and reviewing documents.

Table 5.2 The IT tools used in the case studies and their functionalities (cont'd)

Tool used	Project A	Project B	Project C
SmartUse	-	✓ Sharing plans (architectural, mechanical, structural) with stakeholders (the construction manager, the general contractor, professionals, etc.). ✓ Sharing CCDs. ✓ Sharing instructions. ✓ Sharing shop drawings (mark-up drawings). ✓ Comparing versions. ✓ Adding photos to share project progress. ✓ Adding issues (in existing categories—mechanical, electrical, lighting fixtures, etc.—or new ones) by assigning people and adding priorities, due dates, costs, schedule impacts, etc. ✓ Creating Smart Links to other documents, files, etc.	-

As can be seen in Table 5.2, all three projects use MS suite tools, Adobe Acrobat, and email applications for almost the same tasks. The MS suite tools are used mainly for submitting forms. However, our Canadian industrial partner also used MS suite tools (e.g., Excel) to update the status of the project (e.g., the status of CCDs). Adobe Acrobat is used to finalize documents in .pdf format, add mark-up to drawings, modify documents such as CCDs (e.g., by adding signature), and archive communications (e.g., emails). Email applications are used for collaboration and communication in all three projects as well as to share documents.

The main difference between the projects is that SmartUse is used in project B and a cloud database is used in project C. SmartUse has various functionalities that facilitate the DCM process, including sharing a plan within the platform, marking up drawings, and comparing different versions of a document to identify the differences between them. Using a cloud database facilitates the organizing, storing, modifying, sharing, and reviewing of documents for stakeholders. It is worth highlighting that the Canadian company is using different processes and tools for projects A and B. The variable characteristics of projects and company's roles for each project would explain these differences.

5.4.4 Stages of a DCM Process

Although the processes used in projects A, B, and C to manage DCs have their differences, they follow the same stages. According to the research in (Pourzarei et al., 2022), managing DCs involves the following five stages:

1. Initiate
2. Evaluate
3. Document/Negotiate/Approve
4. Implement
5. Review and Analyze

We present and compare the DCM processes documented based on these stages. In the following sub-sections, we examine the DCM processes used one stage at a time and group the elements of their descriptions into two categories for comparison – activities and IT tools. "Activities" indicates the main activities involved in the stage in question. "IT tools" sets out the tools that are adopted and used in each project.

5.4.4.1 Initiate

This stage of the DCM process is when a need for a change is identified and a DC is requested. The characteristics of this stage are illustrated in Table 5.3.

Table 5.3 The characteristics of the first stage of the DCM process – Initiate

	Description	Project A	Project B	Project C
Activities	Identify needs (DCR/RFI)	✓ Identify needs, of which there are two types: (1) Request For Information (RFI), which comes from the general contractor or a sub-contractor, and (2) Design Change Request (DCR), which comes from the client or professionals.	✓ Identify needs, of which there are two types: (1) Request For Information (RFI), which comes from the construction manager, the general contractor, or a sub-contractor, and (2) Design Change Request (DCR), which comes from the client or professionals.	✓ Identify the need for a DCR: all needs are requested through DCRs.
	Create/submit a DCR/RFI	✓ Create/submit a DCR/RFI.	✓ Create/submit a DCR/RFI.	✓ Create/submit a DCR.
	Respond to the RFI	✓ Respond to the RFI to provide clarification.	✓ Respond to the RFI to provide clarification.	-
	Evaluate the DCR/RFI	✓ Evaluate the DCR. ✓ Evaluate the need to create a DCR from the RFI. ✓ Evaluate the response to the RFI.	✓ Evaluate the DCR. ✓ Evaluate the need to create a DCR from the RFI. ✓ Evaluate the response to the RFI.	-
	Update the status	-	✓ Update the table of RFIs being tracked.	-
	Make a decision on the DCR/RFI	✓ Accept it, reject it, or return it for review.	✓ Accept it, reject it, or return it for review.	-
IT tools	MS suite	✓	✓	✓
	Adobe Acrobat	✓	✓	✓
	Email applications	✓	✓	✓

Projects A and B have the same main activities at this stage with slight differences such as in updating the status of RFIs in the RFI tracking table in project B. The extra step on that project, of updating the status of process elements (e.g., the RFIs being tracked) might be because our partner is fulfilling the role of construction manager, who is responsible for following up on them.

Needs identification leads to two types of results in projects A and B – determining clarification will resolve the issue/problem identified (RFI) or a DC is needed (DCR) – whereas all needs are addressed by DCR in project C. In projects A and B, the RFI is a kind of technical request for clarification that is raised by the general contractor or a sub-contractor. The DCR is a direct request for a DC that is created by other stakeholders. The incorporation of RFIs resulted in there being some extra activities in projects A and B, such as responding to the RFI, evaluating the RFI, and making a decision on the RFI, while there were no such activities in project C. However, there was more attention paid to resolving needs that generate RFIs in project B, which resulted in there being an extra loop between the project's stakeholders (the construction manager, professionals, and the general contractor) to clarify an RFI. An RFI is either resolved by obtaining clarification from the professionals or transformed into a DCR. As mentioned, all requests for changes (from either the client or the general contractor) are documented as DCRs and transferred to the project manager in project C.

5.4.4.2 Evaluate

This stage is when a proposed DC is analyzed and evaluated, and a solution is put forward for it. The characteristics of this stage are illustrated in Table 5.4.

Table 5.4 The characteristics of the second stage of the DCM process – Evaluate

	Description	Project A	Project B	Project C
Activities	Evaluate the proposed change	-	✓ Evaluate whether a Design Change Request (DCR) influences the price/details of the contract.	✓ Evaluate the impact of the proposed DCR.
	Create/revise a Construction Change Directive (CCD)	✓ Generate a CCD (with photos and supplementary documents).	✓ Generate a CCD (with photos and supplementary documents).	✓ Generate a CCD (with photos and supplementary documents).
	Update the tracking table	✓ Update the table of CCDs being tracked.	✓ Update the table of CCDs being tracked.	-
	Evaluate the CCD	✓ Evaluate the CCD in terms of its impacts and consequences based on criteria (the contracts) and options (the rules).	✓ Evaluate the CCD in terms of its impacts and consequences based on criteria (the contracts) and options (the rules).	✓ Determine whether the CCD affects the technical plans.
	Make a decision on the CCD	✓ Accept it, reject it, or return it for review.	✓ Accept it, reject it, or return it for review.	-
	Update the mark-up drawings and relevant documents	✓ Update the mark-up drawings and relevant documents.	✓ Update the mark-up drawings and relevant documents in SmartUse.	✓ Update the mark-up drawings and relevant documents.
	Create supplementary instructions	-	✓ Create supplementary instructions.	-
	Assess the urgency of the CCD	✓ Assess the urgency of the CCD (urgent / not urgent).	✓ Assess the urgency of the CCD (urgent / not urgent).	-
	Notify the team(s)	✓ Notify the team(s) responsible for the CCD.	✓ Notify the team(s) responsible for the CCD.	✓ Notify the team(s) responsible for the CCD.
IT tools	MS suite	✓	✓	✓
	Adobe Acrobat	✓	✓	✓
	Email applications	✓	✓	✓
	Computer-aided design (CAD)	✓	✓	✓
	Cloud database	-	-	✓
	SmartUse	-	✓	-

This stage of the DCM process includes some common activities, such as creating a CCD that includes the requested change as well as a solution, evaluating the CCD, deciding whether or not to accept it, and assessing its urgency. The final tasks are to update the mark-up drawings and relevant documents, and notify the team(s). In all three projects studied, the CCD is the instructions/solution proposed by the professionals for a requested change. It should be mentioned that a CCD does not include agreement on the cost.

A difference in this stage is that the impacts of the proposed change are analyzed before creating the CCD in projects B and C. In project B, the impacts of a proposed change are evaluated to determine whether the change affects the price and/or details of the contract. If it does not, an instruction is given (by the professionals) to implement the change and there is no need to create a CCD. However, if it does, a CCD must be created. We can also see that our industrial partner is tasked with following up and updating the status of the process elements (the CCDs being tracked) in projects A and B, which, as mentioned above, might be because of the role it fulfills in those projects (project manager and construction manager, respectively). All documents (e.g., markup drawings, new versions created) are updated at this stage in all three projects; however, SmartUse helps to facilitate this activity in project B. In addition, in projects A and B, the urgency for the CCD is assessed in this stage, whereas in project C, this assessment is done in the next stage. The final activity in this stage is to inform the team(s) responsible for the CCD. Again, it is important to mention that the type of contract and the company's role in the project can lead to some differences in the activities involved in the DCM process.

In terms of the IT tools used, the SmartUse application, which facilitates tasks such as updating documents and granting all stakeholders access to documents, is used in project B. SmartUse also enables the project team to do more, such as compare versions and track assigned activities. A cloud database, which also facilitates document storage, sharing, and access, is used in project C.

5.4.4.3 Document/Negotiate/Approve

Next, the solution proposed for the DC undergoes an approval process. The approval process can vary depending on the nature of the contract and the project. There may be a different number of participants involved if the project is private versus public, and the approval process might be simple if the DC is not very complex.

The characteristics of this stage are presented in Table 5.5.

Table 5.5 The characteristics of the third stage of the DCM process – Document/Negotiate/Approve

	Description	**Project A**	**Project B**	**Project C**
Activities	Assess the urgency of the proposed change	-	-	✓ Assess the urgency of the CCD (urgent / not urgent).
	Evaluate the CCD	✓ Evaluate the CCD and related tasks.	✓ Evaluate the CCD and related tasks.	✓ Evaluate the CCD and related tasks.
	Create/revise the bids	-	✓ Create/revise (clarify) the bids.	✓ Create/revise (clarify) the bids.
	Create/revise the amendment	✓ Create/revise the amendment.	✓ Create/revise the amendment.	✓ Create/revise the amendment.
	Evaluate the proposed bids	-	✓ Evaluate the proposed bids.	✓ Evaluate the proposed bids.
	Evaluate the amendment	✓ Assess the amendment from a contractual and a technical perspective.	✓ Assess the amendment from a contractual and a technical perspective.	✓ Assess the amendment from a contractual and a technical perspective.
	Approve the bids	-	✓ Accept them, reject them, or return them for review.	✓ Accept them, reject them, or return them for review.
	Make a decision on the amendment	✓ Accept it, reject it, or return it for review.	✓ Accept it, reject it, or return it for review.	✓ Accept it, reject it, or return it for review.
	Update the tracking table / record the decision	✓ Update the table of CCDs being tracked.	✓ Update the table of CCDs being tracked. ✓ Update the table of amendments being tracked.	✓ Record the decision.

Table 5.5 The characteristics of the third stage of the DCM process – Document/Negotiate/Approve (cont'd)

	Description	Project A	Project B	Project C
	Update the tracking table / record the decision	✓ Update the table of CCDs being tracked.	✓ Update the table of CCDs being tracked. ✓ Update the table of amendments being tracked.	✓ Record the decision.
	Resolve any conflicts	✓ In the event there is a conflict, it is handed over to a third party (e.g., an external judge).	✓ In the event there is a conflict, it is handed over to a third party (e.g., an external judge).	-
IT tools	MS suite	✓	✓	✓
	Adobe Acrobat	✓	✓	✓
	Email applications	✓	✓	✓
	Cloud database	-	-	✓
	SmartUse	-	✓	-

First, as mentioned in the previous stage, assessing the urgency of the CCD is done in this stage for project C. In this stage, the main activities include the general contractor and sub-contractor(s) (if any) evaluating CCD and the tasks involved in implementing the proposed change and then proposing bids / an amendment. The proposed bids/amendment are evaluated by the person responsible for doing so, which is different in each of the projects studied. In all three projects, the project/construction manager analyze the bids/amendment from a contractual perspective and the professionals do so from a technical perspective. The client decides whether to accept the amendment, reject it, or return it for review based on technical or contractual recommendations. If there are any conflicts in this stage that stakeholders are not able to resolve, they are handed over to a third party, who should be identified in the contract. Although this activity was not mentioned for project C, a similar conflict resolution activity might be provided for in it. Finally, all the documents are updated, follow-ups are performed, and all decisions are recorded in this stage.

One of the most important activities in this stage is stakeholder negotiation before the proposed change is implemented. In addition, it should be mentioned that if the CCD is considered urgent it is implemented before the approval stage, once it has been approved by the team responsible for doing so (e.g., the professionals).

Like in the Evaluate stage, in project B, SmartUse gives those involved in this stage more options, such as the ability to compare different versions of drawings and share documents with other stakeholders. In addition, in project C, stakeholders can use the cloud database to share and store documents.

5.4.4.4 Implement

In this stage of the DCM process, the requested change is implemented based on the implementation instructions.

The characteristics of this stage are presented in Table 5.6.

Table 5.6 The characteristics of the fourth stage of the DCM process – Implement

	Description	Project A	Project B	Project C
Activities	Release the CCD / amendment / supplementary instruction	✓ The latest version of the documents is released for implementation.	✓ The latest version of the documents is released for implementation.	✓ The latest version of the documents is released for implementation.
	Notify teams of the CCD / supplementary instruction	✓ Notify teams.	✓ Notify teams.	✓ Notify teams.
	Implement the CCD / supplementary instruction	✓ Implement the requested change based on the implementation instructions.	✓ Implement the requested change based on the implementation instructions.	✓ Implement the requested change based on the implementation instructions.
	Monitor and track implementation	✓ Monitor and track implementation	✓ Monitor and track implementation	✓ Monitor and track implementation.

Table 5.6 The characteristics of the fourth stage of the DCM process – Implement (cont'd)

	Description	**Project A**	**Project B**	**Project C**
IT tools	MS suite	✓	✓	✓
	Adobe Acrobat	✓	✓	✓
	Email applications	✓	✓	✓
	Cloud database	-	-	✓
	SmartUse	-	✓	-

In the Implement stage, the requested change is implemented based on the implementation instructions proposed by professionals. The general contractor and sub-contractor(s) (if any) are granted access to the latest version of the documents (e.g., CCD, amendment) to implement the proposed change. SmartUse and the cloud database are used in projects B and C, respectively, to make it easier for stakeholders to access the documents. In addition, the construction/project manager as well as the general contractor are responsible for monitoring and tracking implementation.

5.4.4.5 Review and Analyze

In general, the sample DCM process includes a final stage in which the change that was implemented is investigated in the interest of extracting lessons learned (Pourzarei et al., 2022). Interestingly, this stage is not considered in projects A, B, or C.

In the end, it is important to note that the order of the DCM process stages could differ from what is mentioned above depending on the urgency of a change and whether or not a change impacts the price/details of the contract. There are two possible scenarios[5] in projects A and C,

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[5] "Scenario" is used here to mean that the stages of the DCM process could vary based on various project-specific factors.

and three in project B, that would change the order of the stages. For instance, in project A, a change is implemented before it reaches the approval stage if it is considered urgent. Note that we *didn't* map these scenarios in this article (we considered only the standard processes), though they are included in the BPMN model of each project's DCM process. The BPMN models are attached in the appendix I and illustrate the DCM processes in their entirety.

5.5 Comparative Analysis of the DCM Processes Used in Theory and Practice

In this section, we compare the DCM processes we extracted from our case studies with the DCM process we extracted from the theoretical review we completed in a previous research study (Pourzarei et al., 2022). This section is broken down into three sub-sections. First, we compare the DCM terminology used in practice and proposed in theory. Then, we compare the DCM processes identified by stage and activity. Lastly, we compare the tools used in the DCM processes and their functionalities.

5.5.1 Comparison of the Terminology Used

In this section, we compare the most important terms used in the DCM processes extracted from the literature and from our case studies. The comparison is summarized in Table 5.7.

Table 5.7 Comparison of the terminology used in theory and in practice

Term used in the literature	**Term used in Project A**	**Term used in Project B**	**Term used in Project C**
Design Change Request (DCR) (Mejlænder-Larsen, 2017)	Design Change Request (DCR)	Design Change Request (DCR)	Design Change Request (DCR)
Request For Information (RFI) (Hanna et al., 2012)	Request For Information (RFI)	Request For Information (RFI)	-
Construction Change Directive (CCD) (Hao et al., 2008; Yayla and Tas, 2010)	Construction Change Directive (CCD)	Construction Change Directive (CCD)	Instruction List
Proposal Change Order / Change Order (Hao et al., 2008)	Contract Modification	Amendment	Service/Work Order

As mentioned above, our industrial partners used French terminology, which we mapped to existing English terminology. This may partly explain some similarities between the theoretical terminology and the practical terminology. The first two terms (DCR and RFI) are common to the literature and the case studies considering that RFI is not used in project C. Although "instruction list" is used in project C instead of CCD as in projects A and B, it is conceptually the same as CCD. So, CCD can be considered a common term used in theory and in practice. Last but not least, although the terminology differs when it comes to contract modification, amendment, service/work order, and proposal change order / change order, all these terms refer to the same concept – a change order. In our context, the term "change order" refers to "changes that are generated by unanticipated causes, for example, scope changes from the owner, design/technological changes from the architect, and cost/time changes arising from supplier problems or unsatisfactory site conditions" (Hao et al., 2008).

5.5.2 Comparison of the DCM Processes Used by Stage and Activity

There are various activities involved in a DCM process. This section compares the DCM processes used in theory and in practice to identify similarities and differences between them. We break down our comparison of the DCM processes studied into the same five stages (Pourzarei et al., 2022) identified in Section 5.4.4.

A list of activities is presented in each stage. These activities were extracted from three sources: the DCM processes that are presented in the literature, those that are proposed in our previous research study (Pourzarei et al., 2022), and those that are presented in the previous section (our three case studies). It is interesting to note that the DCM processes reported by practitioners in the case studies feature more detailed activities than the DCM processes in scientific literature do. We extracted a list of activities that are playing important roles (e.g. evaluation and approval activities) in the DCM process. Then, we identified whether they are part of the DCM processes used in theory and in practice to compare the processes considered. Again, it is important to note that we present only the activities that are the most important to / cited in DCM processes, and not all possible DCM activities.

5.5.2.1 Initiate

Table 5.8 presents the activities that belong to the first stage of each of the DCM processes considered.

Table 5.8 Comparison of the activities in the first stage – Initiate

Activity	**Theoretical studies**	**Project A**	**Project B**	**Project C**
Identify potential changes (based on a set of proactive rules)	✓	-	-	-
Receive needs for change (Request For Information, Design Change Requests)	✓	✓	✓	✓
Create/revise a Design Change Request / Request For Information	✓	✓	✓	✓
Evaluate the request	✓	✓	✓	-
Submit the Design Change Request	✓	✓	✓	✓

As can be seen in the above table, identifying potential changes is not included in the DCM processes used by practitioners in projects A, B, and C. This may be because the project/construction manager does not want to budget for a change that has not yet been deemed necessary. According to literature, doing so could help to avoid cost overruns in subsequent stages of a project.

Other activities in this stage, such as receiving needs for change, creating/revising a request, and submitting a DCR, are the same across the board and needs for change can be raised by all stakeholders. It should be noted that evaluating the request may or may not be included depending on the nature of the contract and the project. For instance, in project C, there is no need to perform an evaluation in the first stage; evaluation is done in later stages.

5.5.2.2 Evaluate

This stage generally involves evaluating a proposed change and developing solutions for it. However, some specific activities can differ from one project to the next. Table 5.9 presents the activities that are in the second stage of each of the DCM processes.

Table 5.9 Comparison of the activities in the second stage – Evaluate

Activity	**Theoretical studies**	**Project A**	**Project B**	**Project C**
Evaluate the proposed change	✓	-	✓	✓
Create/revise a Construction Change Directive / solutions	✓	✓	✓	✓
Evaluate the Construction Change Directive / solutions	✓	✓	✓	✓
Approve the Construction Change Directive / a solution	✓	✓	✓	-
Update mark-up drawings and documents	-	✓	✓	✓
Create supplementary instructions	-	-	✓	-
Notify the team	✓	✓	✓	✓
Assess the urgency of the Construction Change Directive	-	✓	✓	-

According to the above table, evaluating the proposed change, creating/revising a CCD / solutions, evaluating them, and approving one of them are performed both in theory and in practice. Updating documents and assessing the urgency of the CCD are performed only in practice (but not in project C). This may be because the DCM processes used in practice are more detailed than the DCM processes described in the literature. However, as mentioned earlier, project B includes an extra loop to determine whether a requested change influences the price/details of the contract before creating the CCD and instructions. Creating supplementary instructions can be incorporated or omitted depending on the company's needs.

5.5.2.3 Document/Negotiate/Approve

The main focus in this stage of the DCM process is to negotiate (revise/evaluate) and approve a bid/amendment. It is important to mention that private projects (projects A and C) and public projects (project B) can have different approval processes depending on the stakeholders involved. Table 5.10 presents the activities that belong to the third stage of each of the DCM processes.

Table 5.10 Comparison of the activities in the third stage – Document/Negotiate/Approve

Activity	**Theoretical studies**	**Project A**	**Project B**	**Project C**
Assess the urgency of the Construction Change Directive	-	-	-	✓
Create/revise an amendment	-	✓	✓	✓
Create/revise bids	-	-	✓	✓
Confirm proposed instruction (evaluation) and evaluate the Construction Change Directive / bids	✓	✓	✓	✓
Evaluate the amendment from a contractual and a technical perspective	-	✓	✓	✓
Approve the proposed solution / amendment	✓	✓	✓	✓
Obtain the client's approval	✓	✓	✓	✓
Update and issue the mark-up drawings, Construction Change Directive, amendment, etc.	✓	✓	✓	✓
Record decisions	✓	✓	✓	✓
Resolve any conflicts	-	✓	✓	-

As mentioned earlier, assessing the urgency of the CCD also occurs in project C, but in this stage instead. However, some of the activities that are part of the DCM processes used in practice, such as creating an amendment and resolving conflicts, are not mentioned in the theoretical studies. This may be because the DCM processes used in practice are more detailed than the ones described in the literature.

Some activities, such as updating documents, obtaining the client's approval, and recording decisions are common to all the DCM processes considered.

5.5.2.4 Implement

In this stage, all the main tasks, including releasing the instructions, implementing the change and monitoring implementation, are performed both in theory and in practice. Table 5.11 presents the activities that are in the fourth stage of each of the DCM processes.

Table 5.11 Comparison of the activities in the fourth stage – Implement

Activity	**Theoretical studies**	**Project A**	**Project B**	**Project C**
Release the CCD / supplementary instructions / Design Change Notice for implementation	✓	✓	✓	✓
Notify teams that the CCD / supplementary instructions / Design Change Notice has been released	✓	✓	✓	✓
Implement the CCD / supplementary instructions / Design Change Notice based on the instructions	✓	✓	✓	✓
Monitor and track implementation	✓	✓	✓	✓

5.5.2.5 Review and Analyze

Last but not least, in this stage, there are significant differences between the activities included in the DCM processes used in theory and in practice. Table 5.12 presents the activities that are in the fifth (and final) stage of each of the DCM processes. Our comparison of the DCM processes extracted from the case studies and the literature reveals that the only activity that is common to all the processes considered is to follow up on the implementation results. We observe that there is more interest in using lessons learned in the literature, which is why performing a root cause evaluation, updating databases, and updating affected deliverables are incorporated in the theoretical studies. Of course, some construction companies might already be recording lessons learned, which would help them to better prepare their team (in the first stage of their DCM process) and have a better plan to identify potential changes.

Table 5.12 Comparison of the activities in the fifth stage – Review and Analyze

Activity	**Theoretical studies**	**Project A**	**Project B**	**Project C**
Follow up on the implementation results	✓	✓	✓	✓
Perform a root cause evaluation (post-change evaluation)	✓	-	-	-
Record lessons learned throughout the project's lifecycle	✓	-	-	-
Update databases (post-change information)	✓	-	-	-
Update the deliverables that are affected by the change	✓	-	-	-

5.5.3 Comparison of the Tools and Functionalities Used

Tools play an important role in the DCM process when it comes to controlling and managing DCs. In this section, we compare the tools that are proposed in the literature (Pourzarei et al., 2022) and used in the cases studied. We broke down the DCM processes into three phases – pre-change, mid-change, and post-change (Hamraz, 2013) – to do so. Table 5.13 presents the tools and functionalities used in theory and in practice in the DCM processes considered.

Table 5.13 Comparison of the functionalities and tools used in the DCM processes

Phase	**Theoretical studies**	**Project A**	**Project B**	**Project C**
Pre-change	✓ Prediction tools (Motawa et al., 2007; Sun et al., 2006; Taghi Zadeh, 2016; Zhao et al., 2010). ✓ Process automatization (Isaac and Navon, 2008; Koch and Firmenich, 2011; Lee, 2006). ✓ A platform (website) for communication (Lee, 2006).	✓ Filling out forms (MS suite). ✓ Transferring documents and communications (email applications and phone calls). ✓ Tracking tasks (MS suite).	✓ Filling out forms (MS suite). ✓ Transferring documents and communications (email applications and phone calls). ✓ Tracking tasks (MS suite).	✓ Filling out forms (MS suite). ✓ Transferring documents and communications (email applications and phone calls).
Mid-change	✓ Dynamic planning (Mokhtar et al., 2000; Motawa et al., 2007; Sun et al., 2006). ✓ Impact analysis (Hindmarch et al., 2010; Lee et al., 2004; Lee, 2006; Mejlænder-Larsen, 2017; Moselhi et al., 2005; Motawa et al., 2007; Zhao et al., 2010). ✓ A platform (website) for communication (Khanzadi et al., 2018). ✓ Process automatization (Isaac and Navon, 2008; Koch and Firmenich, 2011; Lee, 2006). ✓ Tracking the requirements of a change (Isaac and Navon, 2008; Koch and Firmenich, 2011). ✓ Assisting with decision-making (Khanzadi et al., 2018; Lee et al., 2004; Lee, 2006; Liu et al., 2014; Moselhi et al., 2005; Motawa et al., 2007; Zhao et al., 2010).	✓ Adding mark-up drawings (Adobe Acrobat). ✓ Following up on tasks (MS suite). ✓ Transferring documents and communications (email applications and phone calls).	✓ Adding mark-up drawings (Adobe Acrobat and SmartUse). ✓ Following up on tasks (MS suite). ✓ Transferring documents and communications (email applications and phone calls). ✓ Sharing access to documents (SmartUse). ✓ Tracking the requirements of a change (SmartUse). ✓ Version control – comparing versions (SmartUse).	✓ Adding mark-up drawings (Adobe Acrobat). ✓ Transferring documents and communications (email applications, phone calls, and cloud database). ✓ Sharing access to documents (cloud database).

Table 5.13 Comparison of the functionalities and tools used in the DCM processes (cont'd)

Phase	Theoretical studies	Project A	Project B	Project C
Post-change	✓ Process automatization (Isaac and Navon, 2008; Koch and Firmenich, 2011; Lee, 2006). ✓ A platform (website) for communication (Lee, 2006). ✓ Recording lessons learned (Khanzadi et al., 2018; Mokhtar et al., 2000).	-	-	-

The pre-change phase includes two important parts: when the DCR is submitted and when the project team looks to identify potential changes based on pre-defined criteria. The mid-change phase covers the processing of a change through its implementation, including its evaluation and approval. The post-change phase includes the previously mentioned Review and Analyze stage as well as the recording of lessons learned.

In the pre-change phase, prediction tools that are intended to identify potential changes are mentioned only in the theoretical studies, not in the three cases studied. On the other hand, documents always need to be submitted and transferred, and information always needs to be communicated. According to the above table, the theoretical studies illustrate that there are some proposals for this aim. In projects A, B, and C, these aspects are done the old-fashioned way using MS suite, email applications, and phone calls. However, interestingly, project B begins to facilitate the process using SmartUse.

In the mid-change phase, despite the fact that project B uses SmartUse as a collaborative platform to facilitate DCM and tries to have a paperless process, there is less interest in automatizing the process in practice than in theory. For instance, impact analysis or the evaluation of a proposed change is done based on available knowledge in practice, whereas it can be done a variety of ways based on lessons learned in theory. It is interesting to note that some research studies (Liu et al., 2014) propose a DCM framework that can be integrated in

BIM. In addition, the cloud database that is used in project C led to facilitate the sharing of documents and the granting of document access to stakeholders.

There is nothing to report in terms of the tools and functionalities used in practice in the post-change stage, since none of our three case studies mentioned such a step. This may indicate that there is no strong interest in recording lessons learned and signal the gap in process automatization. In the theoretical studies, on the other hand, there are various works interested in automatizing DCM, using an interactive platform for communication, and recording lessons learned. This could suggest that the scientific literature is ahead of practice as various ideas are proposed that are not implemented in the real world.

5.6 Discussion

According to the scientific literature, design changes can lead to cost overruns and delays. They therefore need to be identified and managed through a DCM process. DCM is an important practice in the construction industry and incorporates terminology, documents, stages, activities, and IT tools. In our previous research study (Pourzarei et al., 2022), DCM processes were investigated by means of a theoretical study. In this study, we aimed to investigate and document sample DCM processes that are used in practice in the construction industry and compare the DCM processes and tools extracted from our case studies with those proposed in the scientific literature.

5.6.1 DCM Process

This study documented and compared sample DCM processes used in three private projects from two industrial partners in order to compare the DCM processes in theory and practice. The findings revealed that while there is no uniform terminology for DCM, the DCM processes used in theory and in practice incorporate almost the same stages and activities.

As expected, this research has revealed variations in the implementation of the DCM process between theory and practice. What is particularly noteworthy is the differences that exist between specific projects. For instance, here are two examples of design changes that may be handled differently in the analyzed projects. The first example concerns a request to change the color of a wall, which could be raised by any stakeholder. In projects B and C, this request would undergo a non-urgent process that involves evaluation by professionals, the client, the project manager, and the general contractor, as well as a discussion of price and other details before implementation. However, in project B, if the request does not affect the price or the contract details, a supplementary instruction will be created and sent to the general contractor and any sub-contractors for implementation and there will be no need to follow the complete DCM process. On the other hand, for a more complex request, such as removing all the ceiling evaporators in the apartments and replacing them with wall heads, almost the same process would be followed in all three projects. After the request is raised, professionals or the responsible department would evaluate it and propose a solution, followed by negotiation and agreement on the bid before implementation of the requested change. Hence, the main difference will be the level of detail of the DCM process, not the stages. In other terms, the evaluation, approval, and negotiation activities could be less or more complex based on the differences in the change complexity as well as the number of stakeholders.

In addition, the DCM processes used in the theory and in practice could also vary from one project to the next depending on the role of the company and the nature of the contract. For instance, in the case studies, one company managed projects A and B with distinct roles as project manager and construction manager, respectively. These role differences resulted in varying responsibilities and decision-making powers for the company. As the project manager in project A, the company consulted with the client, whereas in project B, assuming greater responsibilities and control over the DCM process, such as deciding to create supplementary instructions for changes.

Extracting the aforementioned differences in the DCM processes from just theory may not be feasible due to the low level of detail presented in theory, however this research was still able to pinpoint the aforementioned differences and they may be considered the added values of this research.

5.6.2 DCM Tools

This study found that while the construction industry is still using paper copies (hard copies) of documents, collaborative platforms, such as SmartUse and a cloud database, are becoming more commonly used in some of the projects studied. However, the platforms were not used in all projects or by all stakeholders. This study suggests that interest exists in facilitating the DCM process through the use of collaborative platforms, especially in the mid-change stage, for instance, sharing access to documents, tracking the requirements of a change, and version control. While this study does not propose a specific collaborative platform, we find that the use of any such platform is important. In the future, studying the benefits or more specific platforms would be useful.

Moreover, while the study investigated the DCM tools used in the sample projects, we acknowledge that many other applications are used in other construction companies. Indeed, commercial applications, such as Vico, Navisworks, Innovaya, BIMestiMate, Synchro, and Assemble, offer interesting functionalities for comparing models, analyzing impacts on costs and scheduling, and tracking changes.

Although it seems that the theory is more sophisticated compared to the practice of using tools for the DCM process that could be used for dynamic planning, impact analysis, assistance in decision-making, etc., still, in practice, stakeholders showed a great interest in using these tools. Therefore, this study suggests that more investigation of DCM tools and their functionalities is needed, to make better use of theory being transferred to practice.

5.7 Conclusion

Design changes are one of the most commonly encountered changes in construction projects and usually lead to rework (Sun et al., 2006; Sun and Meng, 2009). A variety of design change management (DCM) processes are proposed in the literature and used in practice to manage and control design changes. However, the processes used in the literature and in real life could differ. This article therefore aimed to identify the differences and similarities between the DCM processes described in theory and those used in practice. Three case studies were documented to extract the DCM processes used in them, including DCM-related terminology, activities, and IT tools and functionalities. Then, the findings of these case studies were compared with the findings of our previous theoretical study of DCM processes.

This article reveals three findings. The first is that there is no uniform terminology for DCM; project/construction managers and contractors use their own preferred terminology. There exist some standards, such as those issued by the Canadian Construction Documents Committee, that can influence the terminology used in a construction project, but they are mostly used for public projects, not private ones (although they were used in project B, which was similar to a public project). The second is that the DCM processes used in theory and in practice incorporate almost the same stages and activities. The main differences are that prediction tools are not used, potential changes are not identified, and lessons learned are not recorded or considered in practice. The third is that the tools proposed differ in the same way as the DCM processes considered do. One of the differences between theory and practice is the interest shown in facilitating the DCM process by proposing various tools to address the functionalities required. This interest is stronger in the literature in all three stages of a change (pre-change, mid-change, and post-change) because of the various tools and methods proposed. While the DCM processes used in projects A, B, and C did not incorporate tools to the same extent as the ones proposed in the literature did, the case studies illustrated that interest exists, especially in the mid-change stage, with the use of collaborative platforms.

This article is part of a larger research project that aims to compare design change management in BIM-supported industries and engineering change management in PLM-supported industries, so as to identify and propose potential characteristics and functionalities for cross-pollination between BIM- and PLM-supported industries (Pourzarei et al., 2020).

CHAPTER 6

ARTICLE 3—ENGINEERING CHANGE MANAGEMENT: COMPARING THEORY TO A CASE STUDY FROM AEROSPACE

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6.1 Abstract

Engineering change (EC) is omnipresent in product development and, hence, in the aerospace industry. Engineering change management (ECM) is therefore needed. Various research studies have proposed different ECM processes to manage ECs. However, there may be differences between the ECM processes described in theory (scientific literature) and those used in practice (real world). This article intends to explore the similarities and differences between the ECM processes in theory and in practice. This article investigates and analyzes one case study in an aerospace company. The authors analyzed the ECM terminology, the flow of data and documents, activities, and functionalities of the IT tools in the aforementioned case study. The results of the case study were then compared with the ECM process from theory through ECM stages and activities. This comparison between theory and practice enhances the implementation of ECM in practice and deepens the understanding of ECM in the literature.

6.2 Introduction

In the era of Industry 4.0, complex product design and manufacturing calls for the cooperation of large networks of specialists (Immonen and Saaksvuori, 2013). Such situations involving complex products force companies to specialize (Terzi et al., 2010). Product lifecycle management (PLM) has been defined to enable the integrated management of all product information and processes throughout the entire lifecycle (conception and design, production, distribution, maintenance, and retirement) (Terzi et al., 2010).

Changes are common and inevitable in complex regulated businesses like aerospace industry. Changes need to be managed, especially through the lifecycle of the product definition from the original design in engineering to manufacturing, and aftermarket. However, it is important to distinguish between the general concept of change and engineering change (Jarratt et al., 2005, 2011).

The ECs are inevitable according to the competitive environment of manufacturing and can influence the quality and cost of the products (Huang et al., 2003). Furthermore, EC is a mandatory requirement in the regulated aerospace industry for tracking both major and minor design changes. Implementing manufacturing changes aims to streamline production processes, reduce costs, and enhance overall quality. Various definitions have been proposed for engineering change (Department of Defence, 2020; Hamraz, 2013; Huang et al., 2003; Huang and Mak, 1998; Jarratt et al., 2005, 2011; Kocar and Akgunduz, 2010; Rouibah and Caskey, 2003; Shivankar et al., 2015; Wright, 1997). For instance, ECs are considered as the "changes/modifications to released structure (fit, forms and dimensions, surfaces, materials, etc.), behaviour (stability, strength, corrosion, etc.), function (speed, performance, efficiency, etc.), or the relations between functions and behaviour (design principles), or behaviour and structure (physical laws) of a technical artefact" (Huang et al., 2003).

One of the proposed definition of EC is from Jarratt et al. (Jarratt et al., 2005, 2011):

- "An engineering change is an alteration made to parts, drawing or software that have already been released during the product design process. The change can be of any size or any type; the change can involve any number of people and take any length of time." (Jarratt et al., 2005, 2011)

Engineering changes are playing a critical role in the product development process (Rouibah and Caskey, 2003). For instance, the research of Quintana et al. (Quintana et al., 2012) identify that Bombardier Aerospace company dealt with 13,967 engineering changes in 2001.

It is important to note that although there are some similarities between managing design change in the construction industry (Pourzarei et al., 2022) and engineering change in the aerospace industry, but the focuses are nevertheless distinct with their own issues. The focus of this article is to explore the management of engineering change within the context of the aerospace industry.

It should be noted that managing ECs effectively is a costly and time-consuming process in most industries (Huang et al., 2003). In addition, engineering change management (ECM) is considered an important practice. According to Hamraz (Hamraz, 2013) "ECM can be summarized according to its goals to (1) avoid or reduce the number of engineering change requests (ECRs) before they occur, (2) detect them early when they occur, (3) address them effectively, (4) implement them efficiently, and (5) learn continuously for the future." ECM process, in simple terms, is an engineering process to identify, track, and manage the engineering changes. Various engineering management processes have been proposed for managing ECs (Dale, 1982; Guess, 2002; Jarratt et al., 2011; Kocar and Akgunduz, 2010; Lee et al., 2006; Maurino, 1993; Ouertani et al., 2004; Pourzarei et al., 2022; Rivière et al., 2003; Shivankar et al., 2015; Tavcar and Duhovnik, 2006; Wu et al., 2014).

The ECM process includes various elements such as terminology that include different terms and concepts, different methods and IT tools, different activities, and the involvement of various departments. In addition, different documents are used in the ECM process. According to Huang et al. (Huang et al., 2003), these documents could be classified into three categories based on their special function related to ECM: the first category includes the documents that are used to signal the need for an EC in the initial stage. The second one includes the documents that are used to evaluate the impacts and effects of an EC, and lastly, the third one includes the documents that are used to notify others of an approved EC. It is important to mention that the aforementioned descriptions of the ECM process are quite different in various industries as well as there are also some differences between ECM description in theory (scientific literature) and ECM description in practice (industry). By *theory* we a referring to what is described in the scientific literature, and by *practice* we are referring to what happens in the real world.

Although the current ECM process description, in theory, presents valuable viewpoints, there appears to be a lack of comparative analysis between ECM in theory and in practice.

Conducting such an analysis could yield a more comprehensive understanding of the ECM process, potentially uncovering best practices related to its characteristics and functionalities, ultimately leading to its improvement. To put it differently, this comparison can potentially uncover whether the theory presented aligns with practical implementation.

In this article, we will be addressing the following research question: to what extent do theoretical description of engineering change management process and tools align with their practical implementation in an aerospace product design organization? We investigate these similarities and differences by exploring, documenting, and analyzing a case study that presents the ECM process from an aerospace company. Then, we compare the ECM description in practice with the ECM description from theory. This comparison will be presented through the comparison of the ECM processes and activities. The objectives of this article are:

1. Explore, document, and compare the ECM process and activities used in practice in an aerospace company.
2. Compare the ECM process and activities used in practice in an aerospace company with those found in theory so as to identify similarities and differences.

This article is broken down into seven sections. Section 6.3 presents the research methodology. Section 6.4 reviews the results of the case study. The comparison of ECM processes (both theory and practice) is presented in section 6.5. Section 6.6 discusses the results. Section 6.7 presents the conclusion and future work.

6.3 Research Methodology

This article intends to compare the engineering change management description between theory and a case study from aerospace. The theoretical description of the ECM process are analyzed and evaluated by the previous research study (Pourzarei et al., 2022). Therefore, this article is using the theoretical part from the aforementioned research.

At the beginning, we must identify a company as an industrial partner to provide us with the case study. This led this research to the aerospace industry, which is an industry that has been using PLM for decades, having a well-implemented ECM process, and also manages many engineering changes per year. An aerospace company was selected to be our industrial partner and provide us with the case study.

However, there were various restrictions in front of this research project such as the COVID-19 pandemic as well as confidentiality issues. The whole collaboration between the authors and the research teams at the company was conducted through online meetings. In total, we had five meetings with our industrial partner and the average length of each meeting was about one hour and thirty minutes. These meetings included interviewing the experts for both documenting and validating the extracted ECM process. Besides, we focused on the second and the third stages of the ECM process in this case study. However, the other stages including the first, fourth and fifth are extracted based on the documents that are used by our industrial partner (e.g. the standards).

It is important to note that this article is adopted the methodology from the previous article that compares the design change management process in the construction industry (Pourzarei et al., 2023). The adopted methodology has the following steps document analysis and interviewing the experts, business process mapping, analysis and comparison of the results. These steps are briefly explained in the following steps.

At first, we reviewed various industrial standards and documents that are used by the industrial partner. "*Structuring principles and reference designation: part2: classification of objects and codes for classes (IEC 81346-1)*" ("IEC 81346-2:2009(en), Industrial systems, installations and equipment and industrial products — Structuring principles and reference designations — Part 2: Classification of objects and codes for classes," 2009) and "*General requirements of Digital Mock-Up for mechanical product (ISO 17599 (DMU))*" ("ISO 17599:2015(en), Technical product documentation (TPD) — General requirements of digital mock-up for mechanical products," 2015) are two examples of these standards. Then, various meetings were conducted with the company's experts for extracting the information as well as the validation.

Then, an ECM process is extracted by using Business Process Model and Notation (BPMN). This BPMN process has the following elements:

1. The activities involved.
2. The flow and types of documents.
3. The tools used.
4. The roles and names of the involved departments.

The BPMN models then were presented to the members of our industrial partners for validation purposes.

Next, the authors created a 'metamodel' based on the extracted ECM process. This metamodel helped to organize the information and be able to compare the processes. The proposed metamodel helped this article to organize the ECM description elements into the following four categories:

1. The stages and activities of the ECM process.
2. The tools and their functionalities.
3. The terminology used.

Finally, the information from the metamodel is compared with the findings of the theoretical studies conducted in previous research (Pourzarei et al., 2022) based on the aforementioned categories (stages of ECM process and activities) to identify the similarities and differences.

The following section presents the case study.

6.4 The Case Study

A case study in the aerospace industry is presented in this section. A short description of the industrial partner is presented at first and then followed by describing the terminology, IT tools, as well as the activities of the ECM process.

6.4.1 The Industrial Partner

The aerospace is one of the most common industries that record many engineering changes. For instance, Bombardier Aerospace recorded 13,967 engineering change in 2001 (Quintana et al., 2012). This is why the authors decided to choose an aerospace company as an industrial partner. However, because of confidentiality issues of the aerospace industry, access to the information is usually limited.

Our industrial partner is the manufacturer of major aircraft components. It designs, develops, manufactures and services these aircraft components. The engineering change management process in the examined case study involved different departments in the company such as the configuration management, design office, etc. Indeed, it is important to emphasize the ECM has a central role in our industrial partner's business and has continuously evolved over time.

6.4.2 Terminology

Interestingly, the extracted terminology from our industrial partner is quite same as the terminology in theory, with slight differences.

The following table is presenting the terminology.

Table 6.1 Terminology used in the case study

Term used	Descriptions
Engineering Change (EC)	"An engineering change is an alteration made to parts, drawing or software that have already been released during the product design process. The change can be of any size or type; the change can involve any number of people and take any length of time". (Jarratt et al., 2011)
Engineering Change Request (ECR)	"A form available to any employee used to describe a proposed change or problem which may exist in a given product". (Jarratt et al., 2005)
Design Intent Document (DID)	A Design Intent Document (DID) is prepared by the design team in the early stages of a project, once there is a clear understanding of the owner's expectations. The DID is a dynamic document that includes quantifiable design values. (Faure Walker, 2019)
Engineering Change Order (ECO)	"A document which describes an approved engineering change to a product and is the authority or directive to implement the change into the product and its documentation". (Jarratt et al., 2011)
Daily Issue List	The daily issue list provides easy access to publish engineering changes.
Integrated Product Team (IPT)	"The Integrated Product Team (IPT) is composed of representatives from all appropriate functional disciplines working together with a Team Leader to build successful and balanced programs, identify and resolve issues, and make sound and timely recommendations to facilitate decision-making." (Meister, 1996)
Timestamp	"The timestamp authenticates the time when the data is generated by certain technical means, so as to verify whether the data has been tampered with after it is generated." (Wu et al., 2023)
Classified ECO	The classified ECO signifies distinct statuses of the ECO report, visually represented by different colors, indicating the presence of any restrictions on the ECO.
Engineering Approval Form	A documentation form designed to obtain customer approval for an engineering change.

Not surprisingly, our industrial partner is utilizing common ECM terminologies such as engineering change (EC), engineering change request (ECR), and engineering change order (ECO). On the other hand, the company adopts some other terms based on their needs. For instance, the design intent document and daily issue list used in the company address the characteristics of engineering change proposal (ECP) (Department of Defence, 2020) and engineering change notice (ECN) (Pourzarei et al., 2022) respectively. It is important to note that some of the terms (e.g. DID, IPT, etc.) are described as defined by our industrial partner.

Besides the change board team who approves the change in the ECM process, there is an integrated product team (IPT), in the analyzed case study, that is built to analyze the requested change, propose a solution as well as analyze it. The IPT includes various professionals such as engineers and designers that are selected by the design manager. It is important to note that the membership of the IPT team can be varied based on the needs of the requested change.

The company is also using two interesting terms: Timestamp and Classified ECO. The timestamp serves as a project milestone, indicating the creation of a new draft of the ECO. In essence, each time a new draft of the ECO is generated, a corresponding timestamp is created to mark the event. On the other hand, the classified ECO presents the status of the ECO report. This is a flagging system that shows if there are any restrictions on the ECO. For instance, when there is a restriction (such as there is a need for customer approval), the ECO color would be different from when there is not any.

6.4.3 IT Tools

IT tools play an important role in the engineering change management process, as they offer essential functionalities to support the process. For instance, these functionalities could facilitate document sharing, communication, version management, etc. This section is presenting the functionalities of the used IT tools in the selected industrial partner. Table 6.2 illustrates these IT tools as well as their functionalities.

Table 6.2 The IT tools used in the case study and their functionalities

Tool used	Functionalities
PLM Platform (version 2014)	✓ A collaborative platform for: ➢ Sharing data and information (e.g. ECO reports). ➢ Mark-up drawings. ➢ BOM modifications. ➢ 3D function. ➢ Version management (Version control). ➢ Lifecycle management. ✓ Collaborating and integrating with other applications (e.g. in house applications).
In-house Applications	✓ Record the post-related changes as a repository. ✓ Prepare and issue the change orders, releases, design evaluation changes, obsoletion documents. ✓ Manage and release the revisions. ✓ Provide central item control for all product definition data and all engineering business systems. ✓ Task tracker.
MS Suites Tools (e.g. Excel)	✓ Use to transfer the data and information between Enovia V6 and configuration management applications.
Adobe Acrobat	✓ Adobe applications mainly are used to extract the final version of the documents (e.g. ECO report).
Internal Search Platform	✓ Using as a search engine and connect the user to the internal databases.
Documentum	✓ Use to getting e-signatures.

As mentioned before, according to the confidentiality for this research project with our industrial partner, it is not possible to reveal more features of these applications, precisely in-house applications.

The company is using a PLM platform version 2014 and moving shortly to PLM platform version 2021. This PLM platform is offering various functionalities as a collaborative platform such as sharing data and documents, version management, lifecycle management, etc.

The in-house applications are created/developed in the company based on their needs. These in-house applications offer various functionalities such as managing the information system (e.g. record and control the information) as well as tracking the tasks. For example, internal search platform is an internal search engine that is developed by the company. The main difference between internal search platform and search in the PLM platform is that the search in internal search platform is giving more filtered results rather than all the results.

In addition, the company is running the hybrid environment by using the PLM platform and in-house applications. For instance, the PLM platform kept the ECO authorization as well as the latest version of BOM. While modifications of BOM (add & cancel) are generated in in-house applications. This hybrid environment could increase the productivity of the ECM process in the company.

The company is also using the basic daily used applications such as MS Suite tools (e.g. Excel) and adobe acrobat reader. The MS Suite tools, Excel, play an interesting role between the PLM platform and in-house applications. It is been used as a tool to transfer/convert the data and information between them. In addition, the adobe acrobat reader is used to extract the final version of the documents.

Finally, our industrial partner utilizes some technical and commercial tools that can be integrated into the hybrid environment. For instance, using Documentum for getting e-signatures. They began to use it after they moved to paperless activities in 2016. It is important to note that there is no option in their PLM platform (the version that the company is using) to sign the documents electronically. In addition, this application was the only application authorized by Designated Airworthiness Authority (DAA), so, this is the reason why the company is using it.

6.4.4 Stages of an ECM Process

This section presents the engineering change management process in the examined case study. The extracted ECM process is classified into five stages, according to the research of

(Pourzarei et al., 2022). Precisely, in each stage, there are various activities that are presented in this section. The aforementioned five stages are:

1. Request or initiation (ECR)
2. Instruction or proposal (ECP)
3. Execution or document issuing (ECO)
4. Notification or application (ECN)
5. Review and analyze

The following sections illustrate each stage of the extracted ECM process that includes the main activities involved in the process, terminology, and IT tools that have been used specifically in each stage.

6.4.4.1 Request or Initiation (Engineering Change Request)

The main objective of this stage is to raise the ECR. The characteristics of this stage are presented in Table 6.3.

Table 6.3 The characteristics of the first stage of the ECM process–
Request or initiation (ECR)

	Description
Activities	✓ Identify engineering change (EC). ✓ Fulfill the engineering change request (ECR) form. ✓ Assign the budget to the proposed ECR.
Terminology	✓ Engineering Change. ✓ Engineering Change Request (ECR).
IT Tools	✓ PLM Platform.

Raising the ECR is the first step to beginning the ECM process. There are a few activities in this stage of the ECM. Identifying the engineering change and submitting a fulfilled ECR form are the most common activities at this stage. It is important to mention that assigning the budget is done at this stage of the ECM process. Indeed, the ECM process will not be processed unless there is an assigned budget.

In addition, it should be noted that our industrial partner has started the paperless process since 2016, which is why the whole ECM process (e.g. requesting/submitting ECR) is going through different applications. At this stage, the most used application is the PLM platform.

6.4.4.2 Instruction or Proposal (Engineering Change Proposal)

After raising the ECR, it is time to evaluate the requested change as well as propose the solutions. In this stage, the team of professionals evaluate the change, propose the solutions and then choose one solution for the requested change. Table 6.4 presents the characteristics of this stage.

Table 6.4 The characteristics of the second stage of the ECM process–
Instruction or proposal (ECP)

	Description
Activities	✓ Receive/review the ECR. ✓ Create an Integrated Product Team (IPT). ✓ Evaluate ECR. ✓ Propose solutions (BOM & Markup drawings). ✓ Evaluate the solutions. ✓ Choose a solution. ✓ Finalize evaluation of the selected solution. ✓ Create Design Intent Document (DID). ✓ Sign DID. ✓ Release DID.
Terminology	✓ Engineering Change Request (ECR). ✓ Integrated Product Team (IPT). ✓ Bill of Material (BOM). ✓ Design Intent Document (DID).
IT Tools	✓ PLM Platform. ✓ In-house Applications. ✓ MS Suite Tools. ✓ Internal Search Platform. ✓ Adobe Acrobat.

This stage of the ECM process begins when the design manager receives the ECR. Then, the design manager builds an integrated product team (IPT) based on the needs of the requested change. The IPT team evaluates the requested change and then prepares a list of solutions, including BOMs and mark-up drawings, to address the ECR. The evaluation of the solution will go through three evaluations.

First, the proposed solutions will be evaluated by the IPT team. One of these solutions will be offered to satisfy the ECR. Secondly, the IPT team decides whether to choose a solution or not. This evaluation aims to assure that the chosen solution is capable to address the ECR. If the solution will not be selected, it will go back to the previous step, where the IPT team needs to propose alternative solutions. If one solution (including BOM and mark-up drawings) will be selected, it will go to the next step. In the third evaluation, the IPT team and design manager finalize the chosen solution and then the IPD team creates the design intent document (DID). The DID will be signed and confirmed by the design manager and will be released to the next stage of the ECM process.

All revised documents (e.g. BOMs and mark-up drawings) are updated and accessible in the PLM platform. In addition, the hybrid environment is giving various facilities to the participants in the ECM process such as using internal search platform or in-house applications (record and controlling information).

6.4.4.3 Execution or Document Issuing (Engineering Change Order)

This stage of the ECM process will be followed by evaluating the DID by the configuration management and creating the engineering change order. It's worth noting that the configuration management holds a significant responsibility in the aerospace industry during the ECM process, as most activities at this stage fall under their control. Table 6.5 shows the characteristics of this stage of ECM.

Table 6.5 The characteristics of the third stage of the ECM process–Execution or document issuing (ECO)

	Description
Activities	✓ Create the ECO report based on the DID. ✓ Review the ECO report by designated groups. ✓ Verify if substantiation has been completed & data is available. ✓ Verify if customer concurrence is required. ✓ Issuing the classified ECO: ➢ If there will be shipment restriction. ➢ If there will be no shipment restriction. ➢ To lift the shipment restriction. ✓ Raise Engineering Approval Form (if it would be needed). ✓ Receive customer approval. ✓ Create a new draft of the ECO report (Timestamp). ✓ Verify and sign the ECO report (by different departments). ✓ Final review and sign the ECO report (by Program Manager and DAA). ✓ Final check of the sign ECO report (configuration management). ✓ Finalize and release the final draft of the ECO report. ➢ Release the ECO, if there is no shipment restriction. ➢ Open a new ECO, if there is a shipment restriction.
Terminology	✓ Engineering Change Order (ECO). ✓ Design Intent Document (DID). ✓ Shipment restriction. ✓ Substantiation. ✓ Classified ECO. ✓ Designated groups. ✓ Designated Airworthiness Authority (DAA).
IT Tools	✓ PLM Platform. ✓ In-house Applications. ✓ MS Suite Tools. ✓ Adobe Acrobat. ✓ Internal Search Platform. ✓ Documentum.

This stage of the ECM process can be considered the core stage of the ECM process of this case study because of its importance to the ECM process. At the beginning of this stage, the configuration management (CM) creates the ECO report based on the requirements of DID. It is important to note that every time the CM creates a new draft of the ECO report, there will be a Timestamp in the ECM process. Then, the ECO report will be sent to the designated groups for evaluation. Designated groups are the relevant groups that evaluate the ECO, more precisely evaluating the requested change, proposed solution, etc. Drafting, customer support, and legal departments are some examples of the designated groups. If designated groups will accept the ECO, they might add some complementary documents to the ECO report and send them to the CM. But if designated groups find the conflict(s), they will have a meeting with the program manager and DAA to solve the conflict(s).

In addition, the CM reviews two criteria for the ECO report. The first one is to verify if the substantiation has been completed and data is available. It should mention that the substantiation here is the validation process that is providing the test (e.g. running tests for the design validations). The second one is to verify if customer concurrence is required. If either/both of the aforementioned criteria will not be satisfied, the CM will use the classified ECO, flagging system, to status the ECO and put shipment restrictions. Shipment restrictions here are the restrictions that come from the lack of customer concurrence and/or substantiations, which lead to not delivering to the customer but the productions will not be stopped. The engine(s) will be stored in quarantine till shipment restriction is lifted.

After the aforementioned steps, the CM creates a new draft of the ECO report, Timestamp, and shares it with the change board departments to sign the form, which will be done electronically by using Documentum. The final review and sign of the ECO report will be done by the program manager and DAA respectively.

The CM verifies the signatures as well as supplementary documents (if there are any) and then creates a final draft of ECO report, Timestamp. If there is no shipment restriction, the CM releases the ECO to the next stage. If there is still shipment restriction, the CM will create a new ECO and the ECO stage begins from the first step.

It should be noted that like the previous stage of the ECM process, the hybrid environment) gives various functionalities (e.g. sharing documents) to this stage of the ECM process.

6.4.4.4 Notification or Application (Engineering Change Notice)

After the engineering change order is approved, it is the time to implement the selected solution for the requested change. The term that used as the daily issue list, is same as the engineering change notice. The following table presents the characteristics of this stage.

Table 6.6 The characteristics of the fourth stage of the ECM process–
Notification or application (ECN)

	Description
Activities	✓ Receive the latest version of the ECO report. ✓ Assign the ECO in Daily Issue List. ✓ Implement the change based on the proposed instructions.
Terminology	✓ Engineering Change Order (ECO). ✓ Daily Issue List. ✓ Configuration Management.
IT Tools	✓ PLM Platform. ✓ In-house Applications. ✓ Adobe Acrobat.

According to the above table, there are a few activities at this stage of the ECM process. The latest version of the ECO report will be assigned to the daily issue list and then will wait to be implemented. The implementation could delay if there are any shipment restrictions. In addition, the hybrid environment including the PLM platform and in-house applications will help the relevant departments to access the latest documents and instructions.

6.4.4.5 Review and Analyze

In this stage of the ECM process, the configuration management reviews and keep the executed change. Our industrial partner mentioned that the executed changes are reviewed and documented in the company database and would be used as the lessons learned. However, according to the confidentiality issue in the aerospace industry, we could not reach this information.

6.5 Comparative Analysis of ECM Processes Used in Theory and in Practice

This section intends to compare the extracted ECM process from a case study with the extracted ECM process from theory. This section therefore compares the ECM process (stages and activities).

6.5.1 Comparison of the ECM Stage and Activity

The engineering change process is including various activities. Each activity is playing an important role in the ECM process. The extracted ECM process from the case study is compared in this section with the ECM process used in theory (Pourzarei et al., 2022).

This comparison leads this study to distinguish the similarities and differences between the ECM processes used in theory and in practice. This comparison is divided into the aforementioned five stages of the ECM process (Pourzarei et al., 2022).

To compare the ECM process through these stages, a list of activities is presented in each stage. These activities are extracted from three sources: the activities of the ECM processes that are presented in theory (Dale, 1982; Jarratt et al., 2011; Kocar and Akgunduz, 2010; Lee et al., 2006; Maurino, 1993; Ouertani et al., 2004; Rivière et al., 2003; Shivankar et al., 2015; Tavcar and Duhovnik, 2006; Wu et al., 2014), the activities of the ECM process that are proposed in our previous research (Pourzarei et al., 2022), and the activities that are presented in the previous section (case study). It is important to mention that the ECM processes in practice have more detailed activities than the ECM processes in theory. The authors extracted a list of activities that play an important role (e.g. evaluation and approval activities) in the ECM process. Importance was judged by systematically going through the high frequency of mentions/citations of each activity and then placing them in order. The highest-order activities were chosen (the first 5 to 10 activities were clearly occurring more often). Then we compare them to identify if they are used in the ECM processes in theory and/or in practice.

6.5.1.1 Request or Initiation (ECR)

The first stage of the ECM process is requesting or initiating the engineering change request. Table 6.7 is illustrating the activities of each of the ECM processes.

Table 6.7 Comparison of activities in the first stage–Request or initiation (ECR)

Activity	**(Dale, 1982)**	**(Maurino, 1993)**	**(Rivière et al., 2003)**	**(Ouertani et al., 2004)**	**(Lee, 2006)**	**(Tavcar and Duhovnik, 2006)**	**(Kocar and Akgunduz, 2010)**	**(Jarratt et al., 2011)**	**(Wu et al., 2014)**	**(Shivankar et al., 2015)**	**(Pourzarei et al., 2022)**	**Practice**
Identify the need for change	-	-	-	-	✓	-	-	-	✓	-	-	-
Collect or initiate the engineering change request	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Submit the ECR form (describe reason, priority, type of change, etc.)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Evaluate the request	-	-	✓	-	✓	-	✓	✓	✓	✓	✓	✓
Assign the budget to the proposed ECR	-	-	-	-	-	-	-	-	-	-	-	✓

Most of the activities in this stage are quite the same in both theory and practice such as collecting or initiating the ECR, submitting the ECR form, and somehow evaluating the ECR.

On the other hand, identifying the need for change is an activity that aims to look for the potential engineering changes based on pre-defined criteria. The analyzed literature does not extensively mention this activity. It should be noted that in the case study that was analyzed, no activities were found that identified potential problems based on lessons learned. This activity might be present in other industries.

In addition, assigning the budget to the requested change is an important activity of the ECM process and if there is no budget, the ECM process might not be started. Interestingly this activity is not presented in the theory and it might be because the ECM process in practice has more details than the ECM process in theory and this might be a valid activity in most of the ECM processes in other industries.

6.5.1.2 Instruction or Proposal (ECP)

After raising the engineering change request, the ECR should be evaluated solution(s) proposed. The following table is presenting the activities of this stage of the ECM process.

Table 6.8 Comparison of activities in the second stage–Instruction or proposal (ECP)

Activity	**(Dale, 1982)**	**(Maurino, 1993)**	**(Rivière et al., 2003)**	**(Ouertani et al., 2004)**	**(Lee, 2006)**	**(Tavcar and Duhovnik, 2006)**	**(Kocar and Akgunduz, 2010)**	**(Jarratt et al., 2011)**	**(Wu et al., 2014)**	**(Shivankar et al., 2015)**	**(Pourzarei et al., 2022)**	**Practice**
Detailed evaluation of the requested change (e.g. impact analysis)	-	✓	✓	✓	✓	✓	✓	✓	✓	-	✓	✓
Create a professional team to work on the requested change	-	-	-	-	-	-	-	-	-	-	-	✓
Propose the potential set of solutions (BOMs & Markup drawings)	-	✓	✓	-	✓	-	-	✓	-	-	✓	✓
Analyze the solutions (e.g. impacts analysis)	-	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Choose and propose a proper solution	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Table 6.8 Comparison of activities in the second stage–Instruction or proposal (ECP) (cont'd)

Activity	**(Dale, 1982)**	**(Maurino, 1993)**	**(Rivière et al., 2003)**	**(Ouertani et al., 2004)**	**(Lee, 2006)**	**(Tavcar and Duhovnik, 2006)**	**(Kocar and Akgunduz, 2010)**	**(Jarratt et al., 2011)**	**(Wu et al., 2014)**	**(Shivankar et al., 2015)**	**(Pourzarei et al., 2022)**	**Practice**
Evaluate the chosen solution	-	-	-	-	-	-	-	-	-	-	-	✓
Finalize the analysis of the solution	-	-	-	-	-	-	-	-	-	-	-	✓
Update Markup drawings and documents	-	-	-	-	-	-	-	✓	-	-	✓	✓
Create the engineering change proposal/design intent document	-	✓	✓	-	-	-	-	-	-	-	✓	✓

Various activities at this stage are the same between theory and practice. Detailed evaluation of the requested change, the proposal of the solutions, analyze the solution, choosing a solution are some of these similarities. Although theory and practice are using different terms for ECP, they both address the same activity, which is a document that includes the proposed solution to address the requested change.

Similar to the previous stage, there are certain activities that are observed in practice but not explicitly addressed in theory. This can be because of the detailed version of the ECM process in practice, for instance, create the professional team, evaluate the chosen solution, update markup drawings and document, and finalize the analysis of the solution. It should be noted that there are some differences in the company's characteristics that might need more comprehensive steps for the evaluation.

6.5.1.3 Execution or Document Issuing (ECO)

One of the most important stages of the ECM process is this stage, which aims to do the final evaluation as well as approve the proposed change. Table 6.9 is presenting the activities of execution or document issuing in the ECO stage.

Table 6.9 Comparison of activities in the third stage–
Execution or document issuing (ECO)

Activity	**(Dale, 1982)**	**(Maurino, 1993)**	**(Rivière et al., 2003)**	**(Ouertani et al., 2004)**	**(Lee, 2006)**	**(Tavcar and Duhovnik, 2006)**	**(Kocar and Akgunduz, 2010)**	**(Jarratt et al., 2011)**	**(Wu et al., 2014)**	**(Shivankar et al., 2015)**	**(Pourzarei et al., 2022)**	**Practice**
Create the ECO based on the ECP/DID	-	✓	-	-	✓	-	✓	-	✓	✓	✓	✓
Revise the ECO (e.g. cost-benefit analysis) by the engineering change board/committee	-	✓	✓	-	✓	✓	✓	✓	✓	✓	✓	✓
Evaluate the restrictions for the proposed change (e.g. availability of data, or requiring customer approval)	-	-	-	-	-	-	-	-	-	-	-	✓
Flagging the ECO if there is any restriction	-	-	-	-	-	-	-	-	-	-	-	✓
Raise the engineering approval form (if it would be needed)	-	-	-	-	-	-	-	-	-	-	-	✓
Receive customer approval (if it would be needed)	-	-	-	-	-	-	-	-	-	-	-	✓
Lift the restrictions	-	-	-	-	-	-	-	-	-	-	-	✓
Approve the proposed solution	-	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Update documents (e.g. markup drawings)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Create the final draft of the ECO report	-	-	-	-	-	-	-	-	-	-	-	✓
Team notify (e.g. Program Manager)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

The activities of the third stage of the ECM process can be classified into two main groups. The first group includes the general types of activities that are the same between theory and practice. Creating ECO, revising ECO, approving ECO, updating documents, and finalizing the ECO are the activities of the first group.

On the other hand, the second group includes the activities that are created based on the company's needs and policies. Using classified ECO (flagging system) and lifting the restrictions are two examples of these types of activities.

Finally, it is important to mention that there are certain activities such as raising the engineering approval form that should be similar in theory and in practice. The reason that these activities are not mentioned in the theoretical field would be because the information found in the theory is less detailed than in our case study.

6.5.1.4 Notification or Application (ECN)

Implement the requested change is the aim of this stage of ECM process. The following table represents the main activities of this stage.

Table 6.10 Comparison of activities in the fourth stage–Notification or application (ECN)

Activity	**(Dale, 1982)**	**(Maurino, 1993)**	**(Rivière et al., 2003)**	**(Ouertani et al., 2004)**	**(Lee, 2006)**	**(Tavcar and Duhovnik, 2006)**	**(Kocar and Akgunduz, 2010)**	**(Jarratt et al., 2011)**	**(Wu et al., 2014)**	**(Shivankar et al., 2015)**	**(Pourzarei et al., 2022)**	**Practice**
Released the latest version of the ECO report	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Create a Daily Issue List/ Engineering Change Notice (including textual and graphical information regarding the execution change)	-	✓	-	-	-	-	✓	✓	-	✓	✓	✓
Assign the timeframe for the execution	-	✓	-	-	-	-	-	✓	-	-	✓	✓
Inform the people who are concerned about the requested change (team notify)	-	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Implement the requested change in the production process, servicing, etc., either immediately or be phased in	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Update the paperwork	-	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

The activities at this stage of the ECM process are quite the same in theory and in practice. Releasing the latest version of ECO, creating a daily issue list / ECN, assigning a time plan for implementation, team notification, and implementing the requested change are similar activities at this stage.

Furthermore, the activity of updating paperwork (Jarratt et al., 2011) is a valid activity in both theoretical and practical contexts. However, it is worth noting that our industrial partner initiated paperless operations and activities in 2016. Through the adoption of a collaborative platform and the implementation of a hybrid work environment, the organization has the capacity to enhance productivity and transition into a paperless entity. Nevertheless, it is conceivable that this activity remains relevant in different industries.

6.5.1.5 Review and Analyze

The final stage aims to review the executed change. Table 6.11 illustrates the main activities of this stage.

Table 6.11 Comparison of activities in the fifth stage–Review and Analyze

Activity	**(Dale, 1982)**	**(Maurino, 1993)**	**(Rivière et al., 2003)**	**(Ouertani et al., 2004)**	**(Lee, 2006)**	**(Tavcar and Duhovnik, 2006)**	**(Kocar and Akgunduz, 2010)**	**(Jarratt et al., 2011)**	**(Wu et al., 2014)**	**(Shivankar et al., 2015)**	**(Pourzarei et al., 2022)**	**Practice**
Follow-up the execution's results to identify if it achieved the initial intent	-	-	-	✓	-	-	-	✓	✓	✓	✓	✓
Evaluate the post-changes impacts	-	-	-	✓	-	-	-	✓	✓	✓	✓	✓
Update deliverables that are affected by the change	-	-	-	-	-	-	-	✓	✓	✓	✓	✓
Identify and document the lessons learned	-	-	-	-	-	-	-	✓	-	-	✓	-
Classify and store the lessons learned	-	-	-	-	-	-	-	✓	-	-	✓	-

The activities at the fifth stage of the ECM process could be classified into two groups. The first group includes the most common activity, which is follow-up the execution's results to identify if it achieved the initial intent. This activity aims to assure that the proposed solution could satisfy and address the requested change.

The second group includes the activities that aim to be used as the lessons learned. Identify and document the lessons learned as well as classify them are some examples of them. It is worth to mention although our industrial partner does not have the activities for the lessons learned, they might be different in other industries.

As observed in the preceding stages, it is apparent that the level of detail within the ECM process varies even among the ECM processes in the theory that has been presented.

6.6 Discussion

Engineering change management is an important practice in different industries and more precisely in aerospace product design organization. The ECM process includes various elements such as terminologies, documents, stages and activities, and IT tools. This research study investigated and documented the ECM terminologies, ECM stages and activities, and the functionalities of the IT tools for the ECM from one case study in the aerospace industry.

6.6.1 ECM Process

Unsurprisingly, the ECM process is more detailed in practice compared to the ECM process in theory. The results of this comparison indicate that while theory is more advanced in using lessons learned to identify potential changes, in practice, the process begins only when there is a request for the change. Another interesting point is that the ECM process in practice begins when there is a defined budget for it, which is not mentioned in theory. Furthermore, our industrial partner has started to implement paperless activities, which indicates that practice is moving towards the digital transformation world.

Our observation also show that ECM process can vary depending on the complexity of the requested change and the resources required. For example, a change in the size of a yoke, control wheel, may be less complex than a change in the infusion pumps in an airplane engine. The duration of the ECM process, the number of departments involved, and the engineering change costs will differ between these two examples of engineering changes.

Moreover, different industries may have their own customized activities to enhance the efficiency of the ECM process. For instance, our industrial partner used a flagging system for ECO to impose/lift restrictions in the ECM process.

It is noteworthy that the client may be a potential member of the approval team for the ECM process. For instance, in the aerospace industry, the client's approval might be a critical activity in the ECM process, whereas in a general manufacturing context such as electronic goods, such approval may not be necessary.

6.6.2 Limitations

The limitation work conducted could be classified into three groups. The first and foremost is the confidentiality issue in the aerospace industry. This limitation did not let us investigate deeply through whole ECM process in the company and limited our collaboration to the second stage, instruction or proposal (ECP), and third stage, execution or document issuing (ECO), of the ECM process. Although the importance of the aforementioned stages, investigating the other stages could reveal more information. In addition, the other stages of the ECM process from practice are extracted based on the documents used in the company (e.g. standards), which they were validated with our industrial partner and stayed at a high level. The second limitation of this research study is that the whole collaboration between the research team and industrial partner is held in online collaboration according to the Covid-19 pandemic. This reason led to this research study last more than the time was expected. And the third limitation is that the current results rely on having only one case study, therefore, if we aim to generalize, it would be necessary to include more than one case study.

6.7 Conclusion

Changes are a part of industry life nowadays. Changes can be raised by anyone and at any point in the lifecycle. The impacts of the changes would be increased if they raise through the engineering design and manufacturing process, which these kinds of changes are called engineering changes. Therefore, it is important to identify as well as manage them. ECM process is considered an important practice in the aerospace product design organization, which needs to track and manage engineering changes.

Various processes have been proposed as ECM process to manage the ECs in theory. On the other hand, different ECM processes are used in practice. Between the ECM processes in theory and practice this article aimed to investigate these similarities and differences. Hence, this article is investigating the most cited ECM processes in theory and comparing them with one case study in aerospace industry.

The contributions are the following. First, the terminology used in theory and practice is remarkably similar. The primary terms of the ECM process, such as ECR, ECO, and EC, are utilized in both theory and practice. Nevertheless, some modifications have been made to certain terms, such as the implementation of a "classified ECO," by the industrial partner to streamline the ECM process. Secondly, although there are similarities between the ECM processes in theory and practice, there are some differences in the activities that stem from the detailed ECM process in practice, as well as customized activities tailored to the company's specific needs. Some of these differences include identifying potential changes, creating the IPT team. However, it should be noted that although the activity of assigning a budget to the engineering change request is not explicitly mentioned in theory, it is likely to be a crucial aspect in most ECM processes. This emphasizes the fact that the ECM process cannot begin without a budget allocated for the requested EC. Nevertheless, the initial budget may necessitate additional discussion, especially in the case of complex changes. Finally, the adoption of IT tools in practice varies, with certain industries showcasing a high level of integration and successful implementation. Our industrial partner has notably designed and developed distinctive IT tools, which are in-house applications, and has successfully integrated them with the PLM platform to establish a hybrid environment.

CHAPTER 7

ON CONSIDERING A PLM PLATFORM FOR DESIGN CHANGE MANAGEMENT IN CONSTRUCTION

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7.1 Abstract

Design change (DC) which refers to any type of design or construction modification made once a contract is awarded is an important issue in today's construction. DCs usually would lead to an increase in the cost and time overrun of the project. It is thus important to manage them by using an effective management process. Various design change management processes (DCM) have been proposed by different research studies as well as different DCM processes are used in practice (industry). In addition, IT tools have an important role in the DCM process that could provide various functionalities to facilitate the DCM process. However, according to the scientific literature, there is still a need for improvement/offer of a collaborative platform in construction. This article aims to evaluate whether a platform, typically categorized as a Product Lifecycle Management (PLM) tool, is capable of meeting the collaboration requirements of DCM. 3DExperience is a cloud-based collaborative platform that is used in PLM-supported industry. This collaborative platform is a connected online environment where all the design, collaboration, and data management capabilities are stored in a single user interface. More precisely, this article investigates how PLM platform functionalities could address the needs of the DCM process in construction. By assessing the research findings of this article, it is demonstrated that PLM platforms have the potential to be utilized for DCM. Such an evaluation could lead to improved productivity in the DCM process within construction.

7.2 Introduction

The goal of design change management (DCM) is to establish an organized and effective approach to recording and managing design change (DC) (Pourzarei et al., 2022). DCM plays an important role in controlling and overseeing modifications to a building design throughout its construction phases. It ensures that changes are executed in an orderly and methodical way and that the resulting changes are precise, consistent, and abide by applicable standards and regulations (Hao et al., 2008; Pourzarei et al., 2022).

It is important to mention that building information modeling (BIM) is a collaborative approach that encourages effective communication and information management between all parties involved in a construction project (Jupp, 2013; Sacks et al., 2018). It appears to have the potential to solve some persistent construction difficulties (interoperability, information flow optimization, etc.), which would lead to improved productivity (Boton et al., 2018).

Using a collaborative platform for DCM allows various stakeholders to communicate as well as work together effectively on design changes. This can help to ensure that all necessary parties are informed of DCs and that any issues or concerns are addressed in a timely manner (Motawa et al., 2007). Additionally, a collaborative platform can help to streamline the DCM process, making it more efficient and effective (Hao et al., 2008; Pourzarei et al., 2022). The involved stakeholders (e.g., designers, engineers, etc.) could access and share the data and allow for real-time updates in a collaborative platform. In other terms, a collaborative platform could facilitate the communication and collaboration between the involved departments and teams for both internal and external exchanges (Hao et al., 2008; Isaac and Navon, 2008).

Although various tools and methods have been proposed by different research studies (Motawa et al., 2007; Pourzarei et al., 2022), it seems there is still a need for improvement/offer of a collaborative platform to address the aforementioned needs (Pourzarei et al., 2022). BIM platforms are commonly used in construction projects to support various activities, including DCM. However, some scientific literature (Hao et al., 2008; Pourzarei et al., 2022) advocates that PLM platforms are more advanced and therefore it is important to consider whether they could also be used to support construction activities.

This article intends to address the following research question "*Can a PLM platform be utilized to support design change management in construction?*" Therefore, the objective of this article is to evaluate the potential of a specific PLM platform to support the DCM process in construction projects. By examining the features and capabilities of such a platform, we aim to determine its suitability for managing design changes in construction projects. 3DExperience is typically used in the PLM-supported industry and we selected it as the specific PLM platform for this article. This PLM platform was chosen as the primary focus of this research due to its significance in providing important functionalities for the DCM/ECM process, including revision management, impact analysis, and workflow management (Ghnaya et al., 2023a). Additionally, the authors explored several collaborative applications such as SmartUse, BIM 360, Smarteam, and 3DExperience (Ghnaya et al., 2023b). This platform is a software platform that developed by Dassault Systems[6], which is used for product design, simulation, analysis, and manufacturing. It comprises various applications for different phases of the product development process (e.g., CATIA for design, SIMULIA for simulation, and ENOVIA for data management).

It is important to mention that such a platform provides tools for design change management, which can be used to control and manage changes to the product design throughout its development and manufacturing. It helps to ensure that changes are made in a controlled and systematic manner, and that the resulting changes are accurate, consistent, and compliant with relevant standards and regulations (BIOVIA, 2022).

The aim of this article is to assess the potential of a PLM platform for design change management within construction. It examines the various functionalities of the platform and how they can be utilized to enhance communication, collaboration, and data management in the design change process, ultimately improving the overall efficiency and effectiveness of the construction process. This article, therefore, provides some understanding of how a PLM platform can be utilized to support the design change management process in construction and its potential benefits.

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[6] https://www.3ds.com/

This article is structured in seven sections. The section 7.3 provides a brief overview of existing literature on design change management. The section 7.4 details the research methodology used in this study. The section 7.5 presents the findings of the study, focusing on the results of using 3DExperience as a collaborative platform for a typical DCM process. The section 7.6 discusses these findings, providing insights and analysis on the implications of the results. The final section concludes the article.

7.3 Background Research

The definition of design change (DC) states that it refers to any modification made to the design or construction of a project after the contract has been awarded and signed. An interesting aspect of this definition is that it highlights the timing of the DC, which occurs after the contract has been signed. This similarity between the definition of DC and engineering change is noteworthy (Pourzarei et al., 2022), as both involve changes made to the design or construction of a project after a certain stage in the process has been completed. The primary objective of DCM is to ensure that all design changes are recorded accurately and managed efficiently, so that they do not cause delays, budget overruns or other issues throughout the project lifecycle (Pourzarei et al., 2022).

Design change management helps to identify, evaluate and implement design changes while ensuring that they are consistent with the product's original design intent, technical specifications and regulatory requirements. It helps to minimize the potential for errors and inconsistencies, as well as reduce the risk of delays in the design process (Hao et al., 2008; Hwang and Low, 2012; Ibbs, 1994; Mejlænder-Larsen, 2017; Motawa et al., 2007; Pourzarei et al., 2022; Sun et al., 2006).

Design change management also helps to ensure that all necessary parties are informed of changes, and that any issues or concerns are addressed in a timely manner. This can help to minimize the potential for confusion and misunderstandings, and can ensure that the final product meets the needs of all stakeholders (Mejlænder-Larsen, 2017; Pourzarei et al., 2022).

Design change management also provides a historical record of all design changes, which can be useful for future reference and for compliance with regulations (Pourzarei et al., 2022). The effectiveness of using the DCM approach can vary significantly depending on the specific characteristics of the project. Factors such as the nature, type, complexity, and size of the project, as well as the types of contracts involved, can all play a role in determining how successful the use of DCM will be (Hwang and Low, 2012).

To automate such a process, one must first comprehend the information that needs to be changed. In addition, to enhance its efficiency, one should also have a clear understanding of how the information should be classified, organized, interconnected, and managed (Guess, 2002). However, the overall improvement of the change process cannot be achieved unless all types of business information are integrated, structured, and made easily accessible to all involved parties (Guess, 2002).

Hence, a collaborative platform can significantly enhance the effectiveness of the DCM process by enabling a variety of functionalities such as facilitating information sharing, communication, and ensuring that relevant information is accessible at the appropriate time (Isaac and Navon, 2008). Despite the numerous techniques and tools that have been proposed for this purpose (Pourzarei et al., 2022), research studies have shown that there is still a gap in this area, and there is a pressing need for a collaborative platform that can effectively address the requirements of the DCM process (Pourzarei et al., 2022). This platform should be designed to bridge the gap between the different parties involved in the process and provide a centralized location for all the necessary information and tools.

7.4 Methodology

This research article presents a methodology with four key stages. The first stage entails a thorough examination of the existing scientific literature to understand and analyze the DCM process in construction that utilizes BIM technology. The purpose of this literature review and analysis stage is twofold: to describe the main components of the DCM process and compare them with the ECM process in PLM-supported industry, and to determine the necessary functionalities needed to adequately support the DCM process. The main actions in this stage are literature review and analysis, and requirement gathering.

The second stage of the methodology focuses on extracting and analyzing the tools and functionalities provided by the selected PLM platform to support the ECM process. The end goal is to determine the requirements necessary to effectively execute the ECM process within the environment of the selected PLM platform. The main actions in this stage are platform analysis, functionality identification, and requirement determination.

The third stage of the methodology involves a comparison of the extracted DCM process in construction and the ECM process in PLM side. The aim of this stage is to identify and evaluate similarities and differences between the two processes. These comparisons contribute to mapping the offered functionalities to meet the requirements of the DCM process. The main actions in this stage are process comparison and functionality mapping.

The final stage of the methodology highlights how the functionalities provided by the selected PLM platform can address the requirements of the DCM process. This stage provides a visual representation of the functionalities offered by evaluated platform and illustrates how they can be utilized to satisfy the needs of the DCM process. The end goal of this stage is to present a clear understanding of the capabilities of the PLM platform in supporting the DCM process. The main actions in this stage are functionality demonstration and capability presentation.

It's worth mentioning that this article presents the outcomes of the aforementioned methodology, but it does not present all the stages of the methodology.

7.5 A PLM Collaborative Platform

The objective of this section is to evaluate the different functionalities of a specific PLM platform that can be utilized in managing design changes. To accomplish this, the DCM and ECM are compared in the construction and PLM-supported industry to identify similarities and differences. In the second step, the functionalities of the selected PLM platform used in ECM are briefly presented, along with their potential use in the DCM process. The highlighted functionalities will be aligned with the specific requirements of DCM, providing a comprehensive understanding of how this platform can be effectively employed to manage design changes and meet the needs of construction.

7.5.1 Comparison of the DCM in construction and ECM in PLM-supported industry

In this step, it is necessary to compare the DCM process from construction and the ECM process from the PLM-supported industry. It is worth noting that in our previous research (Pourzarei et al., 2022), we conducted a comparative analysis of DCM in construction and ECM in the PLM-supported industry. The comparison and data presented in this article aimed at identifying the main activities and requirements of these two processes. In addition, this study concentrates on the initial four phases of DCM and ECM since they comprise the majority of activities in these processes. Additionally, the table below compares the features of the DCM process utilized in construction with those of the ECM process in the PLM-supported industry (Maurino, 1993). The table presented below outlines the DCM process extracted from the research of (Pourzarei et al., 2022) and the ECM process extracted from the research of (Maurino, 1993).

Table 7.1 Comparison of the DCM in Construction and ECM in PLM-supported industry

Phase	**DCM process in Construction**	**ECM process in PLM-supported industry**
Phase 1	**Initiate**	**Request**
	✓ Initiate the request for information (RFI) ✓ A design change request (DCR) is collected or initialized. ✓ The DCR should address the reason for the change, the priority, the type of change, and which components are likely to be affected.	✓ The engineering change request (ECR) is submitted.
Phase 2	**Evaluate**	**Instruction**
	✓ The DCR impact analysis and feasibility studies are conducted. ✓ A set of potential solutions for the design change is defined. ✓ One solution will be selected and analyzed by the professionals (change management team). ✓ Update mark-up drawings and documents.	✓ The request is analyzed to determine whether it is worthwhile to make the change. ✓ The change management team analyzes and proposes solutions. ✓ One solution is chosen. ✓ Update mark-up drawings and documents.
Phase 3	**Document/Negotiate/Approve**	**Execution**
	✓ The change management team prepares the chosen solution's documents (drawings, specifications, etc.). ✓ Stakeholders (e.g. contractors, professionals, etc.) hold a series of meetings to discuss the price of the requested change. ✓ Based on the evaluation of the requested change, the change management team decides whether to approve or reject the change.	✓ The change management team prepare the documents (drawings, specifications, etc.) for the chosen solution. ✓ Based on the evaluation of the proposed change, the change management team decides whether to approve or reject the change.
Phase 4	**Implement**	**Notification/Application**
	✓ Released the latest version of the documents (e.g., design change notice) for implementation. ✓ Notify the involved teams. ✓ Implement the proposed change. ✓ Monitor and track implementation.	✓ The solution for the change is carried out at the company level over the specified time frame.

In the initial phase of both processes, a problem is identified. In the case of ECM, these problems can arise from design reviews, manufacturing, or even in the field that would lead to ECR. This definition is consistent with the concept of a DCR described in the scientific literature. Similarly to a DCR in literature, any member of the organization can raise an issue. Once identified, the problem can be submitted, tracked, prioritized, and resolved (BIOVIA, 2022). It's appropriate to note that a request for information (RFI) is a type of technical request used to clarify an issue. If the clarification provided to respond the RFI is sufficient to resolve the issue, the case will be closed. However, if further clarification is needed, it will result in a request for a DCR.

The instruction phase in the PLM side is similar in nature to the evaluate phase in the DCM process. Both phases involve assessing and analyzing proposed changes in order to determine their impact. Specifically, the primary task of this phase for both processes is to perform a thorough examination of the requested change, including an analysis of its potential effects on the over-all project or product. In essence, both the instruction phase in the PLM-supported industry and the evaluate phase in the DCM process are focused on ensuring that any proposed changes are carefully considered and evaluated before being implemented.

The third phase of both the DCM and ECM processes requires obtaining approval from the change management team. A key difference between the two processes is that during this phase of the DCM process, there are usually multiple meetings, negotiations, and discussions between teams and departments to determine the cost of the change. Once the change management team approves the chosen solution, the change order moves to the implementation phase. This phase is critical in ensuring that any changes are approved efficiently and in a timely manner.

Not surprisingly, phase four of both the DCM and ECM processes concludes by emphasizing the implementation of documented solutions across the company within a specific time frame. The updated versions of the documents will be shared with the relevant departments to facilitate the implementation.

It is worth noting that there are several notable similarities between the different phases of both the DCM and ECM processes. These similarities could suggest that the use of PLM solutions can be considered for implementing effective DCM practices within construction.

In the subsequent section, we will delve into the various functionalities offered by 3DExperience and describe how they can be applied to meet the specific requirements of the DCM process.

7.5.2 A PLM Platform for DCM

This section provides an understanding of the functionalities of a PLM platform that can be utilized to support the DCM process. It is divided into four parts, corresponding to the four phases of the D/ECM process in 3DExperience: issue management, change request, change order, and change action (BIOVIA, 2022). The characteristics of this process as well as the functionalities of the platform were gathered from two sources: the 3DExperience user manual (BIOVIA, 2022) and the results of a case study conducted with an industrial partner in the aerospace, which utilizes PLM solutions. It is important to note that while the ECM process presented has four phases, in real-world scenarios, the ECM process may vary, with as few as one phase or as many as four phases depending on user needs. However, for the purposes of this research, the full ECM process, comprising all four phases, is considered. This section also examines how these functionalities can be tailored to the DCM process.

7.5.2.1 Phase 1 : Issue Management—Initiate

An issue is a problem that can be raised by anyone in the field (BIOVIA, 2022). This phase encompasses a range of different functionalities, which are presented in Figure 1. This figure helps visualize the various components, which are classified using three distinct colors. Firstly, the central yellow node indicates the name of the phase, which in this case is "issue management." Surrounding this node are five green nodes, each representing a different functionality within this phase. Finally, the eleven blue nodes located around the green nodes represent sub-functionalities of the functionalities. These groups are also applicable to the subsequent phases.

Legend of the Figure (which is applicable for all phases):

- Yellow node: indicate the phase.
- Green node: indicate the functionalities.
- Blue node: indicate the sub-functionalities.

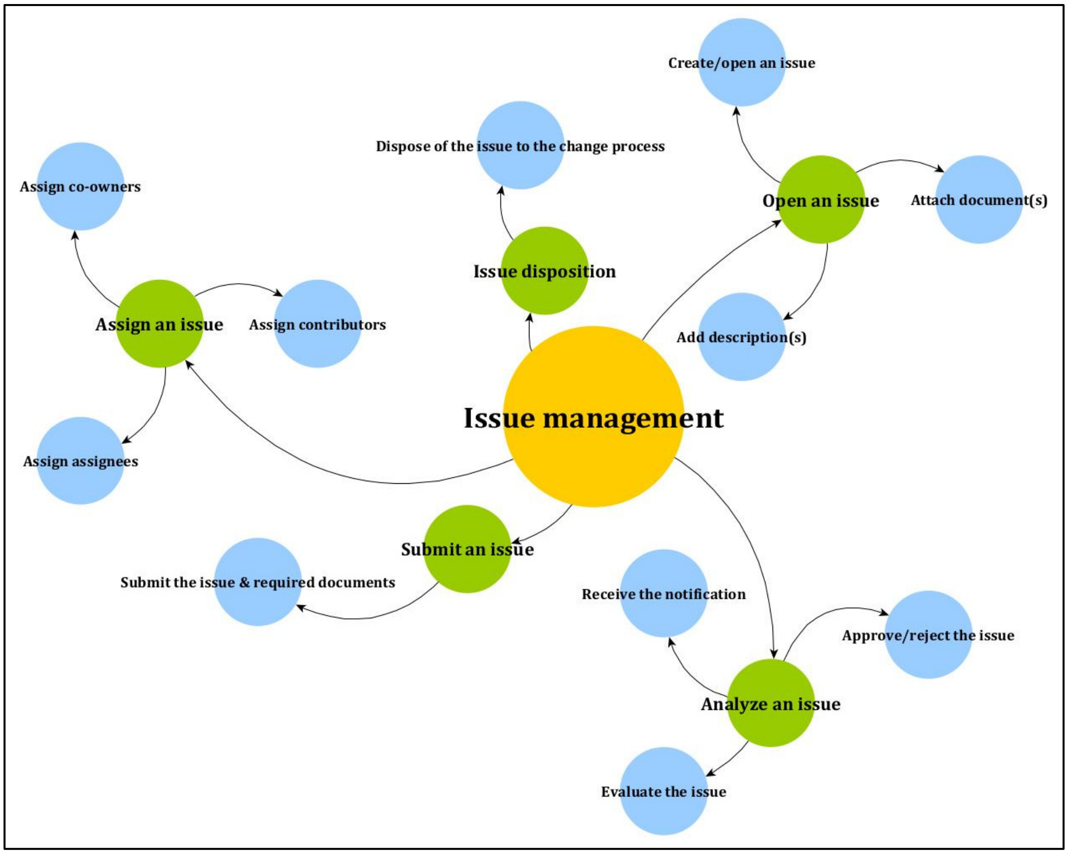

Figure 7.1 Functionalities and sub-functionalities of the issue management phase

During the Initiate phase of the DCM process, these five key functionalities can be utilized. These include opening an issue, submitting an issue, assigning an issue, analyzing the issue, and disposing of the issue. Each of these functionalities has its own set of sub-functionalities that can be customized to fit the specific needs of the project.

The issue encountered in this platform is reminiscent of the RFI/DCR encountered in construction. RFIs are initiated by any user by simply opening a new issue and attaching any relevant documents or explanations for the project team to access. Professionals can then be designated to respond to the RFI and determine whether a DCR is necessary. They perform a pre-feasibility study and provide feedback to the change management team. In this way, the RFI process ensures that all necessary information is gathered and assessed before making any design changes.

7.5.2.2 Phase 2: Change Request—Evaluate

It is at this phase where a thorough analysis of the requested change is conducted to evaluate its potential impact on the project. So it involves the use of various functionalities to perform the impact analysis effectively, which are depicted in the figure presented below. The figure comprises 11 green nodes representing different functionalities, and 34 blue nodes representing sub-functionalities. These elements work to support the impact analysis process and help to identify potential impacts that proposed changes may have on different aspects of a project.

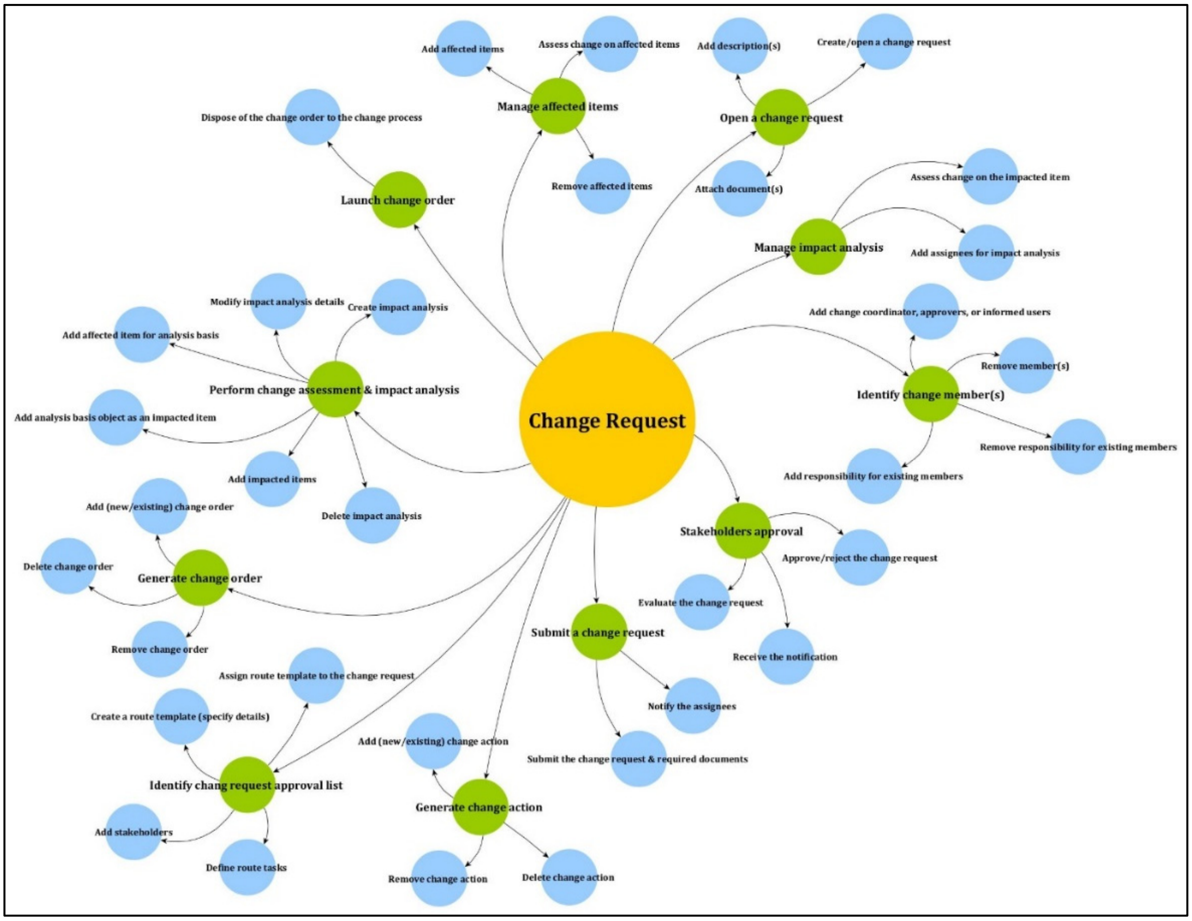

Figure 7.2 Functionalities and sub-functionalities of the change request phase

This phase of the DCM process is a crucial phase as it allows for a thorough analysis of the requested change and the proposed solutions. It is during this phase that the change management team can utilize the functionalities offered by this platform to gain a deeper understanding of the impact of the proposed change. These functionalities include change assessment and impact analysis, which can help in identifying the potential risks and benefits associated with the change, as well as assist in determining the best course of action.

Furthermore, collaboration functionalities (e.g. notify the assignees) are also available for identifying and assigning responsibilities to specific team members. This allows for more effective communication and coordination within the team, ensuring that all members are aware of their roles and responsibilities. Other important activities that take place during this phase include managing affected items, generating a change action plan, managing the impact analysis, identifying and gaining approval from stakeholders, generating a change order, and implementing the approved change order. By managing affected items, the team can ensure that all items that will be impacted by the change are identified and addressed.

7.5.2.3 Phase 3: Change Order—Document/Negotiate/Approve

The third phase of the DCM process may benefit from functionalities depicted in the accompanying figure, which comprises 12 green nodes representing different functionalities and 38 blue nodes representing sub-functionalities

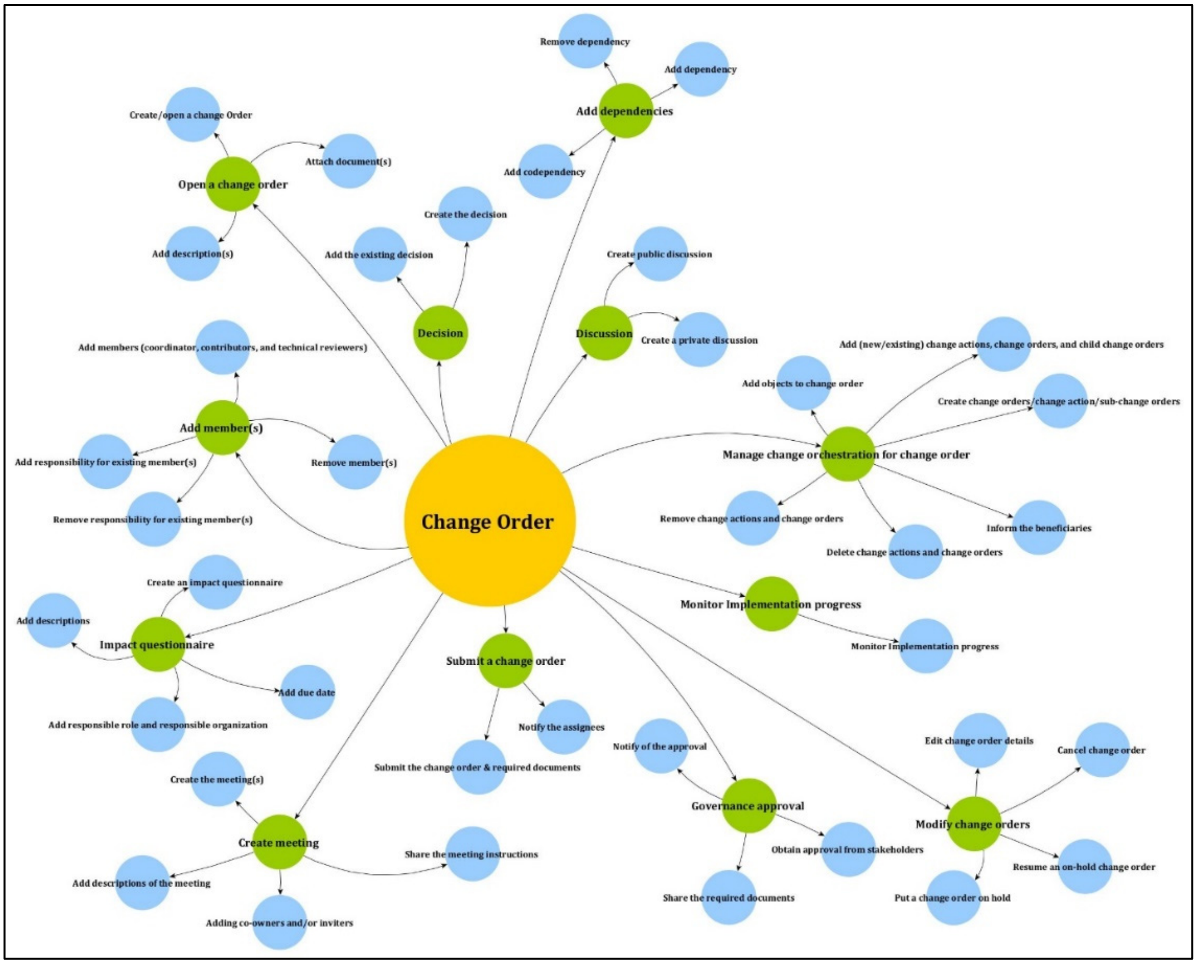

Figure 7.3 Functionalities and sub-functionalities of the change order phase

During this phase, the change management team must make important decisions regarding the proposed change, and negotiate with stakeholders to gain their approval. Additionally, collaboration functionalities are available for effective communication and negotiation with stakeholders, ensuring that all parties are aware of the proposed changes and have an opportunity to provide feedback and approval.

Some of the functionalities that can be applied during the process include creating meetings, discussion sessions, and decisions, as well as gaining governance approval. Creating meetings and discussion sessions allows for effective communication and coordination within the team. These functionalities allow the team to schedule and hold meetings and discussion sessions, and to invite relevant stakeholders to participate.

Creating decisions functionality allows the team to document important decisions made during the process, and governance approval functionality allows the team to gain approval from relevant stakeholders and governing bodies. This is important to ensure that the proposed changes are in compliance with established guidelines and regulations. Overall, the offered functionalities are allowing for effective communication and coordination, as well as making the process more efficient and effective.

7.5.2.4 Phase 4: Change Action—Implement

The activities of this phase include opening a change action, submitting a change action, proposing a change, adding attachments and dependencies, making a decision, and gaining governance approval. The offered functionalities are specifically designed to assist with these activities and are illustrated in the accompanying figure, which includes 7 green nodes representing different functionalities and 21 blue nodes representing sub-functionalities.

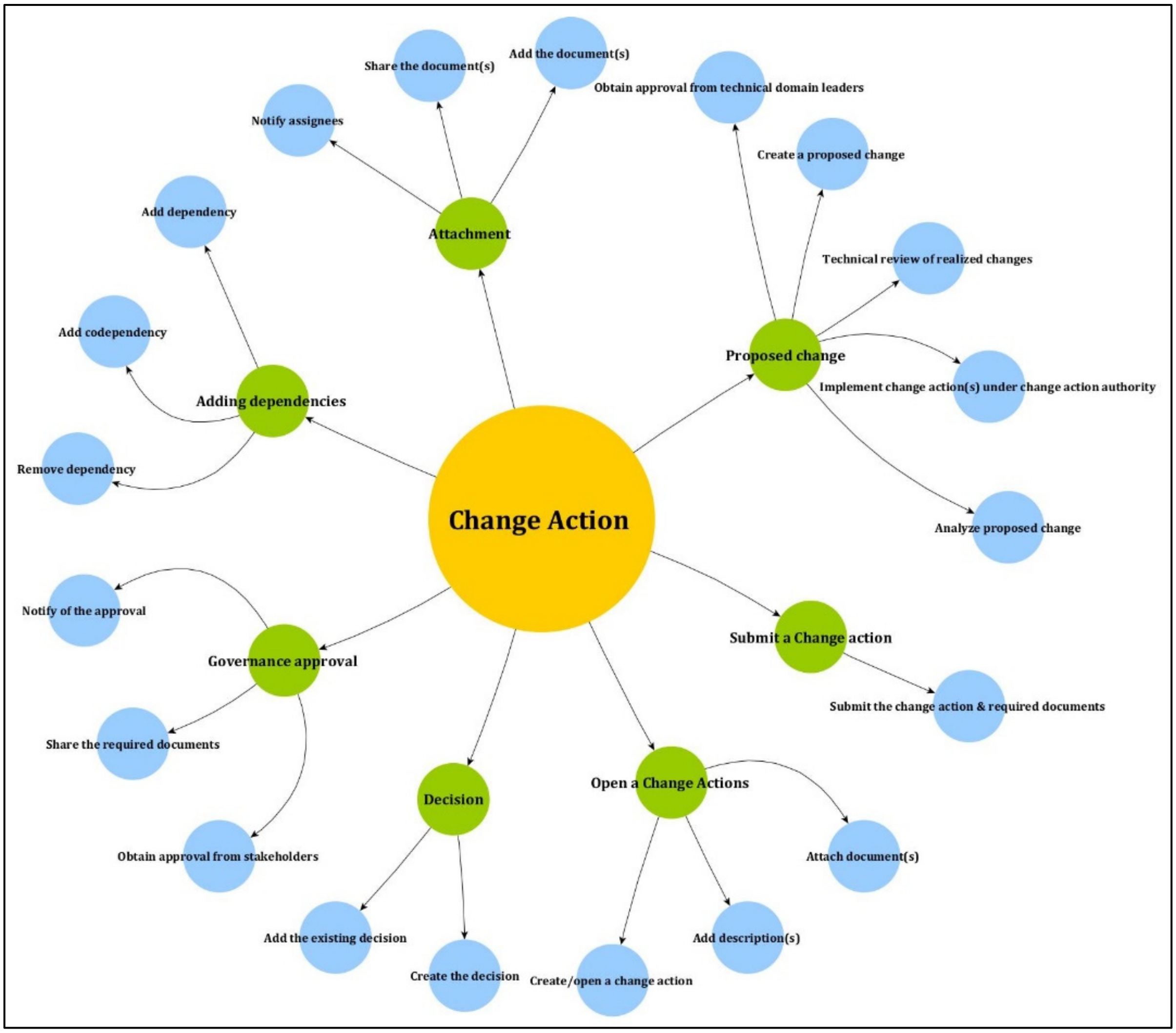

Figure 7.4 Functionalities and sub-functionalities of the change action phase

The Implementation phase of the DCM process requires a number of activities to be completed in order to implement the proposed change. These activities include releasing the latest version of the documents, notifying the involved teams, and monitoring and tracking the implementation (Pourzarei et al., 2022).

Releasing the latest version of the documents is an essential step in ensuring that all parties have access to the most up-to-date information. Notifying the involved teams is another important activity in the Implementation phase. The platform allows the team to quickly and easily notify the relevant stakeholders of the proposed change, making sure that everyone involved is informed about the proposed changes and given the chance to offer their opinions and give their consent.

Monitoring and tracking the implementation is a critical activity in ensuring that the proposed changes are implemented as intended. The platform allows the team to track the progress of the implementation, identify any issues that arise, and take appropriate action to resolve them. This ensures that the proposed changes are implemented efficiently and effectively.

7.6 Discussion

While construction has adopted BIM as a collaborative approach for enhancing communication and information management, the literature suggests that there is still a need for a better collaborative platform (Pourzarei et al., 2020). One potential solution is to utilize the current PLM platform within construction. The implementation of a PLM platform can significantly impact the management of design changes in construction. This is due to the platform's ability to provide a collaborative and integrated environment that enables various stakeholders, such as architects, engineers, and contractors, to effectively communicate and work together on design changes. The figure below illustrates the integration of the DCM process discussed in Section 7.5.1 with the PLM functionalities presented in Section 7.5.2. The purpose of this figure is to depict the potential adaptation of PLM functionalities to the DCM process, thereby mapping their compatibility.

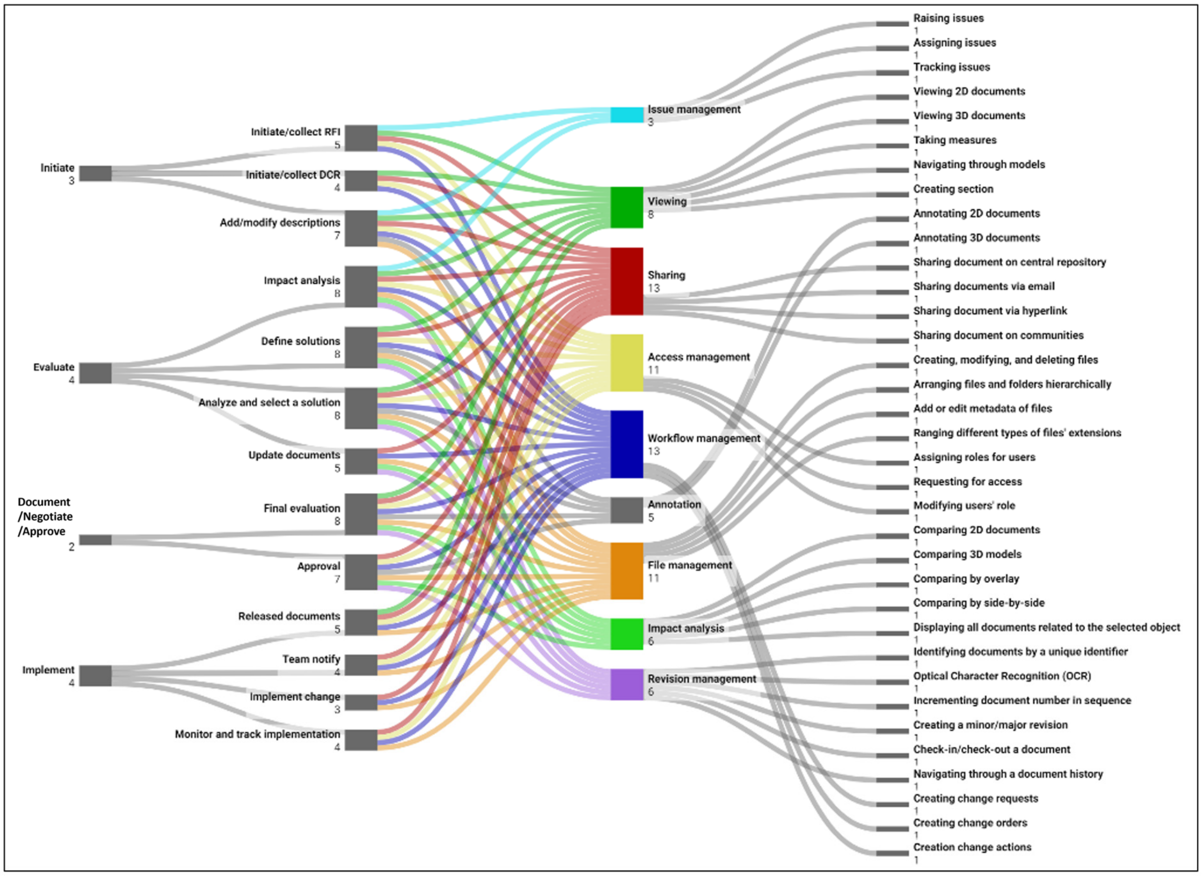

Figure 7.5 Exploring the Relationship between PLM Functionalities and the DCM Process

It is worth noting that the compilation of functionalities and sub-functionalities draws inspiration from the research of (Ghnaya, 2023), and is subsequently generalized. This list effectively categorizes the functionalities and sub-functionalities according to the requirements of the DCM process.

The figure above displays the DCM process stages in the first column, while the second column presents the main activities associated with the DCM process. The third column showcases the categorized functionalities of the PLM platform, with their respective sub-functionalities listed in the fourth column. It is important to note that the numerical values assigned to each activity/functionality indicate the number of relationships it has with others.

The figure 7.5 highlights two notable observations. Firstly, activities such as 'impact analysis,' 'define solution,' 'analyze and select a solution,' and 'final evaluation' have the potential to utilize the most functionalities of the PLM platform. Secondly, 'sharing,' 'access management,' 'file management,' and 'workflow management' emerge as the primary functionalities that can be leveraged in the context of the DCM process. It is important to note that this mapping represents a sample DCM process, and the relationship between DCM activities and functionalities may vary depending on specific company requirements.

The functionalities above could be used in the DCM process to increase productivity in the DCM process. One of the key benefits of using PLM platforms in construction is its ability to provide real-time access to building design data. This allows all stakeholders to access and share the same data, which can help to reduce the risk of errors and inconsistencies, and minimize the potential for delays in the design process. Additionally, the platform's data management capabilities can help to ensure that all necessary parties are informed of changes, and that any issues or concerns are addressed in a timely manner.

The evaluated PLM platform provides tools for design change management, which can be used to control and manage changes to the building design. This can help to ensure that changes are made in a controlled and systematic manner, and that the resulting changes are accurate, consistent, and compliant with relevant standards and regulations.

On the other hand, it is important to highlight that incorporating such a PLM platform into construction may present certain limitations that can be broadly categorized into three areas: complexity, integration difficulties, and cost. The platform may have a complex interface requiring a learning curve for users to be able to use its features and functions. Integrating such a platform with other existing design systems and tools may be challenging and require time and effort. Lastly, implementing a PLM platform can be a costly solution for companies, which might require budget allocation for implementation and maintenance.

7.7 Conclusion

The Design Change Management process plays a crucial role in construction. Its primary goal is to monitor and control design changes throughout the project's lifecycle. Utilizing a collaborative platform for DCM is vital as it provides a communication and collaboration hub for all project stakeholders to effectively manage design changes. This leads to a well-informed team, faster resolution of concerns and issues, and ultimately, a smoother project delivery.

The purpose of this article is to evaluate the potential of a PLM platform for DCM within construction. The findings of this article can be divided into two categories. Firstly, we compared the DCM process from construction with the ECM process from PLM-supported industry to identify similarities and differences. Since there are more similarities than differences, the article then outlines how a PLM platform can support the DCM process in construction. The analysis indicates that the PLM platform (e.g. 3DExperience) can be a potential platform as a collaborative solution for construction as examined from the DCM process standpoint.

CHAPTER 8

DISCUSSION

8.1 Introduction

This chapter provides a comprehensive discussion of the research project in its entirety. It aims to draw connections between and synthesize the findings of the various contributions of this thesis. In doing so, it provides a broader perspective on the research and its implications, and highlights gaps or limitations.

The chapter is divided into two sections. The first section focuses on the findings and contributions of this doctoral project. The second section examines the limitations of the research and opportunities for future work. By analyzing each of these areas, the chapter provides a comprehensive overview of the overall impact of the doctoral project.

8.2 Discussion of the Findings and Contributions

This doctoral thesis intended to make contributions to the scientific literature by addressing research gaps and proposing a novel standpoint for comparing BIM and PLM. While existing studies have offered interesting perspectives on BIM and PLM comparison from different standpoints (Boton et al., 2018; Chen and Jupp, 2019; Di Biccari et al., 2018; Mangialardi et al., 2017), they have involved mainly high-level comparative analyses. However, this thesis provides a comprehensive evaluation of BIM and PLM based on their respective DCM/ECM practices. This thesis is the first to use ECM as a standpoint for comparing BIM and PLM; this approach has not been explored before. An exploratory comparison of DCM/ECM in BIM- and PLM-supported industries made it possible to identify their similarities and differences, and, in turn, unveil potential avenues for improvement in both types of industries. More specifically, the characteristics of DCM/ECM processes and activities, along with the functionalities of IT tools, were thoroughly examined during that analysis.

This doctoral project's first research question was: "is ECM is a suitable standpoint for comparing BIM and PLM?" In Chapter 2, we briefly addressed this question and found that

ECM is an essential practice in both BIM- and PLM-supported industries. The reason we consider ECM to be an adequate standpoint for comparing BIM and PLM is that it is a compact version of the design process (evaluate change, document, approve, etc.) (Quintana, 2011). It is therefore more feasible and easier to replicate and document in the lab than the design process of an entire project. Furthermore, engineering change is omnipresent in the design process. The exploration of DCM and ECM in both theory and practice highlighted their crucial role in influencing company processes. They require a variety of company resources, which can represent considerable time and money. In the (BIM-supported) construction industry, we observed that the DCM process can vary depending on project elements such as the type of contract. Conversely, on the PLM side, our case study revealed that the ECM process followed is obligatory in the aerospace industry. These observations underscore the remarkable significance of DCM/ECM in BIM- and PLM-supported industries and their potential for expansion to the entire product lifecycle.

This doctoral project's second research question was: "how can BIM and PLM be compared from an ECM standpoint?" To answer this question, we needed to perform a thorough comparative analysis of the DCM and ECM processes used in theory and in practice in BIM- and PLM-supported industries and identify their similarities and differences. Three main aspects were compared: the terminology used, the DCM and ECM processes used by stage and activity, and the tools and functionalities used. When it came to comparing the terminology used, the analysis delved into the use of different terms, vocabularies, and descriptions in the DCM/ECM processes considered. The comparison of the processes used involved exploring the activities and stages included in the DCM/ECM processes, as described in both theory and practice. The comparison of the IT tools used focused on the functionalities of the tools incorporated in the DCM/ECM processes in theoretical and in practice. BPMN and metamodels were utilized to document, analyze, and compare the information.

This comparative analysis helped us to characterize the strengths and limitations of the existing DCM/ECM practices. Some of these advantages and challenges are as follows. Regarding BIM and the DCM, speaking of the benefits: efficiency through standardization—standardized DCM process could enhance efficiency by streamlining routine changes and reducing decision-making time. Improved collaboration—detailed DCM process facilitates cross-functional collaboration, enabling better communication and coordination among stakeholders.

Regarding the challenges for DCM, complexity and flexibility—construction industry with complex designs may face challenges in accommodating complex design changes swiftly, requiring adaptable processes to manage varying degrees of intricacy. Balancing cost and creativity—highlining a balance between cost-conscious decision-making and innovative design changes can be particularly challenging, especially in industries with tight budgets.

On the other hand, on the PLM side and for the ECM, some advantages are as follows: risk mitigation—robust ECM process minimizes risks associated with engineering changes, ensuring that modifications align with safety and regulatory standards. Continuous improvement—ECM-driven feedback loops facilitate continuous improvement by capturing lessons learned from previous changes, enhancing overall product quality. Traceability and compliance—industries subject to rigorous compliance standards benefit from ECM process that ensure thorough documentation, aiding traceability and audits.

Regarding the challenges for the ECM, balancing urgency—rapid response to change requests while maintaining a thorough evaluation can be challenging, particularly in time-sensitive industries. Resource management—allocating resources for engineering changes in industries with complex products demands strategic resource management to prevent disruptions. Stakeholder alignment—managing stakeholder expectations and securing approvals, especially in industries with numerous stakeholders, requires effective communication and collaboration.

Once the comparative analysis was complete, we were able to pinpoint the similarities and differences between the processes. Identifying their similarities makes it possible to pave the way for greater collaboration and knowledge sharing between the BIM and PLM domains. To achieve this cross-pollination, we referred to the third research question of this doctoral project, which was: “how can the comparison of BIM and PLM from an ECM standpoint help cross-pollination between BIM and PLM in BIM- and PLM-supported industries?” To address this question, we needed to identify suitable candidates for cross-pollination, and then determine how these candidates can be harnessed for effective cross-pollination. By tackling these points, we can facilitate the transfer of knowledge and best practices between BIM- and PLM-supported industries and, in turn, enhance efficiency and innovation across the board.

The findings of the previously mentioned thorough comparative analysis of the DCM and ECM processes used in theory and in practice served to address the first of these two points (identify suitable candidates for cross-pollination). The following paragraphs outline some components that may be suitable for cross-pollination and examples of potential candidates. It is important to note that these examples are provided to lay the groundwork for cross-pollination efforts by establishing a framework.

When it comes to terminology, it was observed that ECM processes in PLM-supported industry tend to utilize consistent terminology. Conversely, in BIM-supported industry, the terminology used can vary depending on whether the project is public or private. As a result, identifying a suitable candidate for cross-pollination in this category may require developing reference terminology for BIM-supported industry that can be applied consistently across all projects. Establishing standard reference terminology could significantly facilitate and streamline the DCM process for greater efficiency and effectiveness.

As for the DCM/ECM processes used, which encompassed a variety of activities, they represented significant potential for cross-pollination between BIM and PLM. While the activities involved in the DCM and ECM processes considered were generally similar, differences did arise due to the unique nature of each industry and variations in company policies and practices. For example, on the BIM side, predicting potential changes based on proactive rules is a technique used to anticipate changes that may occur during a project. It usually draws upon lessons learned from ongoing and previous projects to identify potential changes that could arise. Although this candidate is not yet widely implemented in practice in BIM-supported industry, it is briefly outlined in the literature and has the potential to be further developed on both the BIM and PLM sides.

In addition to the potential candidates for cross-pollination of process activities, there are other opportunities that should be considered. Improving the evaluation activities, such as pre-feasibility studies, presents a chance for mutual exchange between BIM and PLM sides. Another avenue worth exploring involves the adoption of a tracking approach to oversee the status of changes, exemplified by the flagging system. This approach takes its origin on the PLM side and could be transposed into the BIM side. Moreover, the utilization of insights taken from past experiences (lessons learned) to conduct impact analyses and facilitate decision-making necessitates a strategy on both sides. Lastly, the task of identifying, documenting, and classifying lessons learned, which is inherently rooted in the PLM side, has the potential to cross-pollinate and transition into the BIM side.

The IT tools used also included several potential candidates for cross-pollination. One particularly interesting candidate is the use of a hybrid environment. For instance, our industrial partner on the PLM side currently uses a hybrid environment that includes both commercial and in-house applications. The in-house applications have been custom-built to meet the company’s specific needs and requirements. This raises the possibility of developing a hybrid environment or transferring this one to BIM-supported industry, where it could similarly enhance productivity and streamline processes. By leveraging the benefits of a hybrid environment, companies on the BIM side could potentially improve their IT infrastructure and better manage their workflows, which would ultimately result in more efficient and effective project management. It is important to mention that this idea does not directly provide evidence indicating in-house applications are the best solution. However, it is worth considering that in-house applications offer benefits like greater customization for specific needs and improved data security, which could be why some industries prefer them over other alternatives.

Other potential candidates among the IT tools used included specific software applications or platforms that are used in one industry but not the other. For instance, using a collaborative platform (e.g. 3DExperience) to facilitate document transfer, communication, BOM modifications, version control, task monitoring, and lifecycle management. Additionally, the automation of processes such as paperless workflows, originating in PLM and extending to BIM, has the potential to enhance process productivity. Furthermore, the integration of an internal search engine to optimize database searches, transitioning from PLM to BIM, could offer a simplified search experience for diverse users, ultimately leading to productivity. By exploring these differences and identifying areas in which IT tools from BIM- or PLM-supported industries could be adapted for use in the other type of industries, cross-pollination can help to promote the adoption of more effective and advanced technologies in both BIM- and PLM-supported industries.

When addressing the second of the two points mentioned above (determine how these candidates can be harnessed for effective cross-pollination), it is important to consider the three pollination patterns proposed by Pourzarei et al. (Pourzarei et al., 2020): self-pollination, cross-pollination (transposition), and cross-pollination (combination).

- *Self-pollination* – involves improving or creating components through self-learning or self-improvement. This type of pollination could be employed in both PLM- and BIM-supported industries by implementing best practices and learning from past experience.
- *Cross-pollination (transposition)* – aims to enhance the capabilities of a holistic object by adapting components from another holistic object. Based on the above discussion points, this type of pollination could be implemented in both BIM- and PLM-supported industries by transferring successful DCM/ECM processes, terminology, and IT tools from one industry to the other with some adjustments. This way, each industry can improve its own processes and tools by adapting ones that have proven successful in the other industry.
- *Cross-pollination (combination)* – involves creating a new holistic object by merging components from different sources to enhance the strengths and mitigate the weaknesses of the parent objects. This type of pollination could be used in both industries to create new DCM/ECM processes or tools that combine the best features of both BIM- and PLM-supported industries. For example, a hybrid environment, as discussed earlier, could be created by combining PLM and BIM software tools to increase productivity and improve the management of construction projects.

In summary, the three pollination patterns could each be applied to both PLM- and BIM-supported industries to improve their DCM/ECM processes, terminology, and IT tools. Each pattern offers a unique way to create and improve components of a holistic object, whether through self-improvement, transposition, or combination.

8.3 Discussion of the Limitations and Future Work

Collaborating with industrial partners was one of the major challenges of this doctoral project. Although a variety of companies were considered as candidate partners, the fact that the collaboration process proved to be time-consuming and the project's time frame was limited made collaboration very challenging. Another challenge was that the DCM process could vary from one project to another depending on the company's role, the type of contract, and other factors. In this study, we could focus on only two industrial partners with three private projects on the BIM side. Additionally, confidentiality posed a limitation on the PLM side. Although these limitations restrict the generalizability of the study's results, the results provide insights into the feasibility and potential of cross-pollination between BIM- and PLM-supported industries. Future research could consider a more extensive range of industrial partners and projects to gain a more comprehensive understanding of the potential benefits and challenges of cross-pollination between these two industries.

Additionally, all collaboration between the research team and industrial partners was conducted remotely due to the Covid-19 pandemic. Remote collaboration can involve challenges in terms of communication, coordination, and the quality of data collection, as well as potential delays. As a result, this research project took longer than expected to complete. The lack of face-to-face interaction also made it difficult to establish a strong relationship with the industrial partners and fully understand their needs and expectations. However, the research team made every effort to overcome these challenges by employing effective communication strategies and utilizing advanced online collaboration tools to ensure the collaboration process was productive and efficient.

The other major limitation of this doctoral project was the difficulty encountered in identifying, evaluating, and implementing the potential candidates for cross-pollination. This task requires another period of in-depth investigation and perhaps more collaboration with various industrial partners. Given the scope and time frame of this research study, it was not possible to explore, analyze, and implement all possible candidates for cross-pollination. However, the framework/approach presented in Section 8.2 could be used as a starting point for further research and development. Future studies could build upon this approach and explore additional candidates for cross-pollination using a larger and more dedicated research team and a longer time frame.

CONCLUSION

This thesis explores building information modeling (BIM) and product lifecycle management (PLM) and aims to identify opportunities for improvement in BIM- and PLM-supported industries. More precisely, the overall objective of this thesis project was to compare BIM and PLM from the standpoint of ECM to identify potential characteristics and functionalities for cross-pollination between BIM and PLM. To achieve this objective, this research spanned more than four years and involved extensive investigation, analysis, and evaluation of the scientific and industrial worlds.

The methodology for this doctoral project is structured into four main phases. The first phase encompassed a theoretical study of DCM/ECM, carried out through an in-depth review of relevant literature. Moving on to the second phase, attention shifted towards practical case studies. Three industrial partners—two construction companies and one aerospace company—participated in case study evaluation and data collection. Collaboration enabled the researchers to describe the DCM/ECM processes actually used in these companies and compare theory with their reality. Four BPMN processes were extracted from these case studies and evaluated and compared to identify their similarities and differences. Transitioning to the third phase, the focus was on conducting a laboratory experiment that incorporated DCM/ECM processes. Lastly, in the fourth phase, a framework/approach is proposed to identify the potential characteristics and functionalities for cross-pollination between BIM and PLM.

The contributions of this thesis can be broken down into two main categories: scientific impacts and industrial impacts. There were three main scientific impacts. First, the thesis *improved the descriptions of design change management (DCM) and engineering change management (ECM) practices*. While previous studies offered high-level comparative analyses, this research delves deeper into the specific characteristics and processes of DCM and ECM in each industry. By thoroughly examining the terminology, stages, and activities involved in these practices, the thesis enhances our understanding of how DCM and ECM are implemented in different contexts.

The improved descriptions of DCM and ECM processes can provide valuable insights to practitioners and researchers in both industries, helping them better understand these processes and ultimately leading to more effective and efficient project execution. Here are some examples of how the improved descriptions can contribute to their understanding:

- *Clarity and detail:* enhanced descriptions provide clear and detailed insights into the stages and activities of DCM and ECM processes.
- *Process variations:* recognition of deviations between theory and practice equips practitioners with the flexibility to handle unique scenarios and adapt processes accordingly.
- *Role differentiation:* understanding the influence of role distinctions within project teams enhances decision-making dynamics and responsibility allocation. For instance, as we saw in Chapter 5, the project manager in project A, the company consulted with the client, whereas in project B, assuming greater responsibilities and control over the DCM process, such as deciding to create supplementary instructions for changes.
- *Customization for industries:* recognition of industry-specific practices guides practitioners with tailored approaches while offering researchers avenues for investigating process impact.

As a second contribution, *this thesis characterized the strengths and limitations of existing DCM/ECM practices and sought to combine their strengths and mitigate their limitations*. The thesis goes beyond merely comparing DCM and ECM practices to identify their respective strengths and limitations. By incorporating an in-depth analysis of DCM/ECM processes and activities used in theory and in practice, it highlights the advantages and challenges that are unique to each side. On the BIM side and for the DCM, we could refer to some of the advantages and challenges as follow: efficiency through standardization, improved collaboration, complexity and flexibility, and balancing cost and creativity. On the other hand, on the PLM side and for the ECM, we could refer to some of the advantages and challenges as follow: risk mitigation, continuous improvement, traceability and compliance, balancing urgency, resource management, and stakeholder alignment.

Understanding these nuances opens the door for potential best practice cross-pollination between BIM and PLM. Adopting a transposition or combination pollination pattern makes it possible to integrate the strengths of one industry's approach in the other industry's approach and effectively mitigating their respective limitations. This fosters a collaborative environment in which industries can learn from one another's experience and collectively improve their DCM/ECM practices.

Thus, as a third contribution, the thesis *opened up new avenues for identifying potential candidates for cross-pollination between BIM and PLM to improve productivity in both BIM- and PLM-supported industries*. The novel standpoint—ECM—this thesis uses to compare BIM and PLM provides a new perspective on opportunities for cross-pollination between the two industries. The exploratory comparison of DCM and ECM that was performed as part of this thesis reveals similarities and differences that highlight potential candidates for cross-pollination.

Some of the potential candidates for cross-pollination that are presented briefly in the discussion as s follow: improving the evaluation activities (e.g. pre-feasibility study); using a tracking approach to follow up on the status of changes (e.g. flagging system); predicting potential changes based on proactive rules; using a collaborative platform for transferring documents, communications, BOM modifications, version management, task tracking, lifecycle management, etc.; creating a hybrid environment that includes both commercial and in-house applications; and implementing an internal search engine to facilitate searching within the internal database.

One example of a potential candidate is adopting a hybrid IT environment similar to the one used by our PLM-side industrial partner to enhance productivity and streamline processes in BIM-supported industry. It is important to note that this idea does not directly provide evidence indicating in-house applications are the best solution. However, it is worth considering that in-house applications offer benefits like greater customization for specific needs and improved data security, which could be why some industries prefer them over other alternatives.

By opening up these new avenues for cross-pollination, the thesis provides insights for stakeholders in both industries and encourages knowledge-sharing and innovation for overall productivity improvement.

As for industrial impacts, several insights emerged from the comparison of ECM in theory and practice in the aerospace industry and DCM in theory and practice in the construction industry. The research revealed that the ECM process used in practice is more detailed compared to the theoretical ECM process, with variations in the initiation of change requests and the involvement of different stakeholders, such as the client for approval, depending on the industry context. Similarly, in the construction industry, the DCM processes used in practice generally incorporated the same stages and activities as those proposed in theory. However, differences arose in the level of detail and complexity of the process depending on the nature of the design change and the number of stakeholders involved. Furthermore, while collaborative platforms for DCM are gaining interest in practice, commercial applications offer promising functionalities for model comparison, impact analysis, and decision-making support. Overall, the research provides insight into the practical implementation of ECM and DCM, reveals areas of alignment and divergence between theoretical propositions and real-world practices, and sets the stage for further advancements and cross-pollination efforts in both industries.

Furthermore, the thesis explored the feasibility of adopting a PLM platform, specifically 3DExperience, as a collaborative platform for construction. Despite potential complexities, integration challenges, and the associated costs, the evaluation revealed that the PLM platform provides a promising opportunity to enhance DCM practices and boost productivity in construction. More precisely, this PLM platform provides some important functionalities for the DCM process, including revision management, impact analysis, and workflow management. The platform’s collaborative and integrated environment enables construction stakeholders including architects, engineers, and contractors to effectively communicate with one another and work together on design changes. Despite the limitations identified, the PLM platform’s potential benefits make it a possible candidate to support and improve DCM practices in the construction industry.

This doctoral project's recommendation for future work is to the exploration of cross-pollination candidates. More precisely, it is recommended to employ the proposed framework/approach to explore more in identifying, evaluating, and implementing the potential candidates for cross-pollination between BIM- and PLM-supported industries. For comprehension and validation purposes, it is recommended to conduct additional case studies in both BIM- and PLM-supported industries. These additional case studies will provide valuable insights into how different project elements, such as the company's role and the type of contract, impact the DCM process in BIM-supported industry. This analysis will make it possible to assess the cross-pollination candidates' applicability and effectiveness in practice.

In conclusion, this thesis makes a valuable contribution to BIM- and PLM-supported industries. By identifying opportunities to improve ECM practices, characterizing the strengths and limitations of existing practices, and opening up new avenues for cross-pollination, this thesis can help these industries be more efficient.

APPENDIX I

BPMN PROCESSES

Here are the BPMN processes of projects A, B, and C of the case studies.

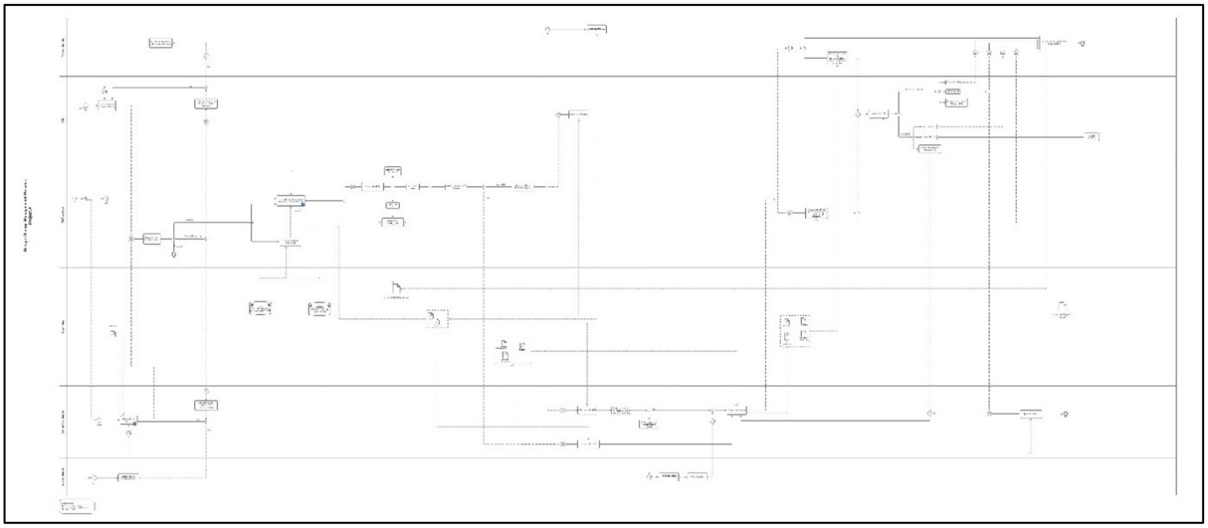

Figure-A I-1 The BPMN process of the project A

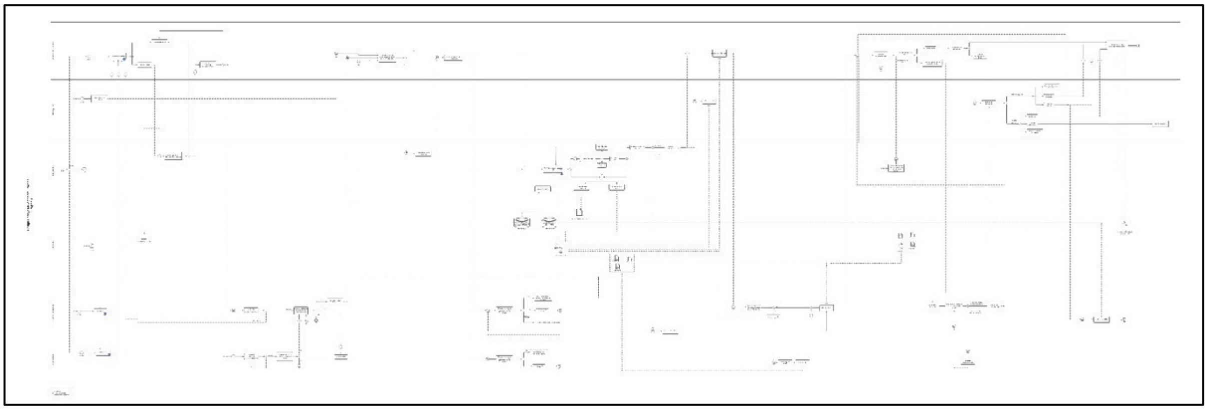

Figure-A I-2 The BPMN process of the project B

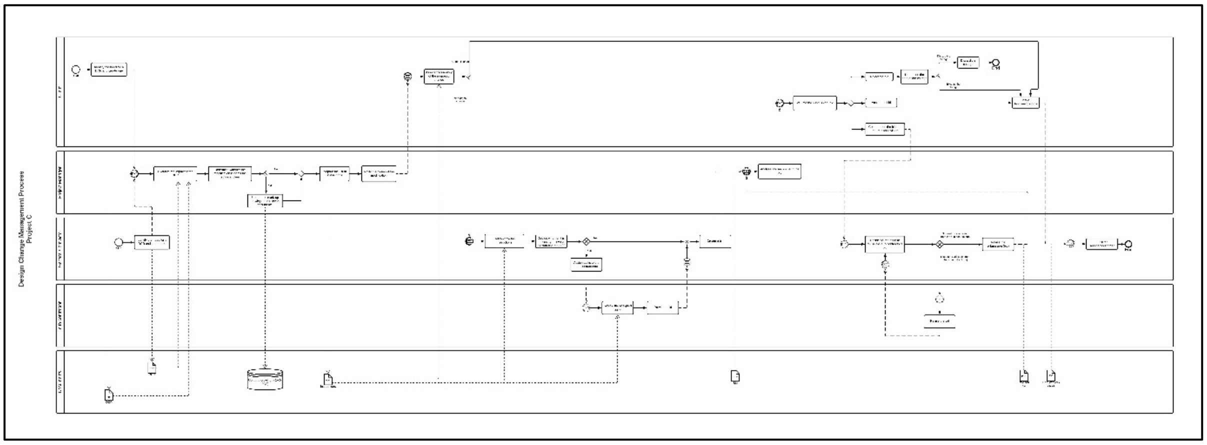

Figure-A I-3 The BPMN process of the project C

APPENDIX II

RESEARCH METHODOLOGY

Here is the research methodology of this doctoral project.

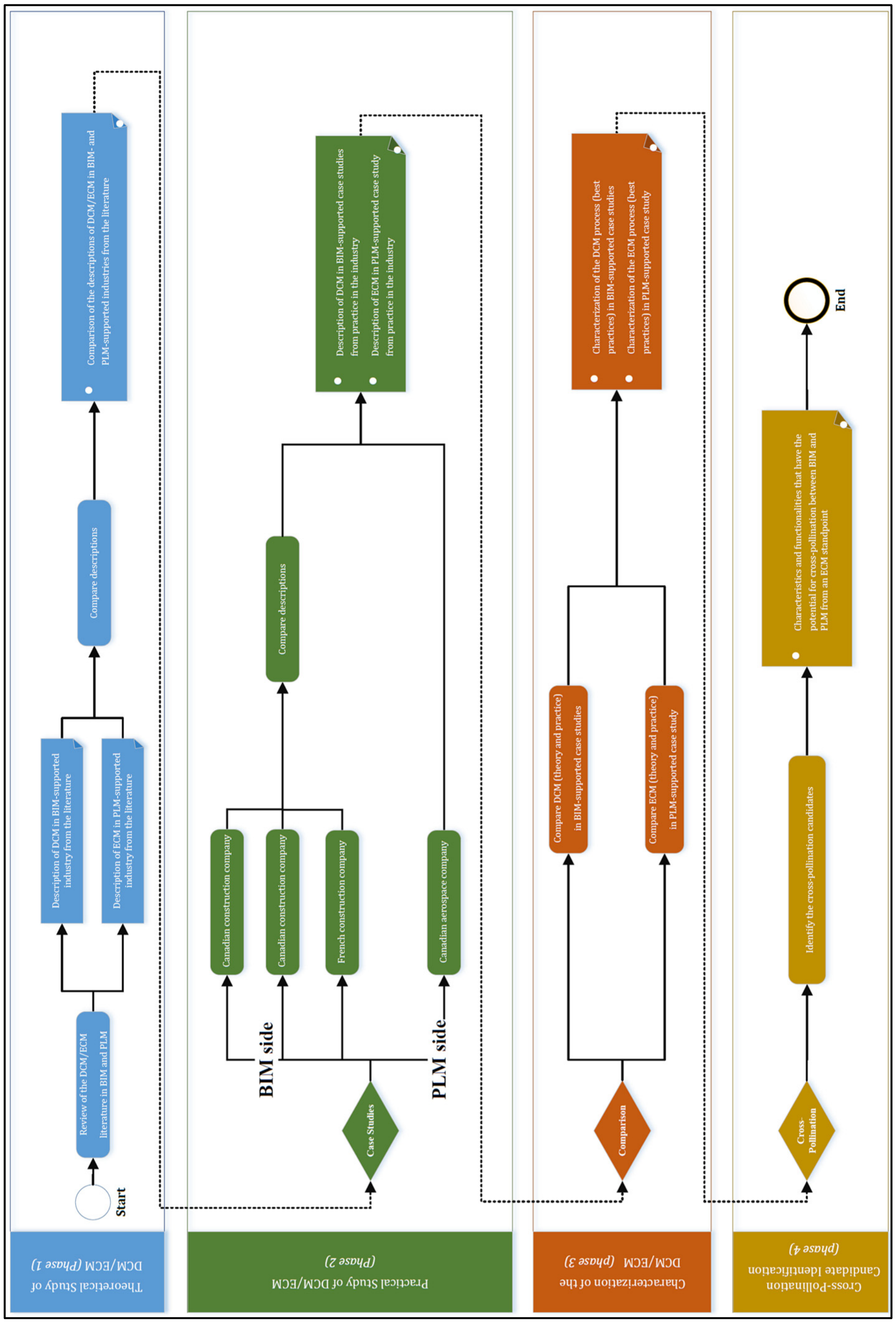

Figure-A II-1 The research methodology

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