A method and a taxonomy to identify the sources of waste in the production and exchange of information in construction

by

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ACKNOWLEDGMENT

Six years ago, I embarked on a new journey not fully knowing what I was getting into. At that time, I was a newcomer in Montreal, an international student who wanted to build something new in a new part of the world.

Back then, I had just finished my studies as an Environmental Engineer with a bachelor’s degree in the Netherlands and a master in Scotland. I came to Montreal and had to start a new master’s in construction engineering to help facilitate my integration into the employment market. As soon as I heard about Building Information Modelling and Lean Construction, I knew I wanted to pursue a carrier in this field. When came the time to start a research project to finish my master’s degree, my supervisors encouraged and supported me to exchange it into a Ph.D. program to further develop my knowledge in this field.

This research project would not have been possible without the help and support of many people. First, I wish to express my sincere gratitude to my advisors, Professor Forgues and Professor Ouellet-Plamondon.

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Une méthode et une taxonomie pour identifier les sources de gaspillages dans la production et l'échange d'information dans la construction

Martin MICHAUD

RÉSUMÉ

Les travaux de recherche présentés dans cette thèse étudient la présence de gaspillage dans les flux d'information de projets de construction dans l'industrie de l'architecture, de l'ingénierie et de la construction (AEC). La modélisation des informations du bâtiment (BIM) a été introduite dans l'industrie de l'AEC en tant que technologie révolutionnaire visant à améliorer la productivité, en partie grâce à une centralisation de l'information. Cependant, la présence de gaspillage, notamment dans les flux d'informations, empêche le BIM d'atteindre son plein potentiel. Il y a une importance grandissante de la gestion des flux d'informations, et la motivation derrière la recherche était due au fait que peu de recherches sur les gaspillages dans la gestion de ces flux sont réalisées. Une explication possible est le fait que la notion de flux d'information reste mal comprise. Il était donc nécessaire d'établir une taxonomie sur les sources de gaspillages au sein des flux d'information de la construction pour permettre une meilleure compréhension de ce flux.

Par conséquent, la question de recherche suivante a été formulée: Comment gérer le problème des gaspillages dans la production et l'échange d'informations dans l'industrie AEC? Cette thèse a été construite sur une méthode de recherche collaborative en Design Science (CDSR) pour aborder des problèmes pratiques grâce à la collaboration de professionnels et de chercheurs. La méthodologie comportait trois étapes principales: diagnostiquer, développer une proposition avec deux sous-étapes qui consistaient à développer une méthode et développer un artefact, et enfin à valider à l'aide de l'approche ShareLab.

Le diagnostic a fourni les bases de l'ensemble de la recherche, l'identification des principales lacunes de la littérature avec la collecte et l'analyse de données qualitatives dans l'identification des problèmes dans les flux d'information de la construction. En conséquence, une méthode a été développé et mis en œuvre pour améliorer les flux d'informations dans la production de modèles BIM. Cette méthode a été conçu pour identifier les sources de gaspillage sur la base d'une taxonomie existante conçue pour les flux de travail. Cette méthode a souligné la nécessité d'une taxonomie des sources de gaspillage axée spécifiquement sur les flux d'informations. Ainsi, en utilisant la méthode conçue, une proposition de taxonomie a été développée et proposée comme un artefact pour la méthode générale de cette recherche. Enfin, l'artefact a été validé en utilisant l'approbation et l'aval d'un professionnel utilisant l'approche ShareLab. L'approche ShareLab a été utilisée dans la recherche comme un moyen de développer un consensus parmi les professionnels de l'industrie AEC concernant la validation de l'artefact.

Pour répondre aux exigences de la thèse, trois articles forment le corps de cette thèse, ils ont été soit publiés, acceptés pour publication ou soumis dans des revues académiques évaluées par des pairs. Le premier article fournit les bases de l'ensemble de la recherche à travers une étude observatoire sur la situation actuelle des flux d'informations dans les projets de

construction BIM. Le deuxième article propose une méthode développé grâce à l'utilisation de la Cartographie de Processus dans une approche de recherche-action collaborative. La méthode est conçue pour améliorer les flux d'informations pour la production de modèles BIM en identifiant les sources de gaspillages. Le troisième et dernier article met en œuvre cette méthode à travers l'utilisation d'une méthode CDSR pour développer une nouvelle taxonomie basée sur les sources de gaspillages dans les flux d'informations des projets de construction. Cette taxonomie est également validée en utilisant l'approche ShareLab et l'approbation des professionnels.

Cette thèse apporte une contribution originale à la pratique et aux connaissances en fournissant une taxonomie des sources de gaspillage dans les flux d'informations des projets BIM. La taxonomie apporte une réponse au manque de littérature concernant la présence de gaspillage dans les flux d'informations des projets de construction, car la taxonomie existante se concentre principalement sur les matériaux et les flux de travail. De plus, une autre contribution à la connaissance est celle de l'utilisation d'une nouvelle approche pour valider un artefact dans une méthode de recherche du Design Science. En effet, la validation de la taxonomie a été obtenue grâce à l'agrément de professionnels lors d'une démarche ShareLab.

Les professionnels peuvent utiliser la taxonomie proposée en utilisant la méthode conçue au cours de cette recherche. En effet, la méthode fournit les étapes que les professionnels doivent suivre pour identifier les sources de gaspillage au sein des flux d'information de leurs projets. Cette méthode aidera à terme les professionnels à améliorer leur productivité. De plus, cette méthode peut être amélioré dans le futur au cas où de nouvelles sources de gaspillage seraient identifiées. Dans les travaux futurs, la méthode pourra être associé à des solutions potentielles pour chaque source de gaspillage présente dans la taxonomie comme indiqué dans une section de cette recherche.

Mots-clés: Building Information Modeling (BIM), gaspillage, flux d'informations, taxonomie, cartographie des processus.

A method and a taxonomy to identify the sources of waste in the production and exchange of information in construction

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ABSTRACT

The research work presented in this thesis investigates the presence of waste within the information flows of construction projects in the Architecture, Engineering and Construction (AEC) industry. Building Information Modelling (BIM) was introduced to the AEC industry as a breakthrough technology aimed at improving productivity, partly through centralized information. However, the presence of waste, especially in the information flows, prevents BIM to reach its full potential. There is a growing importance in the management of information flows, and the motivation behind the research was due to the fact that little research on waste in the management of this flow is realized. A possible explanation is the fact that the notion of information flow remains poorly understood. Thus, there was a need to establish a taxonomy on the sources of waste within the information flows of construction to provide a better understanding of this flow.

Therefore, the following research question was formulated: How to manage the problem of waste in the production and exchange of information in the AEC industry? This thesis was built on a Collaborative Design Science Research (CDSR) method to address practical issues through the collaboration of professionals and researchers. The methodology had three main steps including diagnosing, developing a proposition with two sub-steps which were to develop a method and develop an artefact, and finally validating using the ShareLab approach. The ShareLab approach was used in the research as a way to develop a consensus among professionals from this AEC industry regarding the validation of the artefact.

The diagnosing provided the groundwork for the entire research the identification of the main gaps in the literature with the collection and analysis of qualitative data in the identification of issues in the information flows of construction. Accordingly, a method was developed and implemented to improve information flows in the production of BIM models. This method was designed to identify sources of waste based on an existing taxonomy designed for the work flows. This method highlighted the need for a taxonomy of sources of waste focus specifically on the information flows. Thus, by using the designed method, a proposition of the taxonomy was developed and proposed as an artefact for the general method of this research. Finally, the artefact was validated using the approval and endorsement of professional using the ShareLab approach.

To meet the thesis requirements, three articles form the body of this thesis, that have been either published, accepted for publication or submitted in peer reviewed academic journals. The first article provides the groundwork for the entire research through an observatory study on the current situation on the information flows in BIM construction projects. The second article proposes a method developed through the use of Process Mapping (PM) in a collaborative action research approach. The method is designed to improve information flows

for the production of BIM models by identifying sources of waste. The third and last article implements this method through the use of a CDSR method to develop a new taxonomy based on the sources of waste in the information flows of construction projects. This taxonomy is also validated using the ShareLab approach and the approval and endorsement from professionals.

This thesis brings an original contribution to the practice and knowledge by providing a taxonomy of the sources of waste in the information flows of BIM projects. The taxonomy provides an answer to the gap in literature regarding the presence of waste in the information flows of construction projects, as the existing taxonomy focused primarily on work and material flows. Moreover, another contribution to knowledge is that of the use of a new approach to provide validation to an artefact in a Design Science Research method. Indeed, validation of the taxonomy was obtained through the approval of professionals during a ShareLab approach.

The professionals can employ the taxonomy proposed by using the method designed during this research. Indeed, the method provides the steps that the professionals need to follow in order to identify the sources of waste within the information flows of their projects. This method will in term help professionals improve their productivity. In addition, this method can be upgraded throughout the future in case new sources of waste are identified. In future work, the method can be coupled with potential solutions for each source of waste present in the taxonomy as shown in a section of this research.

Keywords: Building Information Modelling (BIM), waste, information flows, taxonomy, process mapping.

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LIST OF ABBREVIATIONS

AEC	Architecture, Engineering and Construction
BEM	Building Energy Modelling
BEP	BIM Execution Plan
BIM	Building Information Modelling
BPMN	Business Process Model and Notation
BPR	Business Process Re-engineering
CAD	Computer Aided Design
CAR	Collaborative Action Research
CDSR	Collaborative Design Science Research
DMAIC	Define, Measure, Analyze, Improve and, Control processes
DSM	Design Structure Maintenance
DSR	Design Science Research
GC	General Contractor
IFC	Industry Foundation Classes
IPD	Integrated Project Delivery
IT	Information Technology
JIT	Just In Time
KM	Knowledge Management
CAD	Computer Aided Design
LPS	Last Planner System
MEP	Mechanical, Electrical and Plumbing

NIST	National Institute of Standards and Technology
PM	Process Mapping
PPP	Private Public Partnership
RFI	Request For Information
SC	Sub-Contractor
SECI	Socialization, Externalization, Combination and, Internalization
TFV	Transformation Flow Value
TPM	Total Productive Maintenance
TPS	Toyota Production System
TVD	Target Value Design
VSM	Value Stream Mapping

INTRODUCTION

Building Information Modelling (BIM) was introduced in construction as a breakthrough technology to solve the problem of declining productivity in the Architecture Engineering and Construction (AEC) industry. This problem of productivity can be observed through forty years of AEC industry publications. Several causes to this problem have been identified such as poor labour efficiency (Arditi & Mochtar, 2000) and poor communication, exchange of information, coordination and teamwork issues (Weippert & Kajewski, 2004). After ten years of use, it has not been demonstrated that BIM alone can solve this problem. In fact, beyond the causes identified, the stake lies in the organization of work. Lean thinking has been introduced in the AEC industry to rethink construction not as a project but as a production system that can be optimized. Part of Lean thinking aims to improve productivity by focusing on eliminating waste within the processes (Gerber, Becerik-Gerber, & Kunz, 2010). Authors have suggested combining BIM and Lean as a solution (Hamdi & Leite, 2012; Mahalingam, Yadav, & Varaprasad, 2015; Moghadam, Alwisy, & Al-Hussein, 2012). However, the issue of waste in the BIM process is little to not addressed in the literature.

Lean Construction has been adapted to the AEC industry from the manufacturing industry with the notion of flow at its centre (Womack & Jones, 1997). Construction processes are composed of various interrelated flows. The three main flows found in construction are material, work and information flows. The material flow represents the movement of material within the process, the work flow represents the activities composing the process and its available resources and, the information flow represents the information moving between the various stakeholders. There are several ways to transfer information between parties such as face-to-face, documents, phone calls or digital information. The exchange of information can be between humans but also systems or a mixed combination. Moreover, the flow of information can be one-way or two-way allowing the information to flow in one or both directions (Tauriainen & Leväniemi, 2020). Several techniques, tools and approaches can be found regarding the improvement of the work and material flows in the literature (Ballard, 2000; Childerhouse, Lewis, Naim, & Towill, 2003). Moreover, taxonomies on sources of waste already exist for both these flows, the one created by Ohno (1988) for the material flows and the one created by Emond (2014) for the work flows. The concept of waste is central in the Lean principles and represent all activities and work products that do not provide a contribution to customer value (Alahyari, Gorschek, & Svensson, 2019). In the information flow, waste takes many forms such as excess information, information overprocessing or poor-quality information. In recent years, the adoption of BIM has shifted the focus from the workflows toward the information flows. Indeed, BIM provides processes and tools to help the production and exchange of information through a unique and shared platform (Eastman, Teicholz, Sacks, & Liston, 2011). However, issues are still observed today regarding BIM adoption. The notion of information flow in BIM projects is still misunderstood as little research addresses this notion in the literature, especially regarding the waste created by poor or little management of these flows. Indeed, no taxonomy can be found in the literature regarding these flows. Studies can be found in the literature on how taxonomies can be used to manage an issue. For example, Sun and Meng (2009) developed taxonomies for change causes and effects in construction projects. Thanks to their taxonomies, professionals can better understand the various causes and effects of changes in their project; thus, improving their ability to manage these changes. Another example is given by de Oliveira, Leiras, and Ceryno (2019) with the proposition of a taxonomy on environmental supply chain risk management. Their taxonomy provides a definition for the environmental risks and their consequences in supply chain management. The authors aimed to provide a better understanding of these risks to better manage these issues in the supply chain management field. These two examples provide an explanation on how taxonomies can be used to better manage an issue such as risks, changes or wastes. Thus, this leads to the main research question:

How to identify the sources of waste in the production and exchange of information in the AEC industry?

Addressing the research question leads to several objectives to provide a complete and accurate answer. The objectives are to:

1) identify the problems in the information flows,

2) develop and implement a method to identify and reduce sources of waste within the information flows,
3) provide potential solutions and,
4) create a taxonomy of sources of waste specific to the information flows.

This exploratory study is justified by the fact that there is little research on the subject documented in the literature. This research thesis is built on a Collaborative Design Science Research (CDSR) method, which addresses practical issues by diagnosing said issues, developing a proposition through the generation of an artefact and validating the artefact. Three articles are presented as standalone articles that have been either published, accepted for publication or submitted in peer reviewed academic journals, to meet the thesis requirements. The article 1 provides a general diagnostic, while the article 2 allows to go into detail with an understanding of the issues through an immersion in an architectural firm. This is done to systematize the internal design phase of the firm and identify potential wastes in the information flows during the production of BIM models. The article is important to understand and interpret the phenomenon. Finally, the article 3 provides an attempt to generalize the results of the article 2 through the creation of a taxonomy specific to the information flows. The taxonomy proposed in the thesis is high level as it describes the sources of wastes of the global information flows.

In the first article, the information processing in a BIM project was explored to identify conflicting and successful areas. The visualization of the information flows in BIM construction projects allowed to diagnose research gaps as this investigative study provided a significant insight into the current situation in the construction industry. This article provided the groundwork for the entire research. In the second article, a method is developed and implemented based on the gaps identified in the first article. This method is designed to improve information flows for the production of BIM models. Its goal is to identify sources of waste within the flows using Process Mapping (PM). In this article, the waste identification process is based on an existing taxonomy adapted from the manufacturing industry to improve the work flows. This method is implemented into the third article to develop a new taxonomy for the construction industry with a focus on improving the information flows. The sources of waste composing this taxonomy provide a complete picture as it covers all the parts of an organization, which are the human, the process and the technology.

The research contributes to the body of knowledge by proposing a taxonomy of the sources of waste in the information flows of BIM projects. It is accompanied by a method design to implement said taxonomy. This taxonomy is developed as a solution to the recurring problem of low productivity in the AEC industry. Another contribution to the body of knowledge is made in parallel to the taxonomy. Indeed, by using the ShareLab approach, a new validation approach was added to the body of method used to validate artefacts in a Design Science Research methodology, in this case the taxonomy. In addition, this thesis contributes to the practice by providing an executable, comprehensive and reliable method that allows professionals to better understand their own and the other professionals' processes while identify waste. This method provides a way for professionals to reduce their rework, and time, money and productivity losses. Moreover, the method can also be implemented with other existing taxonomies to improve work and material flows during construction projects.

The thesis is constructed as follows, the first chapter provides a literature review focusing on the issues of productivity in construction and the angle of waste in the information flows as one of the reasons. In accordance with the review, a problem statement is given and to close the chapter a research question is formulated with the research objectives necessary to provide an answer. The second chapter provides an extensive description of the research methodology used, followed by a structure of the thesis. The three following chapters are the articles generated as the outcomes of this thesis. Finally, a discussion and conclusion are made to complete the thesis.

CHAPTER 1

LITERATURE REVIEW

A well-known problem about the AEC industry is its lack of progress concerning productivity. Indeed, compared to other industries, productivity in construction stagnates behind. According to the US Bureau of Labor Statistics, for over 25-30 years, the labour productivity has been slowly declining (Teicholz, 2001). More recently, Zhan and Pan (2020) stated that even with the efforts put into improving productivity in the AEC industry, in general, it is still allegedly lower than several other industries. Over the years, several researchers have studied the subject and identified lists of factors impacting productivity in construction (Dixit, Pandey, Mandal, & Bansal, 2017; Rivas, Borcherding, González, & Alarcón, 2011; Shinde & Hedaoo, 2017; Snyman & Smallwood, 2017; Thomas & Sakarcan, 1994). Hasan, Baroudi, Elmualim, and Rameezdeen (2018) conducted a systematic review over the last 30 years to regroup all the factors affecting construction productivity identified in the literature. Their review identified the ten most frequently cited factors: (1) non-availability of materials, (2) inadequate supervision, (3) skill shortage, (4) lack of proper tools/equipment, (5) incomplete drawing and specifications, (6) poor communication, (7) rework, (8) poor site layout, (9) adverse weather conditions, and (10) change orders. A majority of the referred research occurred between 2007-2016, showing the growing interest in understanding and improving productivity problems in construction. A root cause of these factors is related to the poor management of work and material flows (Koskela, 2000; Turk, 2000). Indeed, in the last ten years alone, multiple researchers have proposed potential solutions to improve construction productivity through the improvement of these flows with the aim to reduce waste. Two approaches offer potential solutions: Lean thinking which is centred around the notion of flow and the elimination of waste and BIM. These potential solutions are being discussed in the following section of this literature review.

1.1 Lean thinking and the notion of flow

Lean thinking is derived from the Toyota Production System (TPS) developed between 1948 and 1975 (Bozdogan, 2010). TPS is based on the total waste elimination with two pillars at its centre that are Just-In-Time (JIT) and autonomation (intelligent automation) (Ohno, 1988). This Lean approach developed by Ohno (1988) was conceptualized by Womack and Jones (1997) and qualified as Lean thinking. They argued that, in order to have an accurate use of lean thinking, five key principles must be followed: understanding customers' demands (value), understanding the value stream by identifying the sources of waste, improving the flow by implementing continuous flow, creating a pull system and aiming for perfection (Womack & Jones, 1997).

There are two perspectives of adapting the Lean approach to construction. That of Egan (1998) from whom the principles and tools of Lean Production apply to construction, and that of Koskela, Howell, Ballard, and Tommelein (2002) for whom these principles and tools must be adapted to the context of construction. Indeed, Koskela (2000), adapted the approach to construction, proposing six principles specific to the management of flow: reducing the amount of non-value-adding activities (waste), reducing lead time, reducing variability, simplifying by decreasing the number of steps, increasing flexibility and increasing transparency.

Lean Production is the industrial application of the Lean Thinking principles. Lean Construction is based on similar principles. However, the implementation of the two differs due to major differences in their deliverable. As opposed to manufacturing, construction can be defined as on-site production, one-of-a-kind project, and complex (Salem, Solomon, Genaldy, & Minkarah, 2006). Furthermore, because Lean Construction is derived from Lean Production, researchers have been developing ways to adapt Lean Production tools and techniques to the construction industry. Recently, Sarhan, Xia, Fawzia, and Karim (2017) studied the level of use of tools and techniques with Lean Construction (Table 1.1).

Table 1.1 Lean tools/techniques link to the process and the notion of flow

Lean Tools/Techniques	Mention of Flow	Mention of Process	References
The Last Planner System	X	X	(AlSehaimi, Fazenda, & Koskela, 2014; Ballard, 2000)
Value Stream Mapping	X	X	(Michaud, Forgues, Carignan, Forgues, & Ouellet-Plamondon, 2019; Singh, Garg, & Sharma, 2011)
Standardized Work		X	(Mariz, Picchi, Granja, & de Melo, 2012)
The 5S Process		X	(Bajjou, Chafi, & En-Nadi, 2017; Bajjou, Chafi, En-Nadi, & El Hammoumi, 2017)
Kaizen		X	(Robert & Granja, 2006)
Total Quality Management			(Hofacker et al., 2008; Modgil & Sharma, 2016)
Increased Visualization	X		(Aziz & Hafez, 2013; Sacks, Treckmann, & Rozenfeld, 2009)
Fail Safe for Quality and Safety			(Ogunbiyi, 2014; Salem, Solomon, Genaidy, & Luegring, 2005)
Daily Huddle Meetings		X	(Aziz & Hafez, 2013)
First Run Studies			(Ogunbiyi, 2014)
The Five Why's			(Leino & Helfenstein, 2012)
Just in Time (JIT)	X		(Arbulu, Ballard, & Harper, 2003; Bamana, Lehoux, & Cloutier, 2019)
Plan of Conditions and Work Environment in the Construction Industry			(Aziz & Hafez, 2013; Babalola, Ibem, & Ezema, 2019)
Concurrent Engineering		X	(Aziz & Hafez, 2013)
Pull "Kanban" System	X		(Arbulu et al., 2003; Aziz & Hafez, 2013)
Error Proofing (Poka-yoke)	X	X	(Bajjou, Chafi, En-Nadi, et al., 2017; Tommelein, 2008)
Target Value Design (TVD)			(Zimina, Ballard, & Pasquire, 2012)
Partnering	X		(Eriksson, 2009)
Total Productive Maintenance (TPM)			(Modgil & Sharma, 2016; Ramakrishnan & Nallusamy, 2017)
Computer Aided Design (CAD)			(Sacks et al., 2009)
Six Sigma		X	(Banawi & Bilec, 2014; Pepper & Spedding, 2010)

The Table 1.1 shows that the process and the notion of flow are an inherent part to Lean Construction. Indeed, 13 out of 21 Lean tools/techniques focus on improving them. The flows are an inherent part of the process. The definition of the flow concept helps better understand the relation between flow and process. It is defined as:

> The flow concept emerged in construction nearly fifteen years ago. It considers production as a process of value-adding activities (i.e. transformation) and non-value adding activities, such as: waiting, transport and inspection (Kraemer, Henrich, Koskela, & Kagioglou, 2007).

The construction processes are composed of various flows: work flow, material flow and information flow being the three most important. The work flow is defined by Ballard and Tommelein (1999) as "the movement of information and materials through a network of production units". The information flow refers to the movement of documents and communications among stakeholders within construction processes. The material flow represents the movement of the raw material to the finished product from the producer to the consumer. Several researchers have discussed the topic of categorizing these within construction projects. First, Koskela (1992) described the construction process as a combination of material flow and work flow. Then, Vrijhoef and Koskela (2000) discussed the typical configuration of the construction supply chain including material and information flows as two separate linear processes.

The concept of flow is also at the origin of BIM. In the 1990s, the community on the application of Information Technology (IT) in construction was interested in how information technologies could address the issue of fragmentation in construction. Björk (1999) discussed the material and the information processing activities but described them as two interdependent, nonlinear processes. Another vision of the construction processes was proposed by Turk (2000) with a different and more detailed model including the work flow, material flow and information flow. This conceptual framework proposes three distinct but interrelated approaches and technologies to organize the management of these flows (Figure 1.1).

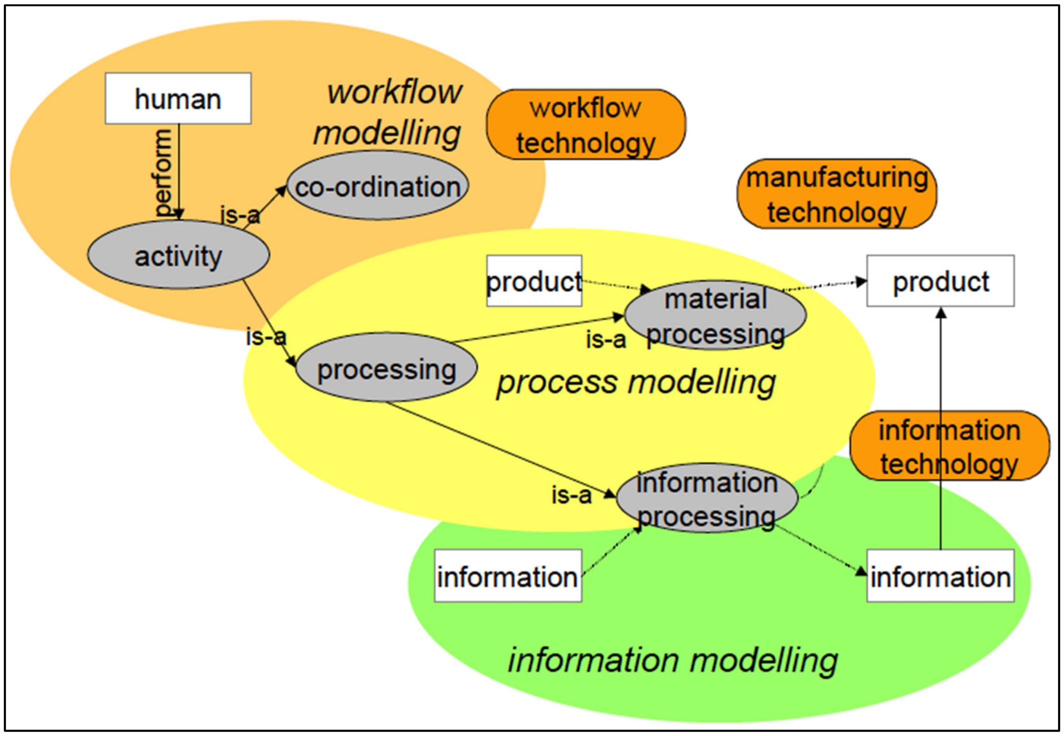

Figure 1.1 Relations between work flow, material flow and information flow
Taken from Turk (2000)

From this perspective, the author brought this conceptual framework showing the interrelationships between the different flows and the modelling to optimize these flows and their interaction. What stands out here is that the planning (modelling) should take place at three interconnected levels. However, compared to the two other levels, the information processing has been little covered in the literature, apart from Winch (2009) who made it the heart of his theory on construction management. Another observation made from this figure is that due to their interdependence, issues and/or waste in one flow will lead to issues/or waste within the other two flows. The concept of waste is well known and well documented in the literature regarding various industries such as the AEC industry or the manufacturing industry.

The adoption of BIM in the AEC industry is a seminal innovation that has the potential to revolutionize the AEC industry and its existing paradigm conceptualized by Turk (2000) and discussed above. Indeed, by placing the information processing at the heart of the management of the real estate asset throughout its lifecycle, BIM potentially brings more efficient delivery and management processes through the implementation of a centralized information system (Allen & Shakantu, 2016). This is a subject little covered in the literature. Indeed, a National Institute of Standards and Technology (NIST) report stated that the waste created by the lack of interoperability between information systems in the industry costs around 15.6 billion of dollars per year to US building owners (Gallaher, O'Connor, Dettbarn, & Gilday, 2004). However, there is no empirical data demonstrating to what extent BIM has reduced this waste nor research focusing on reducing waste by information processing.

Examples of research studies focusing on improving the work flow using Lean thinking approaches or tools can be found in the literature. Kerosuo, Mäki, Codinhoto, Koskela, and Miettinen (2012) stated that collaborative activities may be responsible for challenges and problems contributing to the low productivity in construction today. The authors used the Last Planner System (LPS) tools for Lean Construction to improve collaborative activities in the design phase of construction projects. Arashpour and Arashpour (2015) proposed to solve productivity issues in the work flow by implementing the lean concept of reducing variability[1]. Nath, Attarzadeh, Tiong, Chidambaram, and Yu (2015) also focused on productivity in the work flow. Their goal was to combine BIM processes and Value Stream Mapping (VSM) to re-engineer the work flow for the generation of shop drawings. However, none of these studies consider the notion of waste as a source of decreasing productivity.

The next section of the review provides a definition of the concept of waste, followed by the review of the various existing taxonomy of sources of waste in different industries. Finally, a focus is made on the wastes in construction and the current waste minimization practises that exist in the AEC industry.

[1] Reducing variability consists of identifying and eliminating its sources as it leads to non-value-adding activities (waste)

1.2 The concept of waste and its application in construction

The concept of waste is linked to the notion of flow as non-value-added activities within a flow. Indeed, Koskela (2000) procured a perfect visual representation of waste within a flow with the Figure 1.2 below. The white boxes indicate value-added activities, while the gray boxes indicate non-value-added activities. A value-added activity represents an operation within a process that provides benefit to the customer or product, contrary to a non-value-added activity.

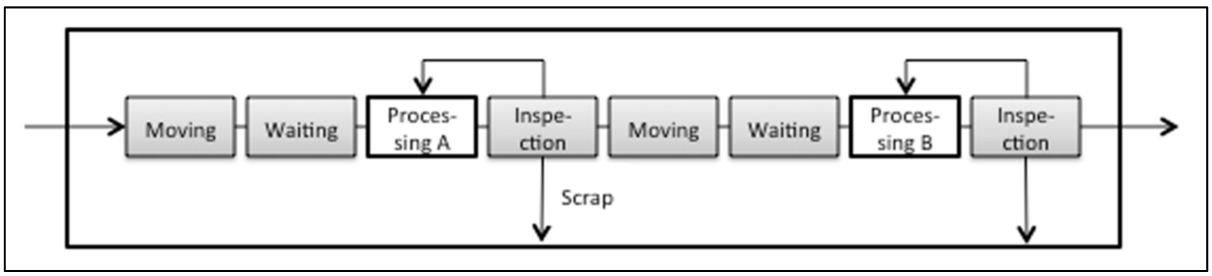

Figure 1.2 Production as a flow process
Taken from Koskela (2000)

The notion of waste is important in construction, especially in Lean Construction, as mentioned in the previous sections. In a discussion of waste, the notion of taxonomy plays an important role. Indeed, taxonomies are used to describe, identify and classify any system. The taxonomy serves as a map in the identification of waste as the latter can only be eliminated once it is known and identified. Ohno (1988) was the first one to produce a taxonomy of sources of waste in the Toyota Production System. The author presented this taxonomy in order to provide a better understanding of the production management and to optimize its processes. This taxonomy has been adopted by other industries such as in manufacturing through Lean Production and the AEC industry through Lean Construction. However, this taxonomy was created in a context of manufacturing work and do not cover the complexity of construction projects. In an attempt to better suit the AEC industry, Emond (2014) gathered sources of waste identified by different authors to produce the second taxonomy. These are currently the only two taxonomies that have been developed and are being used to identify waste. The Table 1.3 below provides both lists of sources of wastes.

Table 1.2 Sources of waste in production versus in construction project management
Taken from Emond (2014)

7 wastes in production (Management of material flow)	**10 wastes in construction project management** (Management of work flow)
• Overproduction • Correction • Material movement • Processing • Inventory • Waiting • Motion	• Under-utilization of talents • Waiting inputs • Information transfer • Unnecessary information • Deficient behaviour • Loss if good ideas • Achievements unappreciated by the customer • Make-do • Resistance to change • Non-management perceptions

The first taxonomy has been developed by Ohno (1988). The author has identified seven wastes in production where management of material flow was the focus. Lean researchers established that the difference between manufacturing and construction is that the AEC industry manages the flow of people and not materials. The seven wastes of Ohno are more suited for Lean Production, whereas the ten wastes of the second taxonomy are more suited for Lean Construction. However, there are examples of the seven wastes being used for the AEC industry in the literature. Indeed, Ansah, Sorooshian, and Bin Mustafa (2016), through a comprehensive literature survey, demonstrated the presence of waste in existing project management models in construction using the seven wastes, while Sarhan et al. (2017) used it to study the types of construction waste was present in the Saudi Arabian construction industry.

Recently, Besklubova and Zhang (2019) organized their research around the notion of waste and finding solutions on how to remove them to improve construction productivity. A total of 29 sources of waste were identified and linked to the flows they impacted. Compared to other similar research, the author did not focus only on the work flow but also on the material, the manpower, the equipment and tools and the information flows. However, their reasoning was still work flow oriented. For example, in their reflection, they decided to remove the overproduction waste from the list because they explained that the goal in construction is to produce a one-of-a-kind product. An apparent gap appears and needs to be addressed which is the lack of research focusing on improving the information flows to improve productivity in construction.

Despite playing a major role in the AEC industry, the study of waste in the information flow is still being left out, as no taxonomy has been developed for it yet. The waste in the production and exchange of information is more of a qualitative nature compared to the waste in the work and material flows as sources of waste are linked to the human aspect. With BIM adoption, the reduction of waste within BIM information flows is crucial as it is centred around collaborative processes and the management of information. Some researchers provided approaches in order to reduce waste in the information flows in construction (Table 1.3).

Table 1.3 Approaches used to reduce waste in the information flows

References	Approach used	Issues
Tribelsky and Sacks (2011)	Collecting quantitative data on sources of waste to measure the quality of information flows	Absence of qualitative data
Dubler, Messner, and Anumba (2010)	Adapting the seven wastes from production to construction	Lack the human side of waste
Al Hattab and Hamzeh (2013)	Comparison of traditional and BIM-based information flows in design phases	Focus on only one source of waste

The three research studies presented in the Table 1.3 show that research is present on the subject of information flows in construction, especially around the notion of waste. While they bring knowledge to the area, each reference lacks a complete picture of the information flows in regard to waste. Indeed, Tribelsky and Sacks (2011) proposed a method to measure the information flows in the design process of construction project by identifying seven numerical indices. However, the data collected by the author was of a quantitative nature and lacked the qualitative data that is present in the information flows such as data on overproduction, issues of coordination or information transfer. Then, Dubler et al. (2010) proposed an adaptation of the seven waste taxonomy for the information flows of construction. While this proposition provides a vision of waste in the information flows, the authors did not consider humans as a source of waste. Indeed, regarding the qualitative nature of information, the human dimension plays a major role in its flow. The issue here is that the taxonomy was originally intended for the material flow of production and did not include the human aspect due to its limited impact on it. Finally, Al Hattab and Hamzeh (2013) through process models proposed a comparison of traditional and BIM-based projects in the design phase. Their goal was to improve the information flow in the BIM process and concluded that there was a need for a better sharing of information. The issue in the study is that the authors focus only on one source of waste in the information flow. The next section provides an insight on BIM as a potential solution for the management of the information flow.

1.3 Building Information Modeling and the management of the information flow

BIM has been introduced in the construction industry in order to improve interoperability and collaboration among parties involved in construction projects (Eadie, Odeyinka, Browne, McKeown, & Yohanis, 2014; Eastman et al., 2011; Gray, Gray, Teo, Chi, & Cheung, 2013). BIM is a breakthrough technology operating around a collaborative process that allows all the stakeholders of the AEC industry to produce and exchange information within a shared platform during a project. Figure 1.3 shows the difference between a traditional project and a BIM project. BIM is a technology change that represents a shared digital model that modifies the creation of building drawings and visualizations. Moreover, BIM is also a process change that significantly modifies all of the key processes used in the design and delivery of a building (Eastman et al., 2011).

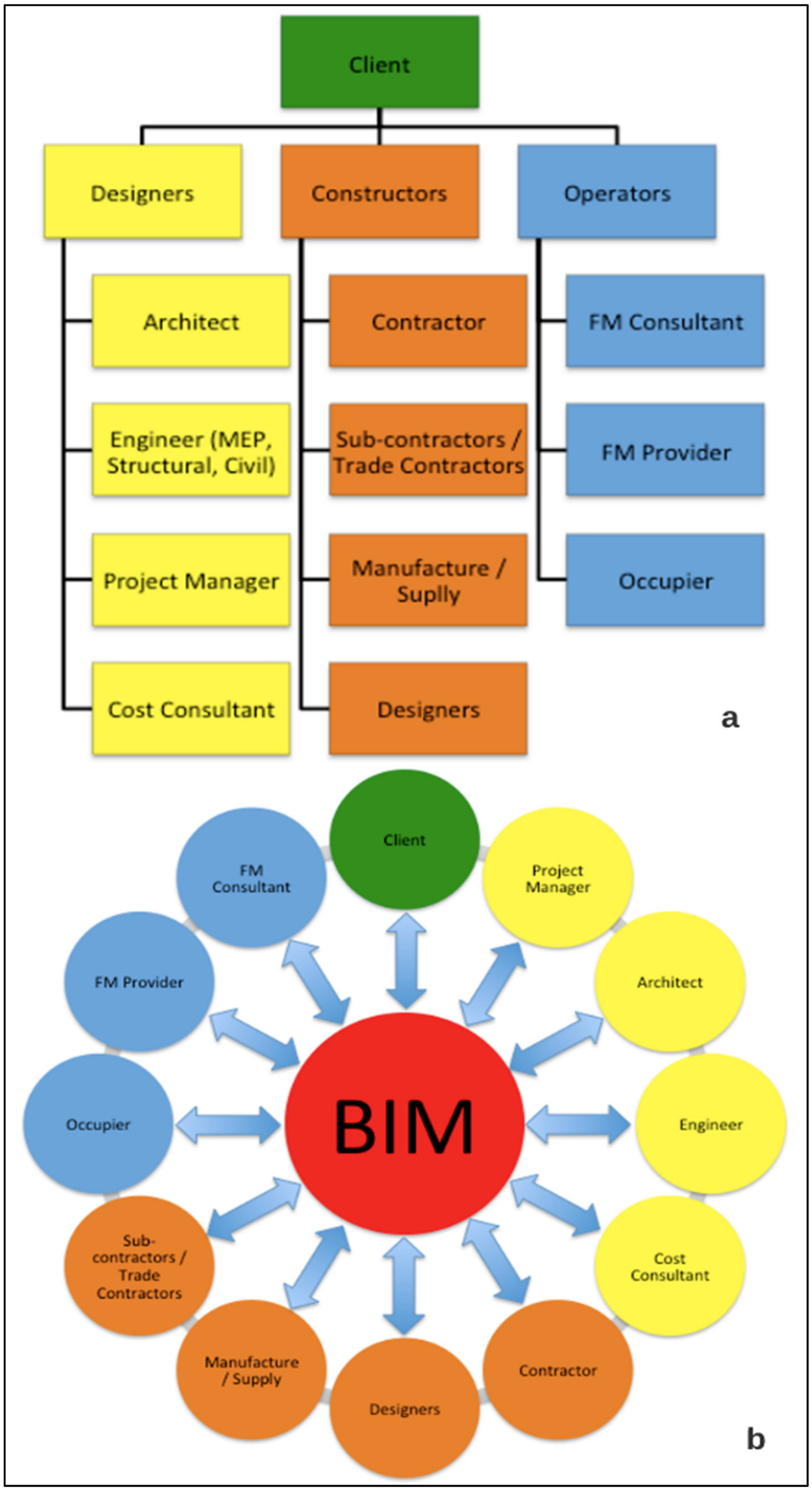

Figure 1.3 Impacts of BIM on collaboration and interoperability
(a) Traditional project, (b) BIM project

Furthermore, BIM implementation requires an adaptation of the involved parties' organization of work due to process changes (Volk, Stengel, & Schultmann, 2014). Indeed, the use of BIM in a project has compelled the actors to make changes in their methods of work and in the way they see relationships among involved parties by leading into a new approach through team collaboration (Gray et al., 2013). The traditional mode of production and exchange of information focuses on managing work flows for producing deliverables by specialty for each activity. In a BIM project, there is a shared platform in which flows must be planned for the production and continuous exchange of information. However, the traditional linear and fragmented structure of construction projects is incompatible with the nature of BIM which is iterative and integrative. Moreover, there are maturity issues in the deployment of BIM, which influences the ability to properly manage information processing.

The heart of BIM is the production, exchange and management of information. Because of the presence of barriers, the full potential of BIM's information processing is still not obtained. Barriers have the effect of impacting the information flows by disrupting the flows through for example lack of communication, coordination or teamwork. A disrupted information flow leads to the presence of waste such as issues in the exchange of information, data loss and/or inappropriate information (Demian & Walters, 2014). Several researchers have presented articles on barriers to BIM implementation. Eadie et al. (2014), through a comprehensive literature review, identified 10 barriers to BIM implementation. Their goal was to help adopters to consider these 10 barriers in their strategy for the BIM implementation. However, this research focused on operationalization barriers and did not consider the question of information processing. During the implementation, the notion of waste is not discussed because the processes are not in place yet. However, the notion of information processing is important because the focus is shifted from the work flow. Another research provided a different point of view on barriers to BIM use. In their research, Forgues, Carignan, Forgues, and Rajeb (2016) identified five barriers: (1) lack of coordination, (2) the quantity and quality of information exchanged between the parties involves, (3) the resistance to change, (4) the lack of understanding of the entire information flows process and, (5) the lack of common shared vision. This research focused on BIM processes and information flows and aimed at developing tools to help stakeholders better understand how information is created and processed. This article provided a step in the right direction with the presentation of a collaborative mapping approach that can be used as a visualizing tool in the identification of issues in BIM processes.

The importance of information with BIM is major. Indeed, from the four major elements defining the BIM rhetoric identified by Miettinen and Paavola (2014), two have a direct link to the information flow: (1) the use of BIM models to regroup all relevant data; (2) a new integrated way of working driven by the need for better collaboration around a shared platform and interoperability between systems; (3) the use of BIM throughout the entire lifecycle of a building; and (4) an increase in productivity and efficiency. The first two elements bring forward the need to use of an information-centric approach compared to traditional projects with the document-centric approach. Issues from the document-centric approach such as, the static nature of data, the slow response to change or the information silos between the professionals are tackled by the information-centric approach where the information is centred and shared between the professionals. Thus, there is a demand for changes in the traditional methods of work and the relationships among stakeholders when using BIM. However, as mentioned in the review, despite the importance of information with the use of BIM and the potential positive impact that BIM can have on the information flows, there is little research being done regarding techniques or tools to reduce waste within these flows. There is clearly a gap in the literature when analyzing the data available on work and material flows compared to the data available on the information flows.

1.4 Research question and objectives

In accordance with the problem statement made, the following research question is formulated: How to identify the sources of waste in the production and exchange of information in the construction industry?

In order to provide a complete and accurate answer, the following objectives were formulated:

- **Objective 01:** Identify and highlight the presence of problems and issues in the information flow of construction projects.
- **Objective 02:** Develop and implement a method design to identify and reduce sources of waste within information flows.
- **Objective 03:** Provide potential solutions to recurring problems in the information flows.
- **Objective 04:** Create an artefact in the form of a taxonomy of the sources of waste specific to the information flows.

CHAPTER 2

METHODOLOGY AND STRUCTURE

2.1 Research Design

The research design used for this study is interventionist. Indeed, the aim is to propose a new framework oriented around the identification and reduction of waste within the information flows of BIM processes. An interventionist approach can be defined as the design and development of interventions (Fraser & Galinsky, 2010). The methodologies of Design Science Research (DSR) and Collaborative Design Science Research (CDSR) can be considered to have an interventionist approach, as the aim of these methodologies is to design and develop an artefact.

Moreover, coherent scientific research must be organized around a rigorous methodology used to validate the results obtained. The methodology of Collaborative Design Science Research (CDSR), although still relatively recent, allows the development and the validation of results in the form of artefacts. In order to implement reproducibly a CDSR method, Hevner, March, Park, and Ram (2004) have developed a set of guidelines that have been followed in this thesis:

- **design as an artefact:** this thesis produces a viable artefact in the form of constructs, models, frameworks and, methods;
- **problem relevance:** the aim is to provide data identifying a practical problem and show why it is relevant to focus our attention on it;
- **design evaluation:** the utility, quality and efficacy of the design artefact are rigorously demonstrated through the use of the ShareLab approach;
- **research contributions:** this research provides clear and verifiable contributions in the areas of the design artefact;
- **research rigour:** rigorous methods are used in the. construction and evaluation of the artefact;

- **design as a search process:** all steps necessary are taken in order to satisfy the laws in the problem environment;
- **communication of research:** this research is done in the context of a Ph.D. and the results are presented in different forms including, this thesis, scientific articles and presentations.

2.2 Research Methodology

The originality of the proposed approach is that it is developed on generating propositions to address practical issues and challenges found in the AEC industry. The CDSR methodology used in this study allowed to complete its objectives through linking professionals and researchers in designing artefacts (Otto & Österle, 2012). These artefacts aim at contributing to the knowledge while solving practical issues. This method is based on the combination of the Design Science Research (DSR) and knowledge creation (Figure 2.1).

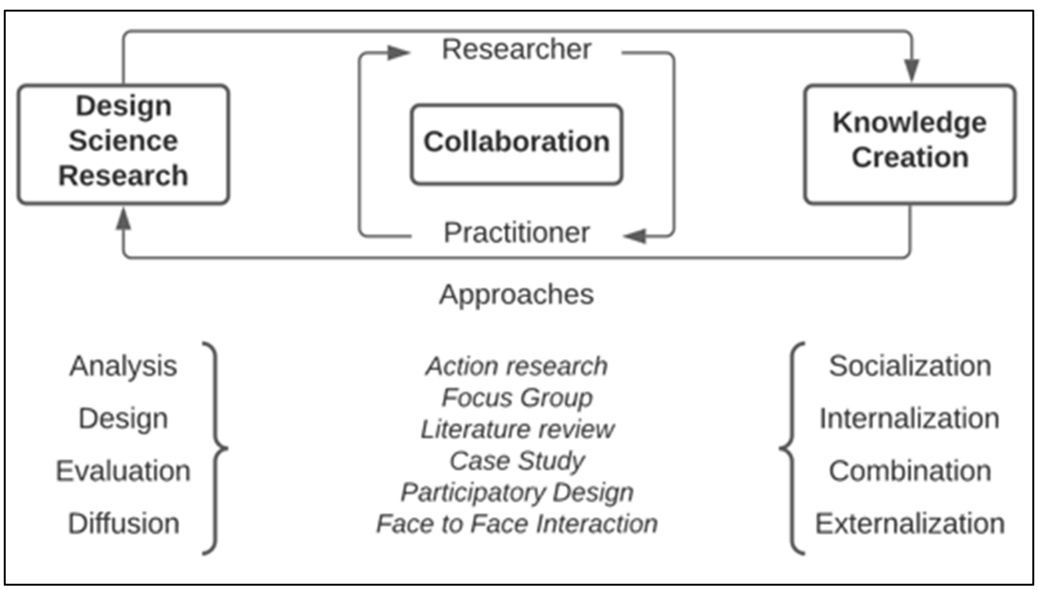

Figure 2.1 Combination of DSR and knowledge creation in CDSR
Adapted from Otto and Österle (2012)

The Figure 2.1 gives a framework for the CDSR methodology organized around the DSR phases and the different options for knowledge creation. In the centre of the figure are all the approaches that are used in this study at one point or another. Based on this framework, this study was separated into three steps (Figure 2.2):

- **Diagnosing:** this first step corresponds the use of the auto confrontation technique, a diagnosing is done on the information processing in BIM projects. This allowed to provide the groundwork for the entire research.
- **Development of a proposition:** This step was divided into two parts. The first one on the development and implementation of a framework designed to improve information flows using Process Mapping. The second was the development of an artefact in the form of a taxonomy through the implementation of the framework.
- **Validating:** Using the ShareLab approach, the validation of the artefact proposed was made through the approval and endorsement from professionals.

The Figure 2.2 and the Tables 2.1 and 2.2 below provide a more exhaustive picture of the global methodology used during this thesis. An explanation for each of the steps is given afterward.

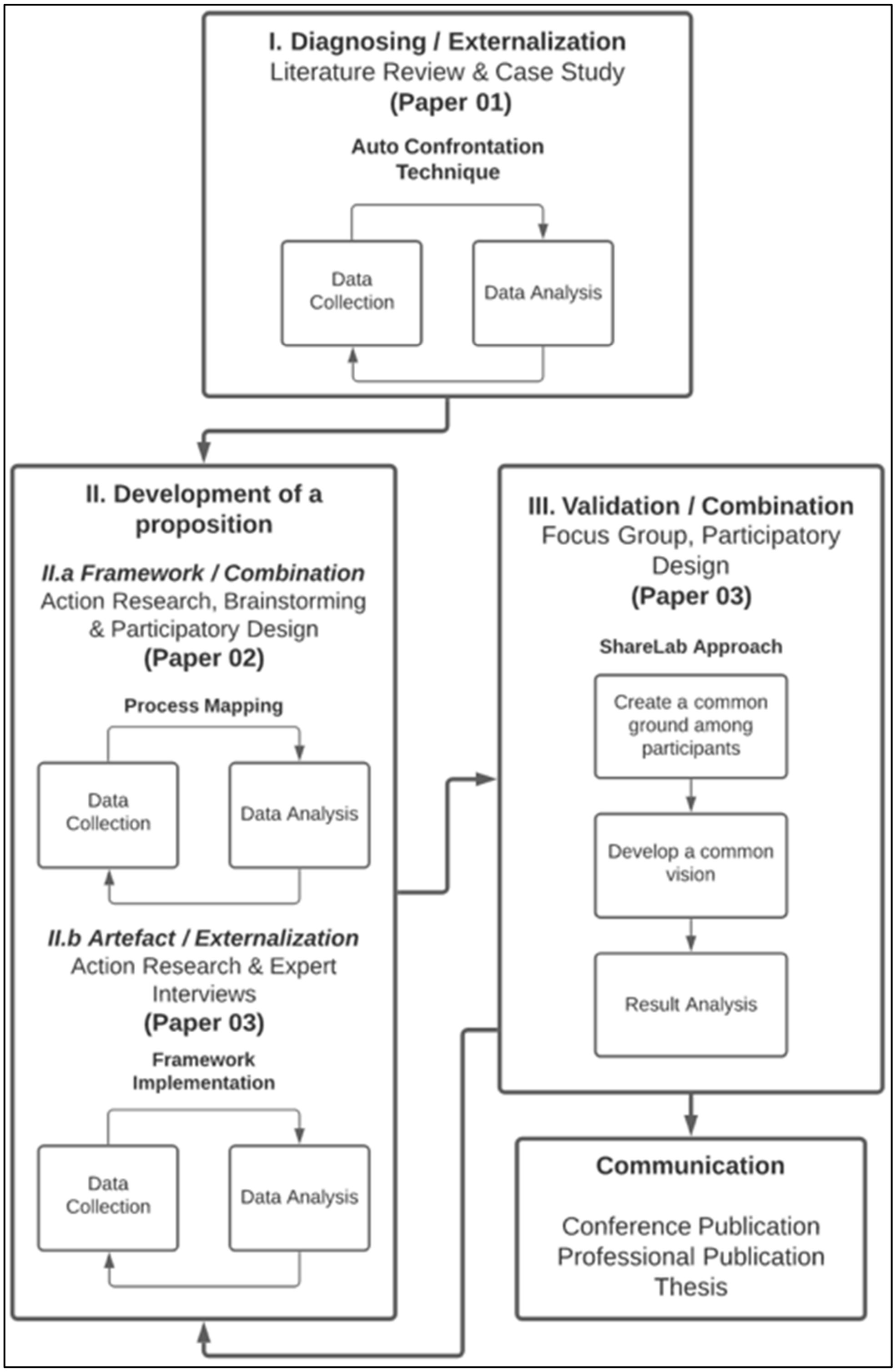

Figure 2.2 Research process of this thesis

The research process presented in the Figure 2.2 follows the general concept of the CDSR methodology but is also composed of various approaches used in the different articles presented in this thesis. The first step of the process is “Diagnosing” also called “Analysis” and uses the externalization approach to knowledge creation through the use of a literature review and a case study. More details about this step of the process are given in the first article presented in CHAPTER 3 called, “A Lean approach to optimize BIM information flow using Value Stream Mapping”.

The second step is the “Development of a proposition” or “Design”. This step is divided into two sections with the first one being the development of the framework coupled with the combination approach of knowledge creation through the use of collaboration, brainstorming and participatory design. More details about this step of the process are given in the second article presented in CHAPTER 4 called, “BIM implementation in an architectural firm: using process mapping to reduce waste in the information flow”. The second section is the development of the artefact coupled with the externalization approach through action research and expert interviews. More details about this step of the process are given in the third article presented in CHAPTER 5 called, “A taxonomy of sources of waste in BIM information flows”.

Finally, the last step is the “Validation” or “Evaluation” coupled with the combination approach through the use of focus groups and participatory design. The choice of the ShareLab approach was made for this step of the research as a way to validate the artefact created. Before this research, this approach was not found in the literature as an approach to validate an artefact in a DSR or CDSR methodology. However, this thesis provides results and details validating its use for this kind of methodology. More details about this step of the process are given in the third article presented in CHAPTER 5.

The “Communication” or “Diffusion” step of this process is realized through the publication of conference and journal articles as well as this thesis.

The Table 2.1 below provides a summary of all the data collection approaches used within this thesis. It provides information on when and where they were used, which approach was used, and the data type collected. The auto-confrontation technique was used as an empirical approach design to observe the stakeholder's individual comprehension of the processes through collaborative mapping. The focus group approach was used to collect qualitative data specific to the study and organized around mapping design processes. The semi-structured interviews were used to collect qualitative data from the various fields of a construction project. Finally, the ShareLab approach was used to collect quantitative data through the use of a workshop composed of 20 professionals from different fields of the construction industry.

Table 2.1 Data collection approaches in this thesis

Articles	**Case Study**	**Data Collection approach**	**Data Type**
A Lean approach to optimize BIM information flow using Value Stream Mapping	Empirical validation of the literature with the observation of issues in the field	Auto-confrontation technique/Interviews	Qualitative Data
BIM implementation in an architectural firm: using process mapping to reduce waste in the information flow	Project implemented in an architectural firm to support them towards BIM	Focus groups	Qualitative Data
A taxonomy of sources of waste in BIM information flows	Data collection from several professionals in various fields of construction	Semi-structured interviews	Qualitative Data
		ShareLab approach / Questionnaires	Quantitative Data

The Table 2.2 below provides a summary of all the data analysis approaches used within this thesis. It provides information on when and where they were used, which approach was used, and the data type collected. The map analysis approach was used during the diagnosing step as well as during the development of the framework. Each time, the participants of the studies were included in the analysis to obtain comments on the results. The qualitative data analysis approach was used for the development of the artefact in the second step of this thesis. The analysis followed the three stages proposed by Miles and Huberman (2003) in their approach. Finally, the analysis of quantitative data obtained through the use of questionnaires during the validation step was the last data analysis approach used in this thesis.

Table 2.2 Data analysis approaches in this thesis

Articles	**Data Analysis approach**	**Data Type**
A Lean approach to optimize BIM information flow using Value Stream Mapping	Map analysis	Qualitative Data
BIM implementation in an architectural firm: using process mapping to reduce waste in the information flow	Map analysis Verbatim analysis of the interviews	Qualitative Data
A taxonomy of sources of waste in BIM information flows	Qualitative data analysis approach	Qualitative Data
	Questionnaire results analysis	Quantitative Data

2.2.1 Diagnosing

Diagnosing was realized through the use of the auto-confrontation technique. It comes from cognitive science and was developed to allow participants to be confronted with their own reality (Clot, Faïta, Fernandez, & Scheller, 2000). This technique was used for the first phase of the research process as a way to collect data to frame the problem identified in this thesis. It was used in this context to map Mechanical, Electrical and Plumbing (MEP) design and construction processes with a focus on the information flow to pinpoint good and bad practices discussed in the literature and to validate the existing theories on issues with these practices. The process maps were co-generated by professionals and the researchers.

The data was of a qualitative nature and collected during interviews between the researchers and the professionals. Several iterations were necessary with each participant to ensure reliant and accurate data. Moreover, while keeping in mind the same goal of collecting reliable and accurate data between the various participants, the mapping was based on the standard graphic of the Business Process Model and Notation (BPMN) as it allowed the participants to generate maps using a small number of elements in simple diagrams (Scherer & Ismail, 2011).

The qualitative data analysis of the diagnosing step was organized around the analysis of the MEP processes with the professionals using these maps. First the maps were reviewed with the participants to allow them to comment on the results. Then, the analysis allowed to pinpoint the differences and barriers between the process maps to highlight the sources of waste in the information flows. More details about the methodology are given in the first article presented in CHAPTER 3.

2.2.2 Development of a proposition

The development of a proposition provided a solution to the problem identified in the diagnosing step. It included two parts: (1) development of a framework, and (2) development of an artefact. The framework is developed as a way to identify the sources of waste in the information flows of construction projects. The purpose of the artefact is, when used in parallel with the framework, to provide the information manager with a description, identification and classification of the potential sources of waste present in the information flows of construction projects.

2.2.2.1 Development of a framework

The focus group method was used to develop the framework based on process mapping to improve the information flows of construction projects. This method is commonly used in research for collecting qualitative data (Gill, Stewart, Treasure, & Chadwick, 2008). Compared to a statistical study using a sample of a broader population, the focus group method obtains data from a selected group of individuals (Nyumba, Wilson, Derrick, & Mukherjee, 2018). Moreover, the data collected revolves around the perceptions, opinions and views of the participants about the topic researched.

A total of 14 focus groups were performed during this step of the research. Each time the group was composed, on one hand of several professionals such as project managers, architects, engineers and designers. On the other hand, there was one researcher responsible for the research project and one professional/researcher who acted as a facilitator/regulator to orchestrate and manage the process. Two iterations were used for each group to refine the process maps and make sure the data collected was accurate.

The qualitative data analysis of the framework step followed the same approach as the diagnosing step with the map analysis with the professionals. However, more data was available at the stage of the research as verbatim of the interviews were generated and then analyzed. The analysis allowed us to identify forms and sources of waste within the information flows of the design phase. The sources of waste presented in this study came from an existing taxonomy designed for the workflows in construction projects. The use of this taxonomy allowed us to test the framework necessary for the next step of the research that was the creation of a taxonomy design for the information flows. More details about the methodology are given in the second article presented in CHAPTER 4.

2.2.2.2 Development of an artefact

The semi-structured interviews were the last method used to collect qualitative data from professionals to better understand the information flows in the design and construction processes. A total of five interviews with five different participants were conducted. The participants belonged to various fields of the AEC industry in order to create a picture as accurate as possible. Indeed, the fields interviewed included architecture, engineering, general contractor, MEP contractor. The interviews were semi-structured with the aim to better understand the exchange and creation of information between the various stakeholders. Furthermore, because this research was part of larger research within the GRIDD laboratory, data from other projects were available in the form of verbatim, reports and other interviews.

For this step of the research, a qualitative data analysis approach inspired by Miles and Huberman (2003) proposed method was adopted. It was composed of three stages. The first one was the data collection through the use of semi-structured interviews. The second one was the data transformation in the form of process maps using BPMN notation. A total of 16 maps were generated showing the workflow between the actors and the information flow between each activity for both the design and the construction phases. The analysis was oriented around three categories which were the source of the information (which actor), the type of project delivery modes because of the presence of variation in the information flows depending on the delivery mode and finally the phase of the project (design or construction). The analysis of the maps combined with the analysis of the verbatim and the data from the other projects allowed to draw conclusions, the third and last stage of the approach.

The goal of this stage was to identify similarities, differences and issues between the actors' processes. This allowed the identification of sources, forms and consequences of waste in the information flows. Providing all the necessary elements for the development of the artefact and the validation process. A complete explanation of the process is provided in the next section.

2.2.3 Validation

The last step of the research was the validation of the created artefact. In a Collaborative Design Science Research (CDSR) approach, the validation is a fundamental aspect of the research. According to Hevner et al. (2004), the utility, the quality and the efficiency of a created artefact have to be demonstrated accurately by researchers, using evaluation methods. Pries-Heje, Baskerville, and Venable (2008) have developed a framework allowing researchers to choose among strategies and methods (see Figure 2.3).

According to this framework, there are two possible evaluation choices that are “ex-ante” or “ex-post” (Pries-Heje et al., 2008):

- An ex-ante evaluation corresponds to an evaluation of the conception; there is no need for the real artefact.
- An ex-post evaluation is based on the produced artefact; it is based on the artefact after implementation.

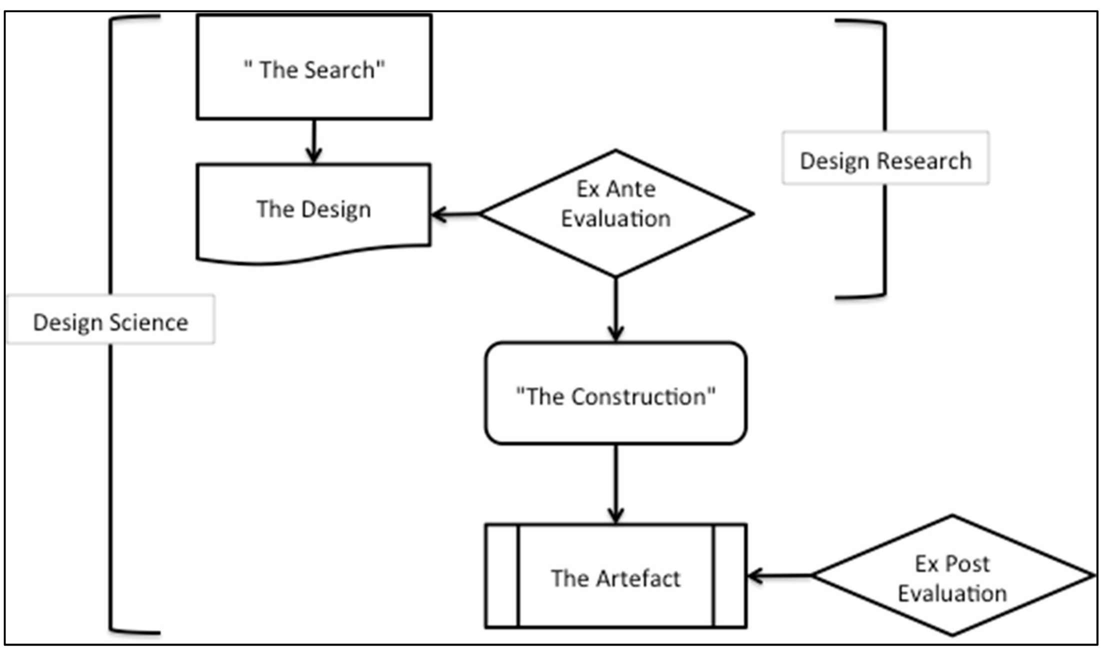

Figure 2.3 Framework for the evaluation of a science design research
Taken from Pries-Heje et al. (2008)

In order to choose which evaluation is best fitted for the research, three questions have to be answered (Pries-Heje et al., 2008):

- **What is actually evaluated?** This question determines what is best suited depending on what is to be evaluated. Indeed, the evaluation can be about the designed artefact or the design process of the artefact.
- **How is it evaluated?** The evaluation can be artificial or naturalistic. A naturalistic evaluation is done in a real environment and allows the evaluation of the real artefact whereas an artificial evaluation is done in a non-realistic environment and allows to control variables, design hypotheses and theories and the utility of design artefacts.
- **When is it evaluated?** The goal is to determine if the evaluation is ex-ante or ex-post or both.

In this research, the goal was to evaluate the actual artefact. This meant that a naturalistic evaluation was necessary in the form of an ex-post evaluation.

Following the choice of the evaluation's strategy, it was important to select the right method to do so. According to Hevner et al. (2004), the evaluation of artefacts is done via several methods available in the pool of knowledge. The evaluation is a necessary step when trying to validate an artefact. The Table 2.3 below presents different existing methods that may be used to validate the artefact created.

Table 2.3 Design evaluation methods for artefacts
Taken from Hevner et al. (2004)

Method	Description
1. Observation	Case Study: Study artefact in depth in business environment
	Field Study: Monitor use of artefacts in multiple projects
2. Analytical	Static Analysis: Examine structure of artefacts for static qualities (e.g., complexity)
	Architecture Analysis: Study fit of artefacts into technical IS architecture
	Optimization: Demonstrate inherent optimal properties of artefacts or provide optimality bounds on artefact behaviour
	Dynamic Analysis: Study artefact in use for dynamic qualities (e.g., performance)
3. Experimental	Controlled Experiment: Study artefact in controlled environment for qualities (e.g., usability)
	Simulation – Execute artefact with artificial data
4. Testing	Functional (Black Box) Testing: Execute artefact interfaces to discover failures and identify defects
	Structural (White Bow) Testing: Perform coverage testing of some metric (e.g., execution paths) in the artefact implementation
5. Descriptive	Informed Argument: Use information from the knowledge base (e.g., relevant research) to build a convincing argument for the artefact's utility
	Scenarios: Construct detailed scenarios around the artefact to demonstrate its utility

While taking into account the existing methods presented in the Table 2.3, another theory was also taken into account. Indeed, according to the constructive research theory, validation can be obtained through the approval and endorsement from the professionals of the recommendations and/or conclusions presented (Lukka, 2000).

Based on both references, the ShareLab approach was the choice made to validate the artefact generated. The interest in using the ShareLab approach in the validation process was that it allowed to develop a consensus among the various fields of a construction project. Through the process of three steps, the aim was to obtain a consensus approval of the artefact. The first and second steps were part of a one-day workshop regrouping 20 professionals from four different fields of the construction industry. During the first phase, through the presentation of the results and discussion on the previous phase of the research, the goal was to create a common ground among the participants that was to recognize the need for solutions to the context of lower productivity growth in the construction industry compared to other industries such as manufacturing. During the second phase, the presentation of the list of sources, forms and consequences of waste identified was given to the professional. An explanation and definition of each was provided. Then, through a discussion, the participants were asked to validate each component presented as well as to rank the sources of waste validated in order of impact. The last step of the process was to analyze the results and to generate the taxonomy with the validated results. This taxonomy is useful for the professionals as it can be used in any construction project as it is adaptable and reusable to any design or construction process. More details about the methodology are given in the second article presented in CHAPTER 5 and the taxonomy is further discussed in the CHAPTER 6 of this thesis.

2.3 Structure of the thesis

This section presents the structure of the three journal articles that provide the complete contribution of this thesis (Table 2.4); that is a taxonomy of the sources of waste in the information flows of construction projects. Each article provides a different research and its own contribution to the general problem statement identified. However, they also follow the common thread to answer the main objective of the thesis: Provide a way to solve the issue of waste in the production and exchange of information in construction through providing a better understanding of the information flows.

Table 2.4 Structure of the articles to answer the research question

Journal articles	Link to objectives	Journals	Status
CHAPTER 3 - A Lean approach to optimize BIM information flow using Value Stream Mapping	Obj 01 - Identify and highlight the presence of problems and issues in the information flow of construction projects Obj 02 - Develop and implement a method design to identify and reduce sources of waste within information flows	Journal of Information Technology in Construction (ITcon)	Published November 2019
CHAPTER 4 - BIM implementation in an architectural firm: using process mapping to reduce waste in the information flow	Obj 02 - Develop and implement a method design to identify and reduce sources of waste within information flows Obj 03 - Provide potential solution to recurring problems in the information flows	Engineering Construction and Architectural Management	Submitted June 2021
CHAPTER 5 - A taxonomy of sources of waste in BIM information flows	Obj 02 - Develop and implement a method design to identify and reduce sources of waste within information flows Obj 04 - Create an artefact in the form of a taxonomy of the sources of waste specific to the information flows	Buildings	Published July 2021

2.3.1 Article 1 – A Lean approach to optimize BIM information flow using Value Stream Mapping

Article 1 provides the groundwork for the entire research with providing data and results to meet the first sub-objective of the thesis. The literature review highlighted the lack of qualitative data on sources of waste in information during the design phase of construction projects. The article provides a way to fill the gap through the use of an investigative method. As a result, conflicting and successful areas in the BIM processes were identified, with a focus on the BIM information processing. It also proposes potential waste reduction strategies for future projects. The article contributes to knowledge by providing qualitative data in the identification of problems in information flows and in identifying possible solutions. It also contributes to practice with the demonstration of the value of adapting VSM for construction as a visualization tool to identify and eliminate sources of waste in the information flow.

2.3.2 Article 2 – BIM implementation in an architectural firm: using process mapping to reduce waste in the information flow

Article 2 presents the development and implementation of a method through the use of a collaborative action research approach. The method is designed to improve information flows for the production of BIM models using Process Mapping. The identification of sources of waste in this research was based on an existing taxonomy adapted from the manufacturing industry and designed to manage the material flow and human behavior. This article aims to fill a gap identified in the literature that is the lack of protocol and standard in the design process of construction projects. This article also provides an answer to the third objective of this thesis. Indeed, by combining the developed method with the approach proposed by Koskela (2000) for waste reduction, solutions in the form of actions are provided to tackle each issue identified in the information flows. A contribution to knowledge was made with the identification and classification of the sources of waste observed in the information flow of the design phase. This classification differs from the others as there was no existing classification on waste within the information flow of the design phase in construction projects at the time of this research. Contribution to practice was made with the proposition of a three-step approach designed to improve the design process in a BIM deployment strategy.

2.3.3 Article 3 – A taxonomy of sources of waste in BIM information flows

Article 3 provides answer to two sub-objectives of this thesis with the proposition of an artefact in the form of a taxonomy of the sources of waste specific to the information flows in construction (objective 04) and development of a method to better identify and reduce waste in information flows (objective 02). The motivation behind this article was the need for new ways to improve productivity in construction. The information flow was at the center of this research article as the information's importance keeps growing in the AEC industry. The taxonomy represents the main contribution to knowledge of this article. All the existing taxonomies focused primarily on the materials and workflows, resulting in a big portion of sources of waste being left out in the projects. The taxonomy adds value to knowledge as it closes the gap regarding sources of waste in one of the main flows of construction projects. A validation of this taxonomy was obtained through the approval and endorsement from professionals. The taxonomy also provides a contribution practice as a tool for professionals to help them reduce rework and time, money and productivity losses. Indeed, by implementing the method developed in the article 2 in combination with this taxonomy, professionals will be able to identify and eliminate their waste in the information flows as they will know what to look for. This method can be run in parallel with any construction project.

CHAPTER 3

A LEAN APPROACH TO OPTIMIZE BIM INFORMATION FLOW USING VALUE STREAM MAPPING

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3.1 Abstract

Building Information Modelling (BIM) was introduced in the Architecture, Engineering and Construction (AEC) industry as a shared information platform that aims to improve productivity through better collaboration. The assumption is that a virtual integration of information among project stakeholders would reduce the issues around the fragmented nature of the processes that still prevail in the construction field. This paper aims to highlight the sources of waste in the information flows between an architecture firm, a Mechanical, Electrical and Plumbing (MEP) engineering firm, a general contractor (GC) and a MEP subcontractor (SC) in a BIM project – an aspect of waste little covered in the Lean literature. The focus is on the MEP process from early design to the final product. This research contributes to the identification of the main barriers to information flow, including the conflicts and waste sources that emerge from using BIM, as well as to the identification of emerging successes. Moreover, the findings offer practical implications by providing a visual of the patterns emerging from the use of BIM. Finally, by providing potential waste reduction strategies such as Value Stream Mapping (VSM) this work allows construction actors to identify and reduce sources of waste in their processes.

3.2 Introduction

The traditional vision of construction management focuses on the division of a project into lots and activities, while BIM projects focus on an information-centric management. Winch (2009) explained that the goal of construction management is to ensure that the process of producing the information describing the deliverables corresponds to what is expected by the client. The problem is the information gaps between the different phases of a project. Indeed, the product is not even defined at the beginning of a project. BIM presents a viable solution to this problem, as it aims to facilitate the exchange of building information by implementing a centralized platform designed to ease information sharing. However, the inherent difficulty in transferring information properly and accurately between the actors throughout the phases of a project limits the advantages of BIM (Coates et al., 2010). The BIM benefits expected in a project are an improved coordination and collaboration, an optimization of scheduling and costs, reduced drafting time with no loss of quality or any increased cost, improved conflict detection and risk mitigation, a high level of customization and flexibility and streamlined building life cycle management. BIM implementation requires an adaptation of the involved parties due to process changes (Volk et al., 2014). Indeed, a successful deployment of BIM requires a review of the way things are done with a transition from a document-centric approach (traditional) to an information-centric approach. BIM can be seen as the reengineering concept founded and developed by Hammer and Champy (1993) and defined as: *“the fundamental rethink and radical redesign of business processes to generate dramatic improvements in critical performance measures – such as cost, quality, service and speed.”* This concept promotes a process-centered organization to provide significant gains in performance.

The value of BIM is often described as providing processes and tools to streamline the production and exchange of information through a unique and shared platform (Eastman et al., 2011); enabling all stakeholders to share the same set of data, thereby avoiding all the issues of information loss, alterations or overproduction (Crotty, 2013). BIM is used as a platform for data management either for the architect, the owner or any other actor in the process to retrieve or display information in a consistent format (Goedert & Meadati, 2008). Information processing plays a major role in construction projects as it includes all the communication, exchange, collection, processing and distribution of information (Zhang, Liu, & Chan, 2018). Several issues have been identified, such as the lack of trust and coordination between the actors of the supply chain, problems with integration in the supply chain, and the difficulties inherent in breaking traditional work patterns. There is currently a lack of research on this subject in the literature.

This paper explores the information processing issues in a BIM project between firms, with a focus on the Mechanical, Electrical and Plumbing (MEP) process of a Private-Public Partnership (PPP) project. The highest stakes regarding the information process are observed within the MEP process, as it is the last process in the design chain, and it provides information concerning a building's operation and maintenance. During a PPP project, the collaboration between professionals and SCs is eased because all stakeholders are engaged early in the project with only one contract linking all the team members. The aim of the research is to identify conflicting and successful areas in the BIM using an empirical approach through the collaborative mapping of stakeholder's individual perceptions. Process maps were produced and compared to highlight what must be improved regarding BIM information processing. This paper offers an observatory study designed to provide significant insight into the current situation in the construction industry. A diagnosis of the current problems is provided in order to find solutions. The main novelty of the paper is its approach that allows the visualization of the information flows in BIM construction projects. This visualization approach provides a tool to better understand the processes and helps to identify the sources of waste within information flows.

After this introduction, this article contains five more sections. A literature review focusing on BIM and its impact on construction processes is followed by a description of the methodology used for the research and a description of the case study. The subsequent section gives an analysis of the results gathered from the case study. A discussion section then provides potential solutions to the problems identified during the study. Finally, the last section summarizes the paper's contributions and limitations and presents the conclusions along with some recommendations for future work.

3.3 The BIM approach and the notion of flow

3.3.1 BIM and its impact on construction processes

Four major elements defining the BIM rhetoric have been identified (Miettinen & Paavola, 2014): (1) the use of BIM models to regroup all relevant data; (2) a new integrated way of working driven by the need for better collaboration around a shared platform and interoperability between systems; (3) the use of BIM throughout the entire lifecycle of a building; and (4) an increase in productivity and efficiency. However, these elements are part of an idealistic BIM view, as several constraints act as barriers to a proper BIM implementation, i.e., the fragmented nature of the construction industry, particularly in the field, rivalry between partners in a project or the presence of disruptions in construction projects. Each of the four elements mentioned by Miettinen and Paavola (2014) can be integrated into the study of construction processes. This section offers a comprehensive literature analysis in an attempt to determine the elements that are preventing BIM from being implemented in the construction field.

Firstly, transferring models into a centralized platform will facilitate information sharing. Having a centralized platform containing all the information of the different stakeholders helps to highlight the incompatibilities between the systems and to facilitate coordination while providing a common 3D vision of the project to all the stakeholders (Deutsch, 2011). The full potential of BIM benefits can only be realized if a common platform is shared among all stakeholders, including the supply chain (Taylor & Bernstein, 2009).

Secondly, a new collaborative way of working will allow to maximize BIM benefits. The traditional way of producing and exchanging information is through documents that are "pushed" as deliverables from phase to phase to the next actors in the process (Kiviniemi, 2011). In contrast, BIM's information-centric approach supports the processes of a project by providing pre- and post-conditions to each activity to limit waste and allow more informed decisions. In a non-lean organization, the work is pushed through the system, whereas in a lean system, actors pull the work, making the system react to the client's demands. For example, in a traditional push system, the architect produces a model and transmits it to the engineer, who creates the next model according to the information provided by the architect. This process goes on until it reaches the sub-contractor responsible for the construction. In a pull system, the architect asks the engineer for the information required to produce an accurate model. This process is repeated with each actor of the process to limit sources of waste, such as rework due to lack of information or overproduction of information.

Thirdly, the use of BIM throughout the entire lifecycle of a building forces the early phases to be planned so as to limit problems during the construction and operation and maintenance phases. With the implementation of BIM and the acknowledgement of the importance of information flows in the construction industry, these processes are now studied to identify sources of waste, such as overproduction of information or problems in information transfer. However, an important aspect rarely considered in the construction industry regarding the reduction of waste is to tackle it from the source. Indeed, up to 33% of waste originates from design (Innes, 2004). Thus, the identification and reduction of sources of waste must be done during the design phase of a construction project. Early actions will help reduce the amount of waste throughout a construction project (Osmani, Price, & Glass, 2005). However, these studies focus only on materials and/or work flows and do not consider information flows as a potential source of waste.

Fourthly, greater efficiency and higher productivity can be achieved by the standardization and proper management of information flows. Turk (2000) investigated the concept of flow in detail. He proposed a model integrating the work flow, the material flow and the information flow that clearly shows how these flows are interrelated. The main problem resulting from not managing these interactions is that when there is a problem in one flow, it affects the other flows' waste. For example, the production of incorrect information will impact the material flow, as it will cause the wrong equipment or material to be ordered, leading the work flow to lose time waiting for the correct equipment/material to be ordered and delivered.

This review has identified four distinct ways in which BIM can impact construction projects: (1) by replacing traditional construction processes with the transfer of models into a centralized platform; (2) by employing a new collaborative way of working; (3) by incorporating lifecycle management into the construction supply chain; and (4) by the standardization and proper management of information flows. These four elements show the importance of information flows in the implementation of BIM.

The concept of flow is an inherent part of lean thinking. One concept of lean manufacturing is that production is viewed as a flow that describes how information and material are being processed (Koskela, 2000). Any discrepancy in the flow creates problems, also called wastes, which can impact the information, work or material flows. To improve these flows in construction projects, the sources of waste must be identified. To date, waste within information flows in construction remains a subject that is not well-documented.

3.3.2 The notion of flow and the importance of information flow

Garcia-Lopez (2017) describes information flows as support flows and explains their importance in construction. As a part of developing the Transformation-Flow-Value generation (TFV) theory, (Koskela, 2000) states that the most important principle is to reduce variability; in other words, to increase standardization. Over the past several years, a number of studies have been conducted to increase standardization in construction (Aapaoja & Haapasalo, 2014; Martinez, Alvear, Tommelein, & Ballard, 2015; Yu, Tweed, Al-Hussein, & Nasseri, 2009).

Many models have been developed to manage information flows with the goal of reducing waste. Otjacques, Post, and Feltz (2003) proposed a proof-of-concept tool designed to help manage information flows during construction projects by mixing push and pull functionalities. Their tool provides solutions to information management problems such as information overload, retrieval or asymmetry, all of which are sources of waste within information flows. However, the research scope is limited to the construction phase, with no accounting of the waste generated by flaws in the design process.

Tribelsky and Sacks (2010) measured information flows in the design process through data collected from several construction projects. The data they gathered was transacted through a web server which allowed their research to access quantifiable data. They identified seven numerical indices (action rate, package size, work in process, batch size, development velocity, bottlenecks and rework) with which to measure information flows and to detect the presence of waste. However, while this research allowed quantitative data on sources of waste to be collected, it did not address the need to collect qualitative data, such as data on issues of coordination, information transfer or on the over-production of information due to misunderstandings about the process.

To facilitate information management, the quality and reliability of the information created must be quite high. Zadeh, Staub-French, and Pottinger (2015) reviewed four types of information quality issues: information incompleteness, value inaccuracy, spatial inaccuracy and model incompatibility. Garcia-Lopez and Fischer (2016) studied flows such as information flows between activities during the construction phase. They collected data to help managers cope with work flow variability in the field. While variability has been identified as a source of problems in construction, no other source of waste was identified during this research.

These problems observed in BIM construction projects are responsible for several sources of waste in the information management process, including rework due to inaccurate or incomplete information or overproduction of information due to the generation of unnecessary information. Standardization must be in the foundation of an improved information flow. Mirarchi, Pasini, Pavan, and Daniotti (2017) recently proposed a method to improve the information flow in construction by increasing standardization using automated IFC-based processes. Their aim was to improve interoperability within BIM environments. While their results offer positive outcomes, their paper's focus was limited to the sharing and exchange of information. In contrast, the approach used in this article aims to identify additional sources of problems and to propose potential solutions for each.

Compared to the Architecture, Engineering and Construction (AEC) industry, research on information flows in other industries is much more advanced and can provide important insights on how to improve information flows in construction projects. Cetin and List (2002) proposed a new approach for integrating the information flow and the physical flow in transportation networks. Their approach focuses on the interaction between flows; to provide a better transportation system, both flows should be expressed in the same model to determine the impact of waste in the information flow. Attempts to reduce waste in work flows and in material flows without including the information flows cannot give optimal results due to the interrelation between these flows. As another example, K. Wang, Guan, Jiang, and Yao (2010) have devised a method that allows the management and control of information processing in the supply chain process in the military industry.

BIM has been introduced in the construction industry to improve interoperability and collaboration among the parties involved in construction projects (Eadie et al., 2014). However, several issues can be observed with BIM collaboration, such as the quality and quantity of information exchanged between the involved parties, the resistance to change, the lack of understanding of the entire information flows process and the lack of common shared vision (Forgues et al., 2016). These issues tend to keep the actors from the same project or even the same process apart, thus facilitating the creation of waste within the information flows. However, recent research has shown that there is a desire to reduce waste in construction processes with the help of BIM. Ahankoob, Khoshnava, Rostami, and C. (2012) studied the potential impact that BIM can have on reducing waste in the design phase by focusing on the materials flow, and Porwal (2013) focused on addressing the methods of waste management at the source while using BIM. Both studies show the potential of BIM in construction and its role in the identification and reduction of waste in BIM processes. However, as seen earlier, while BIM was developed to improve collaboration and information flows, none of these studies have addressed waste in information processing.

Many underlying factors can affect the results from one project to another. For example, the contract type (Moore & Dainty, 2001), or the quality of the project participants as well as their BIM maturity (Kassem & Succar, 2017). The contract defining the project delivery impacts the team integration and group cohesion (Franz, Leicht, Molenaar, & Messner, 2016). For example, with a design-build delivery, all actors join the project during the design phase, changing their relationships. With a traditional delivery, subcontractors are brought into a project much later, leading to a lower level of communication and coordination. Franz et al. identified five classes of project delivery methods and observed that high cohesion and team integration led to positive effects, such as lower costs or higher client ratings for building system quality. However, they did not consider the maturity level of the actors participating in a project. In a BIM project, players do not have the same experience with BIM, impacting the results on the project. As more and more actors are using BIM in their projects, their BIM integration maturity is developing; this ongoing process will solve some problems such as the organization of work issues or semantic gap (Smits, van Buiten, & Hartmann, 2017).

This review has identified several studies focused on information flows, but much work remains to bring the construction field up to the level of other industries. Of particular interest is the need to manage flow and add value through better information processing. This paper provides a way to fill the gap identified in this review: the lack of knowledge during the design phase of construction projects, specifically the lack of qualitative data on sources of waste in information flows.

3.4 Methodology

This paper presents the results, obtained via an investigation, of a case study of a CA$265.7 M jail replacement construction project, a public private partnership (PPP). Due to the increased complexity created by the duplication of all the technical systems required by the security requirements, the general contractor (GC) decided to invite subcontractors (SC) to participate from the design phase to the end of the project, and to use BIM to help reduce design errors and ease collaboration and communication throughout the entire project. Considering these factors, this exploratory research provides data for a PPP project using a design-build delivery with stakeholders that have a range of maturity levels in the use of BIM. The mechanical, electrical and plumbing (MEP) process is the most complex process to coordinate (L. Wang & Leiti, 2016). The research therefore focused on the MEP process coordination.

This study used an investigative method based upon a case study research approach (Fellows & Liu, 2015; Hancock & Algozzine, 2016; Yin, 1994). The data was collected from October 2015 to February 2016 through two interviews (each one and a half hour long) with each participant. The auto-confrontation technique was used during the interviews and was part of the data collection process (Forgues et al., 2016). These interviews occurred at the end of the construction project when the processes were over, and the participants could easily remember what had been done during the various phases of the project. The participants were the project managers of the architecture firm and of the MEP engineering firm, the MEP contractor and the MEP BIM coordinator from the GC. At the end of the construction project, the research protocol was specifically designed to help the participants map the information flow between the parties involved in the MEP process. To obtain accurate and consistent results among the participants, the mapping has been adapted based on the standard graphic of the Business Process Model and Notation (BPMN). BPMN allows actors to create a graphical representation for specific processes in a process model by using a small number of elements in simple diagrams (Scherer & Ismail, 2011) (see table 1). The five main elements are easy to manipulate for process modelling by an unexperienced participant. BPMN's five main elements were used to simplify the mapping and to gather the necessary information about the communication work flow between the various stakeholders, as listed in Table 1.

The data gathering for the process modelling focuses on three important aspects:

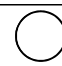
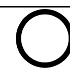
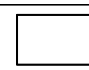
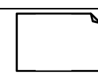
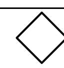
- The work flow between the different actors;
- The input and output of information for each activity; and

- The representation of this information in material objects or documents.

To study interoperability and the number of models in the flows, a new aspect was proposed to support the process:

- A technological tool: The format and software used to transfer the documents and information.

Table 3.1 Elements present in the BPMN mapping

Element	**BPMN - Icon**
Beginning	
End	
Activity	
Document / Information	
Decision	

The auto-confrontation technique used here is a method developed in cognitive science to confront the participant with their own reality (Clot et al., 2000). This technique was used by Forgues et al. (2016) to demonstrate maturity issues with BIM. In that study, the participants and the researchers co-constructed maps between the lifecycle of a construction project and the stakeholders (Forgues et al., 2016). The mapping allows the research collaborators to obtain data highlighting the different points of view of the various actors of a single process, thus pinpointing the issues and reasons for the presence of barriers between the stakeholders and the sources of hindrances to collaboration.

The method was adapted for the identification of the sources of waste by reusing the data collected in this empirical validation. The flows were revised to isolate the good and bad practices that are often mentioned in the literature, as well as to validate the existing theories and observations on issues in these practices. After using the auto-confrontation technique to complete their maps, the participants were asked to individually highlight areas of conflict in the process flows. The efficiencies and inefficiencies in the flows could be identified by studying these areas of conflict and their location in the maps. Next, the analysis phase, the process maps created in the first phase were refined to fit the BPMN model and to allow the participants to comment on the results. By analyzing the maps, the research team isolated the different perceptions, the semantic differences and other barriers, as well as the contradictions between the perceptions and finally, the ambiguity throughout the entire process to highlight the sources of waste in information processing.

3.5 Results

The results are divided into two sections. The first section presents the information processing issues that were diagnosed from the comparison of the process maps produced by the various specialties. The second section presents the good practices in the processes as a suggestion to improve information processing through standardization.

3.5.1 Information processing concerns

Four categories of problems were identified by comparing the maps realized with the stakeholders: 1) the coordination of the work between stakeholders; 2) the variety of software used by the stakeholders; 3) the difficulties in breaking traditional work patterns; and 4) issues in the supply chain integration, as having stakeholders not included in the BIM process led to coordination problems.

3.5.1.1 Coordination of the work between stakeholders

Through the analysis of the flows, two main issues were observed: the gap between traditional and BIM processes and the overproduction of information. The MEP contractor realized the map shown in Figure 1 that shows his understanding of the electromechanical coordination process between the MEP contractor, the GC and the engineer with a focus on the coordination of the electromechanical model between these three stakeholders.

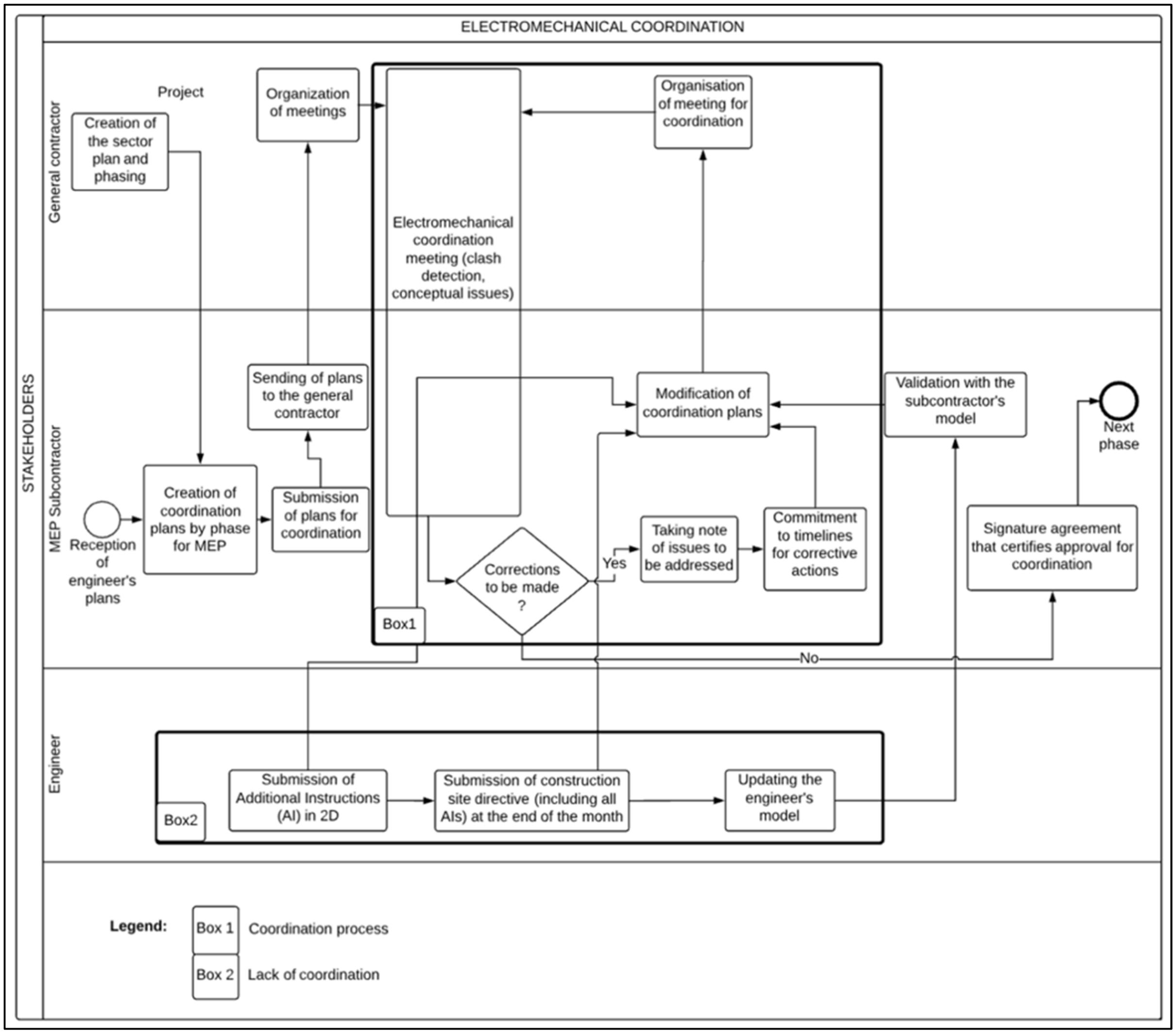


Figure 3.1 Coordination process realized by the MEP contractor

As illustrated in Figure 1, the MEP contractor is responsible for the creation of the coordination plans by phase for the MEP according to the GC's and the engineer's needs. Once the coordination plans are generated, monthly meetings for coordination are organized for the ongoing validation of the plans. The MEP contractor mapped a process with a good coordination (Box 1) and a process with a lack of coordination (Box 2).

Box 1 frames a set of activities that illustrates the coordination process between the GC and the MEP SC. According to the MEP SC, this part of the process was tedious at first due to the implementation by the GC of a new coordination process between these stakeholders. A lack of understanding and resistance to change occurred when moving from traditional to BIM processes. However, at the end of the project, when everyone became accustomed to the new process, it went faster.

Box 2 shows the transmission of additional instructions and construction directives between the MEP SC and the engineer. During this phase, the engineer was not included in the coordination process (Box 1) with the two other stakeholders. Because of this lack of coordination, the engineer could not be aware of the stakeholders' information needs, which led to an over-production of information from the engineer and errors in the engineer's documents. *"There was no communication between the plumbing coordinator and the plumbing installation team because the installers are used to doing a job from point A to point B by the shortest way possible. They did not change their practice and it affected others. Moreover, the electricity installation team was absented from all meetings when it would have been relevant because it resulted in a lot of rework at the end which could have been avoided."* This statement from the GC shows the resistance to change from traditional to BIM practices from two project stakeholders. This lack of coordination led to the creation of waste, such as rework and loss of time leading to the overproduction of information. It also demonstrates that while each specialty may have an excellent knowledge and comprehension of their own work, without BIM, participants cannot have a vision of the overall process and the work of the other specialties. Dossick and Neff (2011) qualifies this as seeing the processes with specialty lenses; these participants were focused exclusively on their own process(es). They ignored the interrelation between their work and that of other actors, especially how their work was affecting the work of the others. This lack of communication and coordination between stakeholders tends to produce information based on their traditional process and their own knowledge. Thus, the information provided does not meet all the recipient's needs (it may include unnecessary information and/or lack some required information), leading to requests for information from the recipient and an overproduction of information.

3.5.1.2 Variety of software among stakeholders

The interoperability between the various software used and the number of models produced by each discipline were major problems during the project. The different stakeholders used numerous platforms, including CAD 3D, Revit, Tekla, etc. (Table 2). Coordination problems were related to interoperability issues between these software products. For example, there were conflicts between the MEP SC's and the engineer's models because they each used and updated their own models in parallel, which created problems with the model coordination. There were also information processing issues in dealing with both 2D and 3D CAD and BIM models: *"Since the MEP SC only got 2D drawings from the engineer, they had to integrate the information in our own model."* This statement from the GC showed an interoperability gap between stakeholders leading to a loss of time for the MEP SC with the remodelling, understanding and coordinating of the changes, considerably slowing the overall process.

Table 3.2 Models and authoring software by specialties

Stakeholders	Number of Models according to specialty	Software
Professionals	Architecture: 6 Models	Revit
	Mechanical engineering: 3 Models	Revit
	Electrical engineering: 1 Model	Revit
	Structural engineering: 1 Model	Revit & Tekla
Subcontractors (SCs)	Ventilation: 1 Model + 15 Plans	Revit & AutoCAD 3D
	Plumbing/Heating: 2 Models	Revit
	Fire protection: 1 Model + 2 Plans	Revit & AutoCAD 2D
	Electricity: 1 Model	Revit
	Structure: 3 Models	Revit

3.5.1.3 Difficulties in breaking traditional work patterns

In a traditional construction project, the parties involved usually work in silos. The inherent lack of coordination and communication limits the knowledge and understanding of the other actors' processes. During this research, the actors revealed some of the difficulties involved in breaking traditional work patterns. Figure 2 shows how the architect perceived the information flow during the final design phase.

The task of the architect during this mapping exercise was to represent his own final design process and that of the engineers with a focus on the information flow and the coordination between them. While the architect's activities and flow are well detailed, the engineering part is almost a black box, with coordination meetings and the production of drawings as the only information exchange link. Figure 3 shows how the MEP SC perceived the information flow during the execution phase.

With the same task as the architect, the MEP SC was asked to map his execution process and those of the other stakeholders. Figure 3 shows that the MEP SC was not able to separate the sources of information inputs from different professionals; he decided to group them as one stakeholder. Furthermore, it appears that, he perceived the production and exchange of information with professionals as being limited to only one activity during the whole process.

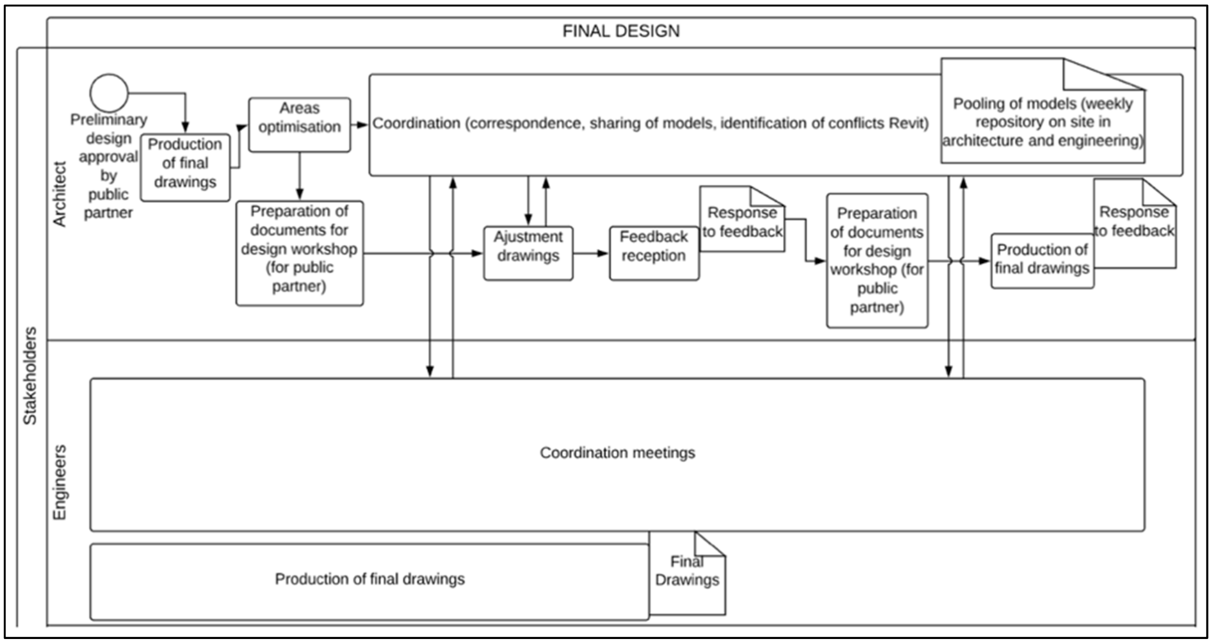


Figure 3.2 Examples of problems with mapping the processes of other actors from an architect's perspective

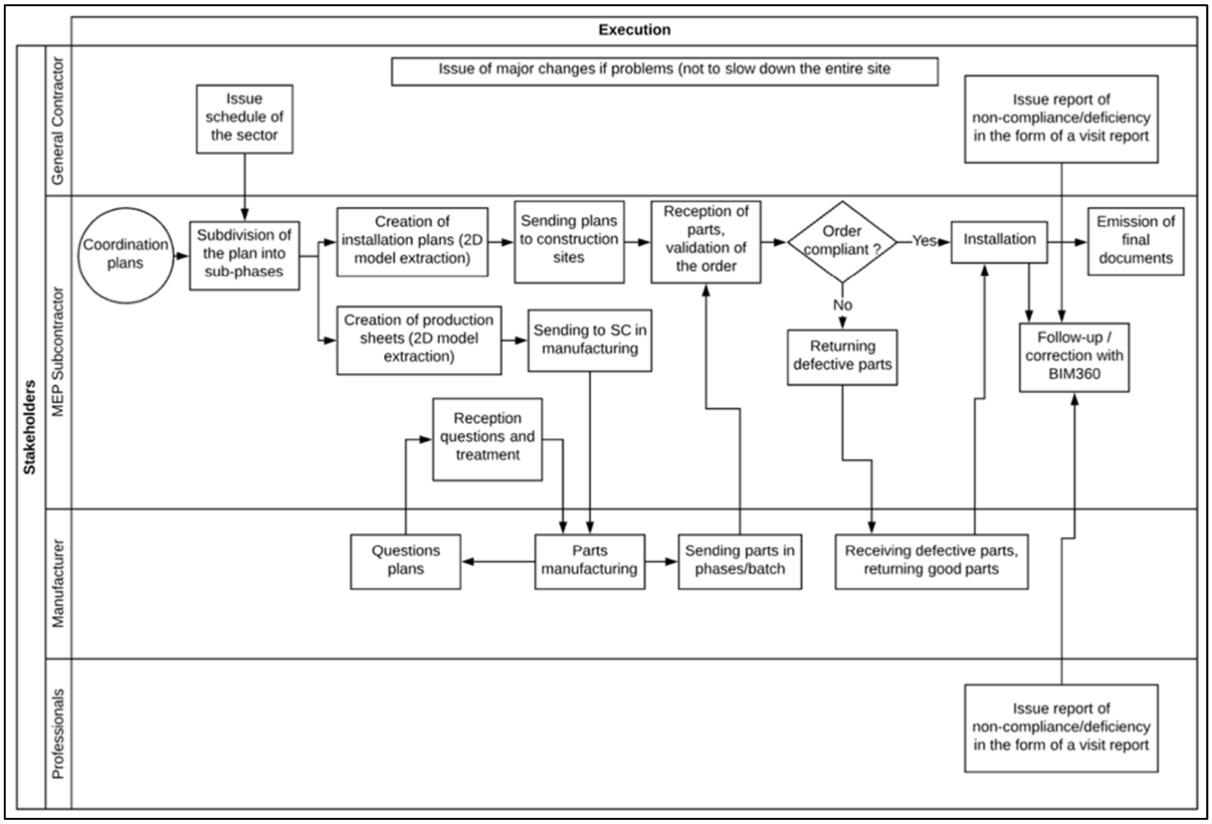


Figure 3.3 Examples of problems with mapping the processes of other actors from a MEP SC's perspective

Analysis of these mappings and interviews indicates a limited understanding of the information needs between the various stakeholders. This could be explained by the traditional Push approach to the production and exchange of information. Even if there is a shift from a fragmented to an integrated information platform, the practices deeply imbedded in specialists' mental models remain. The traditional pattern of producing and exchanging information is repeated. The prescriptive approach in which design information is "pushed" using static contractual documents (drawings and specs) in a linear design and construction cycle conflicts with the need to understand the information required for each use of BIM in subsequent processes (the Pull approach). Without the knowledge of each other's needs, the actors create the information they need for their deliverables with no concern for the inputs required by the other specialties, creating an overproduction of information. This situation leads to the main source of waste in information processing.

3.5.1.4 Supply chain integration

A major problem in construction supply chain management is the lack of consideration for the role that manufacturers can play in the overall information processing strategy. In this case, they either did not participate in coordination meetings or did not use BIM technologies. As Taylor and Bernstein (2009) argue, the integration of all the stakeholders in the BIM processes reduces the conflict areas and enhances the productivity and efficiency of the overall project. For example, the fact that the manufacturer was not included in the process created coordination issues, resulting in other sources of waste. The MEP SC stated: "[…] a lot of manufacturing errors, the fast-track approach was too much for him and he was not the best choice among the different manufacturers during the bidding phase due to the fixed-price bid to the lowest bidder." The MEP SC concluded that it would be better to go with manufacturers who work with BIM, even if it costs more, as that time loss is more expensive than paying more to a manufacturer.

3.5.2 Potential success factors for BIM integration

Thanks to the visualization of information-processing problems that allowed the various maps to be compared, some emerging practices were discovered, easing the overall process and collaboration between the partners. Two success factors were highlighted by the study participants: the standardization of the processes within the BIM integration, and long-term relationships.

3.5.2.1 The standardization of processes

A BEP (BIM Execution Plan) is the document that drives the implementation of BIM on a project. Normally, one of the main goals of a BEP is to formalize how information is to be produced, to identify the roles and responsibilities in this production of information and, to describe the workflow for the production and exchange of information. The problem in traditional Design-Bid-Build (DBB) contracts is that the GC and SC are not involved in the production of the BEP.

Since the PPP procurement approach requires an integrated team of design professionals and builders, it was possible for the GC to propose an overall information management strategy. The GC had a seasoned BIM team managing the project. The strategy, tools and processes used to produce, and exchange information were detailed in a BEP produced by the GC, who was also responsible for the BIM implementation for the project. This plan also identified the uses of BIM, based on the Penn State use taxonomy (Messner et al., 2010), and provided a detailed representation of the BIM processes throughout the building's life cycle.

The BEP presented a framework to produce a coordinated 3D model, which included the production of the information required by the client CMMS systems for the operation and management of the building. This rigorous 3D coordination process was designed to manage the detection and elimination of conflicts. Furthermore, the general contractor was already using BIM in other projects and was convinced of the advantages that BIM could bring to the realization of this project. Two platforms were deployed to manage the coordination process as well as the conflicts and deficiencies that occurred during the project. Aconex was used for managing monthly meetings and deficiencies, as it is a collaborative platform. Aconex provides a solution for BIM management, quality and safety, incorporating Request For Information (RFI), etc., with a centralization of the documents produced by all parties involved in a project. BIM 360 Glue was utilized to resolve conflicts and to manage weekly meetings, as it forces the implication of all parties involved in the entire process. This software demonstrates the value of having an integrated formula with a BIM-competent GC.

At first, the stakeholders were confused and reluctant to adhere to the BEP and found the BIM coordination meetings to be time consuming. However, over time, the meetings became more effective, and their relevance was recognized by the project team. Figure 4 shows a simplified version of an iteration of the 3D coordination of the models described in the BEP. The 3D coordination process required that the MEP SC receive the models from the architect and the engineers before coordinating the models and starting his work. Once the MEP SC completed the coordination of the models, having used them to detect any conflicts, they were sent back to the respective professionals with all the information necessary for them to continue their work. This model coordination process was carried out on a weekly basis to avoid major problems. Figure 5 shows the map realized by the GC concerning the 3D coordination process.

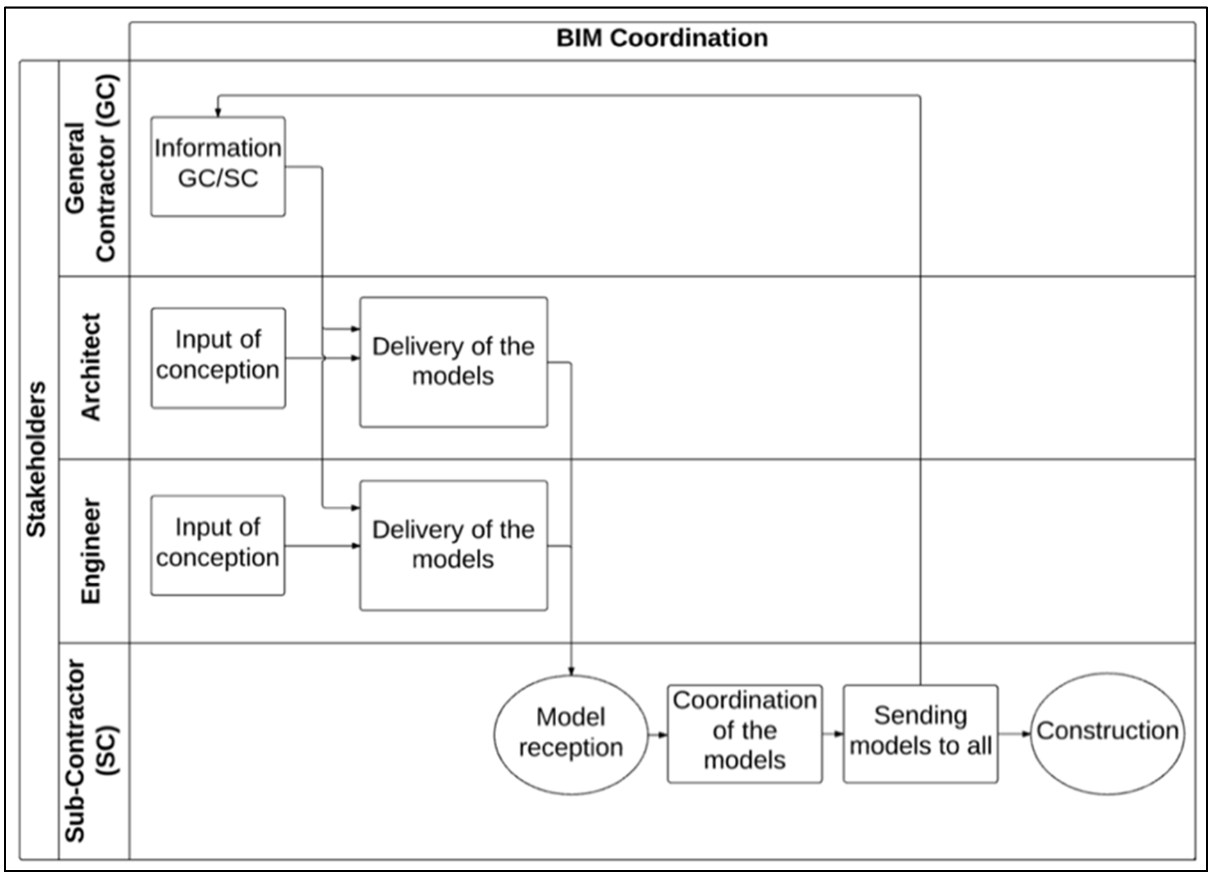


Figure 3.4 Basic iteration of the 3D coordination of the models between the actors

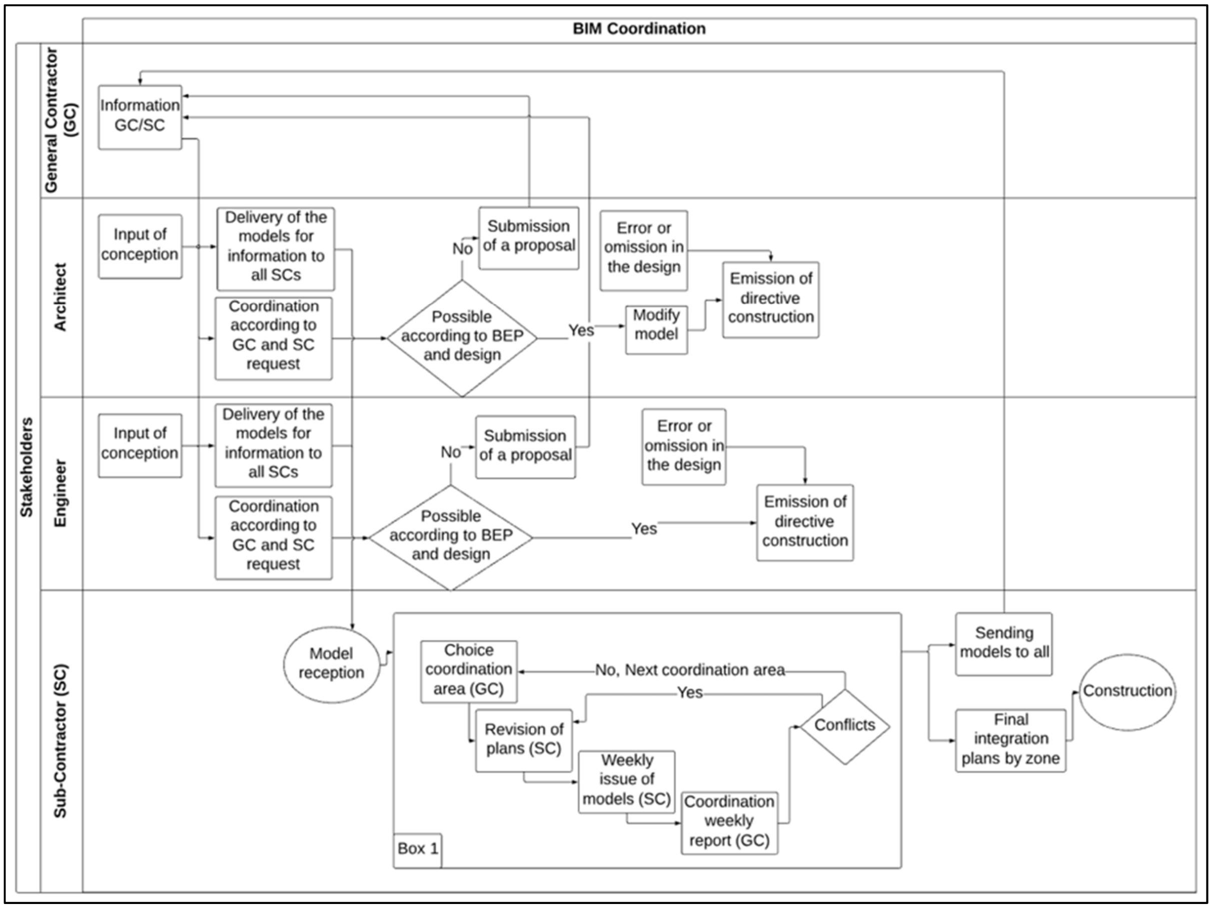


Figure 3.5 3D coordination process from the GC's point of view

The 3D coordination process demonstrates the success of the GC in making all the project stakeholders aware of the overall information processing related to the project's progress. Once the various models of the professionals' designs were received, the coordination process was realized by the SC. The 3D coordination of the models was based on various sections of the model. When a section was complete, the SC coordinated its information, and the process was repeated for each subsequent section (Figure 5, Box 1). The 3D coordination was done for specific areas defined by the GC and revised by the MEP SC. During the interviews, the actors admitted to having avoided many on-site errors thanks to this 3D coordination. The MEP SC also stated: "I can no longer imagine doing a project of this magnitude without the tools I have learned to use [BIM 360 Glue, Field, Revit, etc.] and the resulting collaborative methods." This statement clearly demonstrates the positive impact of collaboration on a construction project.

3.5.2.2 Long term relationships

Another advantage of using a procurement mode that favors an integrated supply chain is the possibility for the GC to select firms based not only on cost but also on their experience and performance based on previous relationships. As Egan (1998) suggested, "the industry must replace competitive tendering with long-term relationships based on clear measurement of performance and sustained improvements in quality and efficiency." Having worked successfully with these firms in other projects, the GC had developed long-term relationships, with a better understanding of each other's work patterns and ways of managing information using BIM. With the GC's deep knowledge of BIM, he was able to address the Push issues in information processing for the BIM 3D coordination process. For instance, the interviews were conducted when the project studied in this research had been completed and a second project had started with the same project team. With a better understanding of mapping workflows and information flows in the GC's BEP, the interviewees noticed a great improvement in how they managed their production and use of BIM models. Thus, it is possible to assume that visualization and trust relationships and the transition to new BIM methods improved and facilitated the relations in the second project. Moreover, the auto-confrontation exercise enabled them to better understand their own general process in addition to understanding the problem areas. By drawing the maps, they realized that the problems identified in the first project were no longer occurring in the new project. In this case, the transition to new practices was remarkably fast. However, the process was slowed down due to new stakeholders entering the process and/or not participating. The assumption is that the methods, once acquired, made it possible to improve the quality, efficiency and performance, and especially the management at the on-site level, which is the objective of the GC.

3.6 Discussion

This discussion focusses on the identification of sources of waste in the information flows of a BIM construction project. For each source of waste identified in this research, potential solutions are proposed to provide a way to increase BIM benefits in future construction projects.

An overview of the identified sources of waste is given in Table 3, together with their cause(s) and the level of impact they can have in a construction project and the proposed potential waste reduction strategies to reduce waste in future construction projects.

Table 3.3 The identified sources of waste, their cause, impact and proposed potential solutions

Source of waste	**Cause**	**Level of impact**	**Proposed potential waste reduction strategy**
Overproduction of information	Lack of understanding of information inputs needs Semantic gaps Decentralization between the design and construction phase Speciality lenses Interoperability gaps Lack of common vision	Time loss Non-value-added information Money loss Creation of tension between stakeholders	Standardization of processes Collaboration & Communication BIM execution Plan Pull approach
Rework	Semantic gaps Decentralization between the design and construction phase Speciality lenses Interoperability gaps	Time loss Non-value-added activity Money loss Creation of tension between stakeholders	Standardization of processes Collaboration & Communication Formation Pull approach
Transfer of information	Decentralization between the design and construction phase Interoperability gaps Lack of common vision	Time loss Money loss Creation of tension between stakeholders	Standardization of processes Collaboration & Communication BIM execution plan
Difficulties in understanding how the technology could affect practices	Organization of work issues	Time loss Non-value-added activity Money loss	Standardization of processes Collaboration & Communication Training

Seven causes of waste were identified during the case study. These causes are regrouped into four sources of waste, as shown in Table 3. The four sources of waste discussed in this research are from the literature and are derived from the seven sources of waste identified by Ohno (1988) for workflows and material flows. The causes of waste come from the analysis of the results that can be categorized into the sources of waste. First, in a document-centric approach, the information, which is prescriptive in nature, is pushed, whereas the basis of an information-centric approach is to know the information needs of the next actor in the process in order to satisfy them. Not knowing those needs has a double impact: overproduction by not knowing the nature of the information required and thus working with incomplete information, which then leads to corrective actions and rework. Second, the semantic gap can also be linked to the overproduction of information, as well as to the need for rework. Differences in semantics leads to misunderstandings between the stakeholders, which in turn leads to mistakes in the generation of information or in work errors. Third, the decentralization between the design phase and the construction phase results in several sources of waste, such as the overproduction of information, rework and information transfer. The analysis showed that while the flow between traditional partners in the design phase was good, conflicts appeared in the construction phase because the roles and responsibilities were not clear. In addition, the exchange of information was not standardized between the engineers and the SCs. Fourth, specialty lenses lead to knowledge gaps because actors focus exclusively on their own specialty to realize their work as quickly as possible, neglecting other specialties. The stakeholders can understand and explain their own processes but cannot do the same with other stakeholders' processes, even when they are part of the same project. This situation leads to the overproduction of information and to the need for rework. Fifth, various software products were used during the project and several models were created. The use of numerous models led to coordination problems due to the loss of data when transferring information from one software platform to another, or when stakeholders were using and updating their own models in parallel without synchronizing them, creating coordination problems. Interoperability gaps lead to the overproduction of information, rework and problems in the transmission of information. Sixth, the transition from traditional to BIM practices requires major changes. Taylor and Bernstein (2009) treated the subject of changing the paradigm trajectories and noticed how stakeholders had difficulty understanding how the technology could affect their practices. Stakeholders are accustomed to their traditional practices, and it takes both time and effort to adapt to a new practice. Finally, the lack of a common vision was observed between stakeholders, a lack that was partly responsible for some of the problems observed in collaboration and communication, contributing to the overproduction of information and to problems in information transmission.

Depending on the source, several solutions are proposed to address the waste issues identified in this study. It has been demonstrated that increasing standardization helps to decrease waste (Koskela, 2000). In this context, the standardization must be oriented towards the processes. Indeed, the standardization of activities and information should decrease waste three ways: first, by helping to close the semantic gap with a standardized vocabulary for all the stakeholders; second, by helping to reduce the decentralization of information between the design and the construction phases with standardized information transfer procedures between the stakeholders in each phase of a construction project; and third, minimizing the lack of knowledge with a better visualization and understanding of their own process as well as of the processes of the other stakeholders. During this study, with the help of the BEP, there was an attempt to standardize the transfer of information, with positive outcomes. However, even with positive results, this could not prevent the presence of waste in the information flows.

An approach from Lean Production, the pull approach, could be implemented to reduce the overproduction of information and need for rework. As mentioned in the literature review, the pull approach allows stakeholders to produce their information according to the needs of the other actors, thus limiting the amount of information in the process. With the BIM approach, there is supposed to be an improvement in the collaboration and communication among the parties involved in construction projects (Y. Liu, Van Nederveen, & Hertogh, 2017). Indeed, with the centralization of production and exchange of information, the BIM approach will compel stakeholders to change their traditional work methods into a new method of team collaboration and communication (Gray et al., 2013). For example, to address the standardization of processes for the transfer of information, the BEP will cover the collaboration and communication among the stakeholders from the design phase to the end of the project to limit the interoperability gaps and specialty lenses, thereby reducing the appearance of tension between stakeholders. Finally, training makes it easier to understand the new technology. Indeed, when transitioning from a traditional to a BIM approach, changes are made in the processes. This training and experience will help stakeholders understand and use the new processes.

The use of VSM in this case was key to visualizing and to identifying sources of waste with the generation of current state maps of the various processes utilized in the project. Developed by Lean Production, the VSM tool is used to improve the workflows. It has also revealed its potential to be used to improve information flows (Long, Ng, Downing, & Nepal, 2016). The aim of VSM is to identify and reduce sources of waste in the processes. The aim of the research was to provide potential solutions to the recurring problems identified in this study. The proposed solution would be to create a framework combining the various propositions listed above to reduce waste in BIM information flows. For future projects, the use of VSM could help reduce waste with the generation of future state maps to consider and remove all the identified problems and sources of waste.

3.7 Conclusion

BIM was introduced in the construction industry as a way to decrease fragmentation and inefficiency in project lifecycles by proposing a shared platform to centralize the production and exchange of information. A key finding in this research is that the project stakeholders must adapt the way they are handling information in order to leverage the benefits of BIM technology. Even when using new tools, the old way is still a major source of waste. While extensive research has been conducted regarding waste reduction in workflow and material flow, little has been done regarding the identification of problems in information flows or in identifying possible solutions, the main contribution of this paper. Another contribution is the demonstration of the value of adapting VSM for construction to visualize, identify and eliminate sources of waste in the information flow process. The study of information flows made it possible to demonstrate the presence of problems and successes in BIM processes.

This exploratory research focused on identifying conflicting and successful areas in the BIM processes between construction actors using an empirical approach. It also highlighted contradictions and issues in the BIM information processing and provided waste reduction strategies:

- Construction project stakeholders had difficulties moving from a document-centric to an information-centric approach, repeating traditional patterns of pushing information related to their specialty, leading to the overproduction of non-value information and to more rework;
- Collaboration was not optimum between the actors of a same process even with the use of BIM. It was demonstrated that there was a need to improve information processing between the different actors to reduce information waste; and
- Waste reduction strategies were proposed following the results analysis. These strategies aim to reduce the sources of waste identified for future projects.

Some of the limitations of this study are that only one project has been studied, limiting the amount of data used to develop and provide the solutions. One of the major problems in research in construction engineering is that all projects are different, making it difficult to generalize. For example, the maturity level with the use of BIM varies between project stakeholders, in this case, especially in the construction phase. This could accentuate the issues observed. However, a first taxonomy of waste for BIM information flow was based on this research.

While this exploratory study has contributed to generating knowledge about the deployment of BIM, this project is part of a larger research effort aiming to improve information processing with BIM. This research shows the need to develop or adapt tools like VSM to better identify sources of waste in the production and exchange of information as a next step. With a better definition of the sources of waste in the information flows, more solutions can be proposed and tested in the future.

CHAPTER 4

BIM IMPLEMENTATION IN AN ARCHITECTURAL FIRM: USING PROCESS MAPPING TO REDUCE WASTE IN THE INFORMATION FLOW

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4.1 Abstract

Purpose – Building Information Modelling (BIM), as a breakthrough technology, creates hopes of more efficient design practices. BIM adoption is considered as a disruptive technology, which requires rethinking these practices. However, BIM tools are still used following the traditional design process, not using the technology full potential, and there is little research on how to improve the information flow in the production of design models. This research focuses on identifying and removing the waste in this flow to streamline the design process using BIM.

Design/methodology/approach – A collaborative action research approach was used to develop and implement a method to improve the information flows for the production of BIM models within an architectural firm. The research was divided into three phases: establishing the Current State, identifying the Desired State and implementing and validating the new BIM design process framework.

Findings – The use of Process Mapping (PM) allowed us to identify and reduce the sources of waste and, to streamline the process and information flows. Principles and actions have been identified for each source of waste to help reduce them within the design process for future projects.

Originality – This article provides the proposition of an approach to identify and help reduce waste in the BIM information flow during the design through standardization of the process.

Keywords Building Information Modelling, Process Mapping, Information flow, Non-value-added actions.
Paper type Research article

4.2 Introduction

Building Information Modelling (BIM) was introduced in the AEC industry with the aim of tackling the issue of fragmentation by improving interoperability and collaboration among parties involved in construction projects (Eadie et al., 2014). In theory, the BIM approach is proposed as a solution to decrease inefficiencies in the production, exchange and management of the building information within a unique and shared platform during the whole project lifecycle. Therefore, the concept of information flow management is crucial when using BIM. Indeed, BIM contributes to translating the client's value proposition into a successful project by implementing a continuous information flow (Al Hattab & Hamzeh, 2013). While in theory, this holistic BIM data environment should improve productivity and lead to better buildings, design professionals are, however, still struggling when it comes to understanding that BIM is much more than merely drafting a 3D model.

Several barriers have been identified to explain the problems stand in the way of fully reaping the benefits provided by BIM; these include a lack of BIM coordination, the quantity and quality of information exchanged between the parties involved, resistance to change, a lack of understanding of the entire information flows process, and a lack of a common shared vision (Forgues et al., 2016). Central to these issues is that the focus should be on the notion of managing information flow instead of managing the production and exchange of documents which is static by nature and produced in silo. However, the notion of managing information flow is not well understood in construction, which is problematic for the efficient use of BIM. According to Winch (2009), information processing should be the main activity in construction management. In construction, it is represented by the exchange and transfer of information between all parties involved in the construction processes. Extensive research has been done to study the management of information flows. However, the same is far from true with respect to managing waste in these flows in construction. Because information production is poorly structured during the design phase (Winch, 2009), a large amount of waste is generated due to a lack of formalization of the process. Wastes are tabulated as non-value-added activities, as opposed to value-added-activities, within a process.

The notion of flow is inherent to the Lean Production theory (Koskela, 2000), which may explain why BIM is often associated with Lean. In this theory, flow improvement is associated with the identification and removal of waste. One approach that uses Lean principles is the Lean Six Sigma, which itself employs Process Mapping (PM) as a way to achieve continuous improvement (Pepper & Spedding, 2010). The aim of the Six Sigma methodology is to reduce variations in processes, while Lean aims to reduce the volume of non-value-added activities. While both approaches have indeed been used in the construction industry (Banawi & Bilec, 2014; Gaikwad & Sunnapwar, 2020; Matt, 2014), the referenced studies, however, focused on improving certain processes, such as production planning, supply chains or production processes, but ignored the improvement of information flows.

The present research aims to use PM to provide a method to improve information flows in the production of BIM models in an architecture firm; this method will then be used to identify and reduce waste, reconfigure the design process and formalize it within the practice of the firm. The goal is to increase standardization and reduce waste within the information flows during the design phase in order to improve productivity and value generation using BIM. The choice to focus on the design phase was motivated by the fact that it is architects who produce and manage the greatest amount of information in the project lifecycle. A collaborative action research approach was adopted in conducting this research following a request from an architecture firm to help increase the efficacy and efficiency in their use of BIM.

This article starts with a literature review, followed by the methodology adopted and a description of the BIM deployment strategy used by the firm. Results from the three-step approach used are presented and discussed. Finally, the conclusion summarizes the contributions to knowledge through the identification and classification of the forms of waste observed in the information flows and makes recommendations for future projects.

4.3 BIM implementation issues and the identification of potential solutions

4.3.1 BIM and issues of adoption

In a traditional construction project, information is provided through a document-centric approach (with documents including plans, budgets, estimates, etc.), which creates barriers to communication and coordination between the different project stakeholders (Isikdag & Underwood, 2010). During the design phase, the various actors also still tend to work in silos and push the information they generate toward the next actor in the process (Aibinu & Venkatesh, 2013). Conversely, the information-centric approach provides conditions for each activity to support the different processes, allowing the reduction of waste and a more informed decision making (Michaud et al., 2019). With BIM and the use of an information-centric approach, the focus should not be in its implementation, but in obtaining its full potential during its use. The missing part in the BIM implementation is the need for planning to structure the flow of production and exchange of information. The absence of such planning is a major source of waste when using BIM.

BIM involves a process change in the organization of work that significantly modifies all the key processes used in a building construction project: moving from a silo mentality with low coordination and communication between stakeholders to a centralized approach through a unique and shared platform. Because of these process changes observed with BIM implementation, the parties involved in BIM projects must adapt their way of working from the traditional ways to the BIM processes (Volk et al., 2014). Indeed, the use of BIM demands changes in traditional methods of work and in the relationships between the parties involved, and helps improve team collaboration (Gray et al., 2013). However, several barriers, classified as technical and non-technical factors, must be overcome in order to reap the many BIM benefits identified in the literature (Mahalingam et al., 2015).

This required change of approach generates interest in the Lean Construction approach. In traditional projects, the Push approach is generally used, whereas Lean Construction uses the pull approach, where resources and/or information are obtained from stakeholders whose inputs are needed for the next activity in the process (Ghosh, Reyes, Perrenoud, & Coetzee, 2017).

Several tools or approaches used in other industries or even in the construction industry can help improve construction industry processes. These include various tools adapted from Lean Production, namely, Value Stream Mapping (VSM), Continuous flow, Pull approach, etc. (Ansah, Sorooshian, Bin Mustafa, & Duvvuru, 2016). The Last Planner System, developed for the construction industry from Lean Construction, is also a tool available to improve construction processes.

4.3.2 The interest of the Lean approach for BIM

BIM and the Lean approach are two different concepts used in the construction industry, and both of them aim to the improve the industry's performance (Hamdi & Leite, 2012). According to Kjartansdóttir (2011), using BIM and Lean principles, the project will have an enhanced construction process, which will help secure the project team a more successful delivery. The literature contains similar conclusions stating that when combined, BIM and Lean methods provide an improved construction project (Khanzode, 2011; Khanzode, Fischer, Reed, & Ballard, 2006). Moreover, research has established the presence of a strong synergy between Lean principles and BIM (Sacks, Koskela, Dave, & Owen, 2010). Based on these conclusions, Sacks, Barak, Belaciano, Gurevich, and Pikas (2013) developed a prototype called "KanBIM" (Kanban using BIM), which combined BIM and Lean to form an integrated process designed to streamline the management of information during construction. Moghadam et al. (2012) have also been able to integrate BIM and Lean Construction in a modular construction manufacturing process. The authors used VSM in combination with BIM to generate a map of the factory workflow using the schedules of building components. BIM provided a way to automate the design and drafting process, while VSM was used to visualize the workflow and identify sources of waste, the resource usage, and the time needed.

The notion of waste is fundamental to the Lean approach. According to Koskela (2000), in production, there are three root causes of waste, linked to the three aspects of production management: design, control and improvement of production. The list of seven wastes developed by Ohno (1988) is used in Lean Production to tackle these issues. However, in Lean Construction and in the AEC industry, waste reduction strategies are still not in broad use as a means of increasing productivity. Bølviken and Koskela (2016) identified several potential answers to why waste reduction strategies are not more commonly used in construction: the notion of flow is less understood in construction than is the case in production; construction processes are more complex than production processes, contract management tends to be prioritized over production management in construction, and the list of seven wastes is not entirely applicable and relevant for construction. Several research studies have proposed ways to identify and/or reduce sources of waste. Tribelsky and Sacks (2011) developed a method to measure the quality of information flows within the design phase of the project, using a web server to manage information exchanges. However, while this research allowed collecting quantitative data on sources of waste, it did not address the need to collect qualitative data such as issues related to coordination, transfer of information or overproduction of information. Jacob and Varghese (2011) explored the integration of the Design Structure Matrix (DSM) in the information flows of BIM design processes. The DSM is a management tool used to develop feedback and cyclic task dependencies in information flows to improve the design process. Al Hattab and Hamzeh (2013), through process models, provided some understanding on how information flows in the BIM process can be improved. Their models allowed a comparison of traditional and BIM-based design phases. Their conclusion showed the need for a better sharing of information through the study of interaction between participants. However, to obtain a lean and waste-free process as suggested by the authors, the focus cannot be only on one source of waste in the information flow. Indeed, Emond (2014) brought together sources of waste identified by different authors in construction: (1) underutilization of talents, (2) waiting inputs, (3) information transfer, (4) overproduction of information, (5) deficient behavior, (6) loss of good ideas, (7) achievements unappreciated by the client, (8) make do, (9) resistance to change and (10) non-management of perception. Aka, Emuze, and Das (2017) carried out a research study on the identification of waste in the design phase using VSM. The work focused on engineering and stopped at the Current State, with the identification of waste and recommendations for strategies to reduce waste. VSM is one of several tools available to map processes. The next section will present a review of VSM and PM in construction to determine the more appropriate tool for this research.

4.3.3 Process Mapping to improve BIM adoption

Both VSM and PM were developed for production, and have been adapted to the construction context. VSM was first developed for the manufacturing industry, in a bid to identify and eliminate waste and improve productivity (Rother & Shook, 1999), while PM is used in the Six Sigma methodology to improve processes through a structured and systematic approach designed to reduce defects (Pepper & Spedding, 2010). In construction, when it comes to the production of information flows within BIM Execution Plans (BEP), it is the Business Process Model and Notation (BPMN), a form of PM, that is recommended. We argue that the PM (an important tool used in the Six Sigma methodology) provides a viable alternative to VSM for visualizing the information flows in construction. Indeed, certain research studies have proposed frameworks or procedures using PM to improve processes in the construction industry. For example, W. Wu and Issa (2013) suggested an integrated PM for BIM implementation, through integrated green BIM process maps. In their research, the authors provide a way to improve standardization of processes, but do not however target waste reduction.

Based on the works discussed in the above review, this exploratory research aims to fill the current gap in knowledge by providing an approach using PM to improve standardization and reduce waste in the information flows of the design process of an architectural firm. This approach differs from Business Process Re-engineering (BPR) its focus is on an analysis of information flows, whereas BPR focuses on the workflows and business process. Furthermore, PM is used as a visualizing tool to facilitate BIM adoption by identifying and solving problems before they occur.

4.4 Context of the study and methodology

This study is part of an ongoing research project that started in 2015 jointly with a Canadian architecture firm. The initial goal of the research was to develop a methodology to change management practices in order to improve BIM adoption in the AEC industry. The firm is multidisciplinary and is composed of six departments (Architecture, Engineering, Sustainable Development, Corporate, Retail and Design Studio), and has over 200 employees. The problem to solve was the absence of a structure to the firm's internal information flows. The proposed approach consisted of the identification and reduction of waste within the information flows of the design process in order to improve productivity and quality through standardization.

The collaborative action research (CAR) approach used in this study provides a framework in which researchers work closely with professionals, allowing a contribution to practice with the creation of changes and a contribution to theory with the creation of new knowledge (Azhar, Ahmad, & Sein, 2010). The collaborative dimension of this methodology involves the co-creation of knowledge by both the research and professional communities. In the present research, we adopted the set of principles laid out by Otto and Österle (2012) for CAR: (1) formalize and share goals, (2) collaborate through action, (3) conduct full learning cycle, (4) allow for trial and error, (5) make significant commitments and, (6) involve complementary roles.

The Lean Six Sigma cycle for PM was also adopted: (1) define, (2) measure, (3) analyze, (4) improve and, (5) control processes (DMAIC). Based on the Lean Six Sigma cycle, the research was organized into three main steps: 1) define the Current State map, 2) devise a Desired State map, and 3) ensure control through monitoring the process (Figure 4.1).

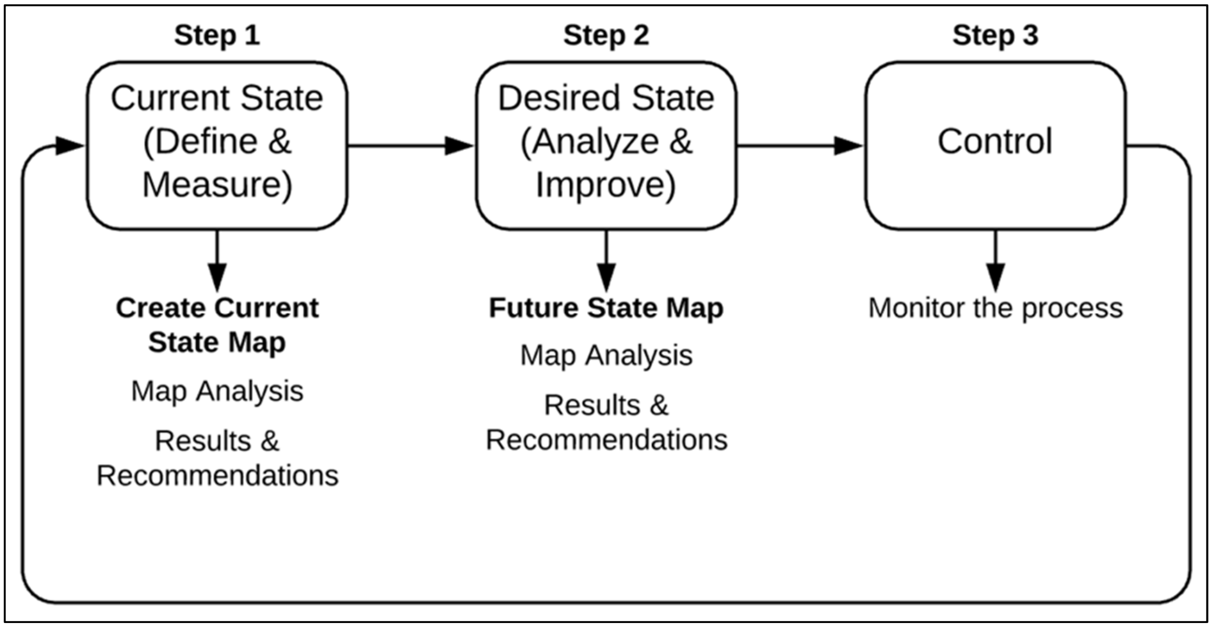

Figure 4.1 Three steps of mapping based on Process Mapping

The first step, the Current State map creation, took place over a three-month period, going from September to December 2018, and involving nine focus groups (one focus group per department, and four for the Architectural department because four different building projects were studied). The role of the focus groups was to provide data and information needed to generate the Current and Desired State maps of the approach developed. Each focus group was conducted with several members of the departments involved, such as department heads, project managers, architects, engineers and designers. The focus groups were consulted twice, each time for an hour and a half: the first time was for the creation of the maps, and the second time, for comments on the maps created.

For the second step, which lasted for six months, the data collected from Step 1 was used to identify gaps and waste and to standardize activities for generating the Desired State map. To create this map, five focus groups were conducted with several members of each department in the same manner as in the first step. Engineers were not included in this step, as the focus was on an architectural perspective. The third step is still active to date, and is taking place within a continuous improvement process with a constant monitoring of the design process.

For both mapping exercises, the researcher acted as the facilitator to orchestrate and manage the process. For the Current State map, the mapping was drawn up based on the standard Business Process Model and Notation (BPMN) to allow accurately and consistently representing results for each department. BPMN allows stakeholders to create a graphical representation for specific processes in a process model by using a small number of elements in simple diagrams (Scherer & Ismail, 2011). In the present work, BPMN helped facilitate the visualization of the information flows as it provides a standard notation that is readily understandable by all stakeholders of a project. The Pareto principle was used during the mapping exercise to identify the 20% of the most common activities and information that could be found in 80% of the projects. When the first mapping exercise was complete, the process maps created were refined to facilitate the identification of process gaps between the different departments. Each participant was then asked to comment on the final Current State maps to ensure accurate results. An analysis of the Current State maps and the observation made during the focus groups allowed the identification of forms of waste by determining, for each activity and piece of information, whether any value was added to the process. These forms were identified by the researcher, and then categorized within the ten sources of waste identified in the literature. The next step in the method was to develop solutions based on principles proposed by (Koskela, 2000).

For the Desired State map, only one general map was created to include the processes of all the departments of the firm. BPMN was still used for this step of the research. However, after considering the observations and comments from the first mapping exercise, during which the exercise focused on the actors of the process, the Desired State map focused on the information and workflows. After the second mapping exercise was completed, each participant was asked to comment on the final map to ensure accurate results for the Desired map.

4.5 Results

4.5.1 Current State

The goals of the Current State maps were first, to provide a visualization tool to help the participants better understand their processes and, second, through an analysis of the maps, identify the sources of waste within the current processes.

The analysis of the final Current State maps showed that, even if the participants had a good understanding of their own process, the problem was more about picturing the entire process of the design phase in their respective departments due to a combination of silo work and the use of a Push approach. Prior to the mapping exercise, the participants were unable to visualize the sources of waste, given that it was difficult for them to visualize the overall process. The mapping exercise helped to tackle this issue and provided the participants with a global vision of their actual information flows around the plans or models. Furthermore, it allowed them first to understand the information flows of the other departments, and secondly, to see the differences and similarities in their design process. For example, it helped the participants acknowledge that many activities and documents – such as 2D/3D plans, the budget and the timetable – were similar, and that there was a possibility of standardization between the departments. The main difference observed between the workflows of the different departments was the level of detail achieved in the production of the models, which varied according to the type of project of each department, as is discussed in the next section.

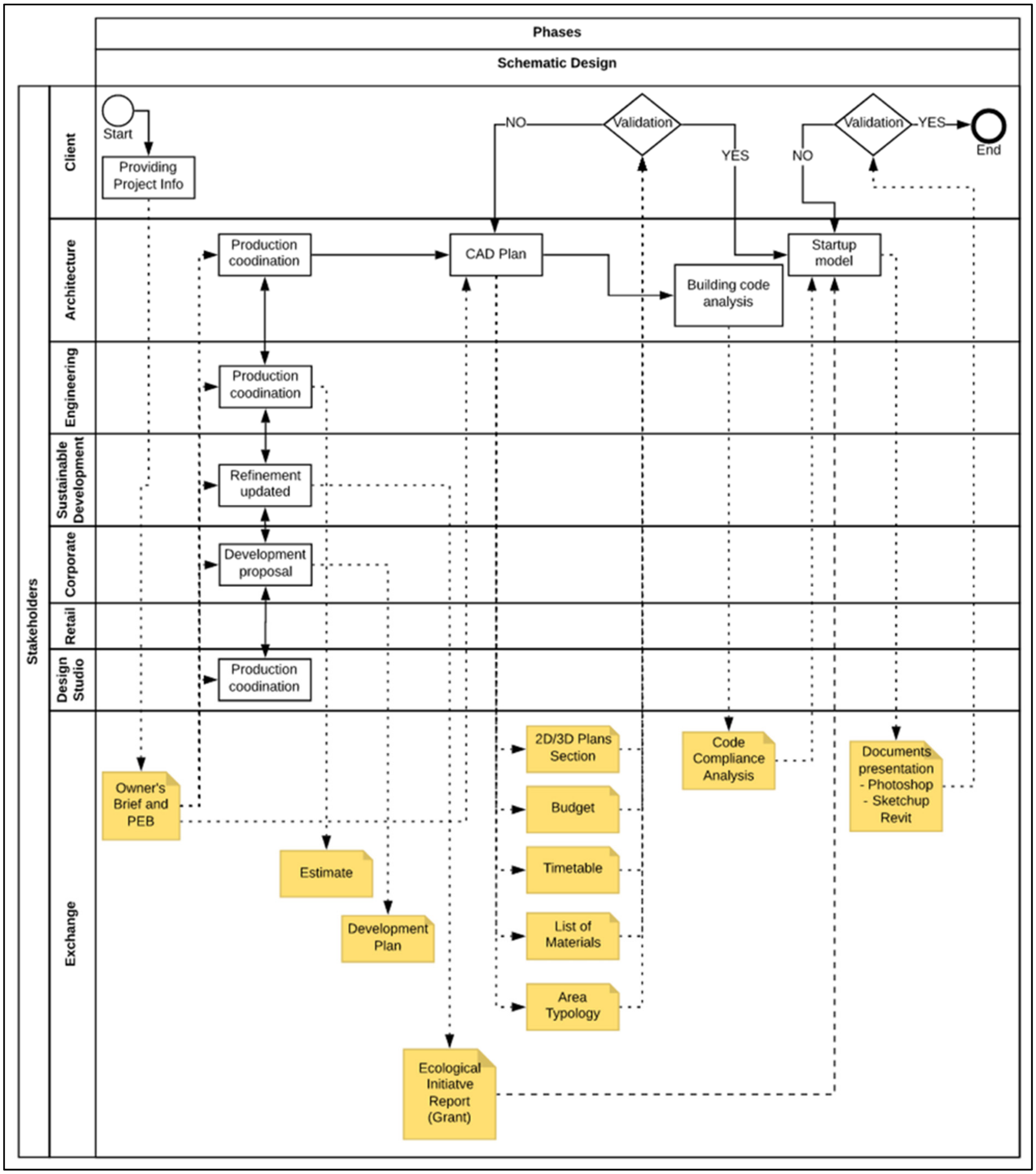

Figure 4.2 Example of a Current State map for the schematic design

Figure 4.2 shows a section of the Current State map realized in the architectural department, which shows how the architects perceived their own process and information flow during the schematic design step of a typical construction project. They were also requested to map their exchange of information with the other departments of the firm. The study of these maps clearly shows several forms of waste. First, the lack of knowledge and understanding of the entire process, with only a little bit of information known of the other department processes, was stated during the focus groups. This issue can be seen as a barrier to the deployment of BIM, but in this case, is considered as a form of waste in the information flows. Secondly, there was the matter of the use of the Push approach with only a little bit of coordination between the different departments. Finally, the focus group participants acknowledged that there was little to no contact between the departments during the development of the BIM models, leading to sources of waste, such as the overproduction of information, problems with information transfer or loss of good ideas.

The analysis of the Current State maps, combined with the observations made during the focus groups, allowed the identification of the forms of waste presented in Table 1. These are grouped together into eight sources. As the goal was to generate a single Desired State map for the entire firm, each form of waste identified has been processed to be eliminated from the firm's new information flows.

Table 4.1 Wastes identified in the Current State maps

Forms of waste	**Sources of waste**
Lack of new ideas	Under-utilization of talents
Semantic difference Lack of knowledge and understanding Lack of communication and coordination	Waiting inputs
Silo mentality Lack of communication and coordination	Information transfer
Lack of knowledge and understanding Repetition of activities Push system Lack of communication and coordination	Overproduction of information
The information created is not reused between the departments or the different projects Silo mentality	Loss of good ideas
Misunderstanding between the client's needs and their interpretation Lack of communication and coordination	Achievements unappreciated by the customer
Lack of knowledge and understanding Lack of communication and coordination	Make do
Desire to keep the traditional processes	Resistance to change

The sources of waste presented in Table 4.1 come from the list of 10 sources previously listed from the literature. While these sources were identified for the construction process, eight out of them proved to be relevant to the specific context of analyzing information flows in design. The two sources that were not identified are deficient behavior and non-management of perception. This does not mean that they do not exist in the design process of construction project. The waste sources found in the literature were used to categorize the forms of waste identified during the analysis.

The underutilization of talents (D’Antonio & Chiabert, 2018) was identified during the mapping exercise in the form of lack of new ideas. The implementation of modifications requires flexibility in the work processes. Indeed, continuous improvement is obtained when processes are always evolving with new and better ideas.

Waiting inputs was a source of waste identified in various forms. First, the semantic difference was observed during this study, and included issues such as different names used across the departments for the same document. The differences led to misunderstandings between stakeholders, thus creating unnecessary waiting between activities. The creation of a semantic agreement helped reduce variability in the process. Second, the lack of knowledge and understanding of the processes led to the production of unnecessary information, because the actors did not know the information the other stakeholders had.

Problems relating to information transfer were due to two forms of waste. First, the silo mentality (Cilliers & Greyvenstein, 2012) within traditional construction projects involves little collaboration as the work is distributed according to the specialty. Consequently, the participants are not able to determine what information is needed, when it is needed and for whom, thus creating issues in the information flows. Second, this little collaboration is limited to coordination between the various sub-deliverables, whereas BIM technologies impose a unified work framework. Both of these forms of waste were addressed through a reconfiguration of the design process.

Overproduction of information is a major source of waste in construction projects, as it has been identified in four different forms of waste. First, the actors who push the information tend to overproduce. Because the information needs are not acknowledged in a push system, the actors produce information for their activity without knowing the information required by the next person in the process. This leads either to the production of unnecessary information or to a lack of information for the next actor in line, thus requiring rework and causing overproduction of information. By implementing a Pull approach, information needs are better defined, which reduces information overproduction. Second, the use of PM makes it possible to identify and reduce the number of non-value-adding activities (waste), thus reducing the number of steps in the process. Third, the PM improves transparency, allowing the participants to visualize and better understand their own process as well as those from the other departments of the firm. Finally, lack of communication and coordination has already been tackled within the two preceding sources, through a reconfiguration of the design process.

Loss of good ideas was identified during the mapping exercise because the information created is not reused between the departments or the different projects. By creating a shared database within the firm, the information is centralized, thus allowing the employees to find needed information and recall good ideas.

Deliverables unappreciated by the owner was identified because of misunderstandings between the owner's needs and their interpretation. An increased transparency using PM was the principle used to reduce such problems for future projects. Furthermore, the reconfiguration of the design process with the Desired State map allowed to better define the client's needs with a better understanding of the overall process.

Make do was identified in two forms. The make do concept means that the actors have to manage situations with limited or inadequate means available. On the one hand, there is a lack of knowledge and understanding, which leads the actors to do the work with what they know and not what is really needed. On the other hand, the lack of communication and coordination drove the actors to create the information they need for their deliverables without worrying about the information needed by the other specialties. By implementing information centralization, the enhanced communication and coordination will help decrease the make do source of waste.

Resistance to change was observed within each department, as they wanted to maintain the traditional processes. This source of waste was tackled by increasing transparency through a mapping of the desired process using PM. Indeed, with more transparency in the new processes, the actors have a better understanding and knowledge reducing the likelihood of resistance.

4.5.2 Desired State

The goals of a Desired State map were, first, to visualize the existing processes in order to observe the impact of moving to BIM from Push to Pull, and second, to remove the sources of waste from the equation, following the six principles proposed by Koskela (2000). As for the Current State maps, the Desired State map (Figure 4.3) was generated using the BPMN notation. However, as the goal was to increase standardization, the process was organized toward a common workflow and information flow for all of the firm's departments. Figure 3 shows a section of the design process, with a standardization of the workflow of the different departments of the firm.

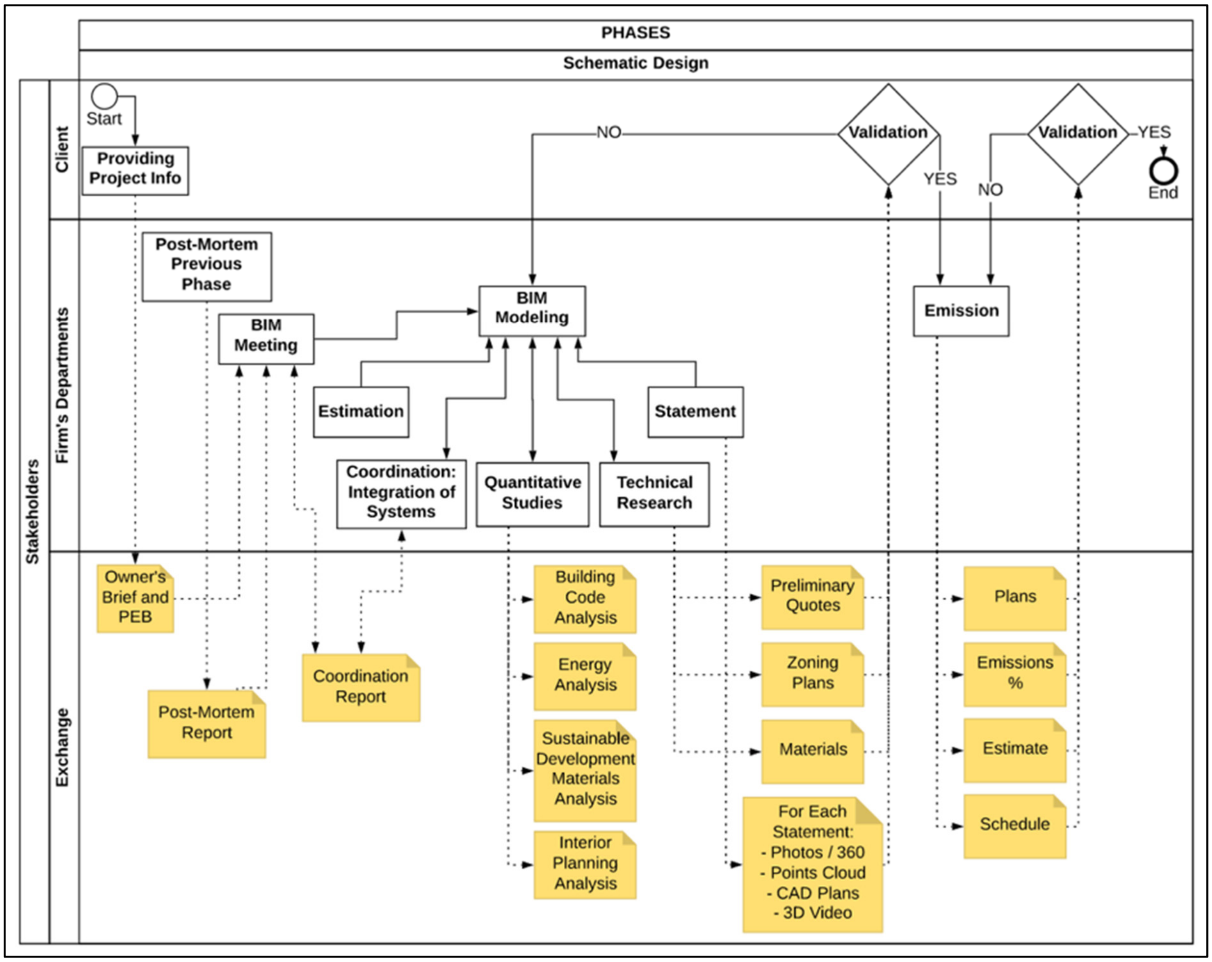

Figure 4.3 Desired State map of the schematic design step in the design phase

The mapping of the workflow is divided into three sections. First, are the value-added activities "post-mortem previous phase" and "BIM meeting" that are not directly linked to the BIM model. They facilitate the coordination between the design phases and the stakeholders, add value to the process, and facilitate the BIM uses (defined in the BIM deployment strategy) during the projects. Second, are all activities that are directly linked to the BIM model generation. Activities that create and provide information from or to the BIM model generation. Third, are the activities leading to the end of the phase and to the next step, such as a presentation with various media (pictures, virtual reality, 3D models, etc.).

The information flow is presented in the exchange section of the map. The input of information usually provided by the client is complemented by the post-mortem report and the coordination report, providing data for the production of the BIM model. The information output is extracted from the BIM model in the form of documents, tables and/or plans. The creation of a unique process map for the different departments of the firm allowed to reduce forms of waste, such as the silo mentality, the repetition of activities or the fact that information created was not reused between the departments. All this was made possible by using Koskela's principles.

Table 4.2 summarizes the principles and approaches used during the study to help reduce waste within the design process for future projects of the firm.

Table 4.2 Forms of waste, Koskela (2000) principles and actions used to eliminate waste

Forms of waste	**Koskela principles**	**Proposed actions**
Lack of new ideas	Increase flexibility	Ease the implementation of new ideas
Semantic differences	Reduce variability	A semantic agreement
Lack of knowledge and understanding	Increase transparency	Use of Process Mapping (PM), Current and Desired State map)
Silo mentality		Reconfiguration of the design process using PM and centralization of information
Lack of communication and coordination		Reconfiguration of the design process using PM and centralization of information
Repetition of activities	Reduce the share of non-value-adding activities Simplify by minimizing the number of steps	Use of PM Reduce the share of non-value-adding activities Simplify by minimizing the number of steps
Push approach		Implementation of the Pull approach with the help of PM
The information created is not reused between the departments or the different projects	Reduce variability	Creation of a shared database
Misunderstanding between the client's needs and their interpretation	Increase transparency	Use of PM to reconfigure the design process
Desire to keep the traditional processes	Increase transparency	Facilitate the change

Koskela's principles to reduce waste were then presented to the participants, in conjunction with PM, to define actions that may reduce or eliminate the waste previously identified. The first action was to tackle variability (which is responsible for two forms of waste), firstly, by adopting a shared vocabulary and definitions, and secondly, by the development of a shared database for all departments in order to reuse and standardize information created from one project to another or by different departments.

Empowering the staff to advance new ideas in order to improve BIM practices in the firm stimulated them to find new ways to improve their work processes, by using the principle of increasing flexibility in defining the work patterns. A visualization of their work processes through PM proved to be quite powerful in terms of increasing transparency. When participants were able to visualize the way they were handling the production of the BIM models for the first time, they were able to identify issues in their current process, allowing them to facilitate change. They were able to identify redundancies in their processes, leading to a reduction of non-value-added activities and simplifying their information processing by minimizing the number of steps required. Moreover, as the design was reconfigured using the BIM principle of centralized information in the generation of the Desired State map, the process was reoriented towards an information-centric approach to enhanced communication and coordination.

Regarding the three remaining forms of waste (silo mentality, lack of communication and coordination and Push approach), the core principle of Lean Construction, moving from a Push to a Pull approach, was explained to the participants and mapping sessions were conducted to reconfigure the design process following this principle. These sessions helped to break the silos between disciplines, allowing participants to work in a collaborative way and to rethink how to better work together. It also helped increase transparency by allowing a better understanding of how Lean thinking could be applied to their design process.

4.6 Discussion

As mentioned in the literature, the implementation of BIM in the construction industry faces certain challenges as it requires a change in the work approach. A big part of this change relates to the information flow and how it is structured. As information occupies an increasingly important place in the construction industry, an absence of structure in its production and exchange represents a significant source of waste.

The notion of waste is largely discussed in the literature with a multitude of tools, approaches and techniques developed across different industries, as discussed in the literature review. Furthermore, there are also existing taxonomies identifying sources of waste. However, most existing approaches were developed for materials and/or workflows. Indeed, the present research used an existing taxonomy developed for construction, with a strong focus on the management of materials and workflows. Furthermore, this taxonomy was adapted from the original one developed by Ohno (1988) for the production industry with a sole focus on the management of material flows. This study demonstrated that several sources of waste can be found in different flows, such as work, materials and information. However, it also demonstrated that others are specific to a single flow. Indeed, two sources of waste from the taxonomy used in this research were not observed in the information flow of the design process. This suggests that there are sources specific to information flow, which are not considered in existing taxonomies. Thus, a taxonomy needs to be created for the sources of waste in information flows.

4.7 Conclusion

The collaborative action research in the present study was motivated by the need for an architecture firm to provide solutions for the recurring problems in its information flows; specifically, recurring problems causing waste within these flows in the BIM model production. This article contributes to knowledge through the identification and classification of the forms of waste observed in the information flows of the design phase. This is followed by action proposals to reduce these wastes. This is achieved by using the approach or method developed during this research to reduce waste in the information flow and to standardize the design process. The combination of the BIM principle of centralized information with the approach proposed by Koskela for waste reduction, and PM – shows how communication, coordination and an understanding of the process could help streamline the information flows by shining a light on waste in the production of BIM models. It also contributed by demonstrating the advantages of PM as a visualization tool clarifying all the information flows and highlighting issues and gaps in producing BIM models. The work contributes to practice by proposing a three-step approach providing a way to improve the design process in the BIM deployment strategy (information-centric approach). This approach helped the design professionals of this firm identify and reduce their existing sources of waste in the information flows of their design process, thus providing a better framework for implementing BIM while increasing the value-added activities within their process.

The study are some limitations. The results are based on just one case, meaning that more cases are needed for a generalization of the conclusions drawn herein. Moreover, not all the actors in a construction project were implicated in the study as most of the participants were architects. Thus, while the results provided allowed to improve internal processes, research is still needed to cover entire process, including all parties involved in a construction project.

This collaborative study is part of a larger research aimed at improving the information flows between all parties involved in the process. The next step will be to develop an approach that can embrace the whole supply chain for a better collaboration and communication in the production and exchange of information.

CHAPTER 5

A TAXONOMY OF SOURCES OF WASTE IN BIM INFORMATION FLOWS

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5.1 Abstract

Since its introduction, Building Information Modelling has evolved into a major technology in the construction industry, where information flows play a major role. However, the very presence of waste within these flows prevents the technology from reaching its full potential. This paper aims to develop a taxonomy focused on the sources of waste within information flows in BIM projects since existing taxonomies focus primarily on work and material flows. Using a collaborative design science research approach, the study was divided into two phases: first, semi-structured interviews were used to collect data on BIM practices. The data was then used to identify similarities and contradictions in the information flows using process maps; second, the ShareLab approach was used to validate the findings through a common agreement. The paper's main contribution is the taxonomy of sources of waste in BIM project information flows as it closes knowledge gaps in one of the main flows of construction projects. Another contribution is its use of a new approach to validate an artefact in a Design Science Research methodology named the ShareLab approach.

Keywords: Building Information Modelling; nD modelling; information flow; taxonomy; waste

5.2 Introduction

BIM was introduced to the construction industry with the aim of improving productivity thanks in part to centralized information (Eadie et al., 2014). Initially, BIM was largely considered to be a tool designed as a 3D digital model (Penttilä, 2007; Succar, 2009). However, traditional construction processes are compatible with the use of BIM technologies. This requires an evolution of construction industry practices to adapt to the new BIM related processes (Messner et al., 2019). Today, the different dimensions of BIM, also called nD modelling, are revolutionizing construction practices and technologies (Charef, Alaka, & Emmitt, 2018).

An improved collaboration and interoperability between project stakeholders are fundamental in the BIM approach. This explains the major role of information flow within BIM processes. In order to guarantee the efficiency of the BIM approach, information flow quality must be optimal. A potential solution to a recurring problem is to identify and eliminate sources of waste in the flow of information. This solution has in fact been implemented in other flows found in construction processes. In that regard, certain tools, approaches and techniques have been developed to improve work flows (Heigermoser, de Soto, Abbott, & Chua, 2019; Olivieri, Seppänen, & Granja, 2018) and material flows (Turner, Williams, & Kemp, 2016; Vilaysouk, Schandl, & Murakam, 2019). The information flow is part of the three main flows found in construction processes, with the others being work and material flows. These three flows are interrelated (Turk, 2000). Existing research focuses on specific cases of waste, without necessarily defining the cause and without seeking to classify and/or prioritize the sources (Dubler et al., 2010; Mirarchi et al., 2017). Implementations focusing solely one or two flow types thus provide only partial solutions. Regarding waste, taxonomies have been developed to improve processes related to work and material flows, whereas none has been established for information flows. Some waste sources are present in multiple flows, while others are specific to a single flow. Thus, when using existing taxonomies developed for the work or material flows, the sources of waste specific to the information flows go untouched because they are not identified. With the advent of BIM, eliminating waste within information flows offers the best opportunities for major gains in quality, predictability and productivity.

The objective of the present research is to form a taxonomy of waste sources in BIM information flows. This research choice was motivated by the need to improve productivity in construction projects, with a focus on information flows. This is because the role of information in BIM implementation at the industrial scale is becoming central to the management and delivery of construction projects. The impact of waste elimination for information flow management is significantly broader than for other flows, as it covers the entire lifecycle of a project. The National Institute of Standards and Technology (NIST) report (2004) is the only one that has studied and quantified the issues of waste in the management of information flows throughout the building lifecycle (Gallaher et al., 2004). This article presents the results of an exploratory research aiming to improve the entire life cycle of BIM construction projects. The use of a taxonomy allowed to facilitate the description and analysis of the results and to communicate knowledge (Ein-Dor, 2011).

This research is based on an exploratory approach involving inductive reasoning (Woo, O'Boyle, & Spector, 2017). Data collection was realized in collaboration with BIM consultants, one client and professionals from four different fields of the Canadian construction industry (architecture, MEP engineering, general contractor and MEP contractor) on commercial and residential type constructions. Also, Design-Build and Design-Bid-Build projects were studied, as well as three BIM dimensions: 3D with the use of BIM Execution Plan (BEP) and the Level of Development (LOD), 6D with sustainability, and 7D with operation and maintenance. This extensive data collection allowed a complete and more accurate picture of information flows in construction processes.

This paper starts with a literature review focusing on the sources of waste within the information flows of the different BIM dimensions. A description of the methodology used for the research follows, along with a presentation of the participants in the study. The next section provides the results and their analysis, with the generation of a taxonomy of the sources of waste in the information flows of BIM projects. Finally, the last section summarizes the paper's contributions and limitations and presents the conclusions and recommendations for future work.

5.3 The concept of waste in BIM information flows

5.3.1 Information flow and waste

The concept of flow has been used in the manufacturing industry for decades through the use of Lean production. One of the five key principles of Lean thinking involves improving the flow by implementing a continuous improvement (Solaimani, Van Der Veen, Sobek II, Gulyaz, & Venugopal, 2019). Based on the same principles, Lean thinking has been adapted to the construction industry to improve its processes. However, with the emergence of new approaches such as BIM, new processes have been developed, with information flow playing a major role (Zhang et al., 2018). Indeed, the BIM implementation was designed to provide a centralized platform aimed at facilitating information sharing (Michaud et al., 2019). These authors provided a guide describing a structured procedure for creating and implementing BIM in a construction project. However, several barriers have been identified as being at the root of problems that prevent reaping the benefits of BIM. These include a lack of BIM coordination, the quantity and quality of information exchanged between the parties involved, resistance to change, a lack of understanding of the entire information flows process, and a lack of a common shared vision (Forgues et al., 2016). Indeed, a recent Scientometric analysis concluded that an extension of collaboration between parties in off-site construction would enhance dialogue and debate on ideas and initiative for future work (Hosseini et al., 2018), showing that these issues are still present to this day.

These issues highlight the notion of waste and its impact on BIM projects. Ohno (1988) was the first to develop a taxonomy of sources of waste. This taxonomy is oriented toward waste in production, with a focus on work and material flows. The notion of taxonomy is used in the model of Knowledge Management (KM) as a means of communicating knowledge (Ein-Dor, 2011). In their paper, the authors Sarayreh, Mardawi, and Aldmour (2012) explain the SECI model developed to establish a knowledge transfer process. According to this model, the transfer of knowledge is divided into four processes: Socialization, Externalization, Combination and Internalization. In the context of this paper, two of these processes are used.

First is Externalization, which proceeds through the use of dialogue, interviews and workshops. The process is used to transform implicit knowledge into explicit knowledge. Second is Combination, which for its part is the process of conveying the explicit knowledge into various forms, such as documents, databases and taxonomies (Sarayreh et al., 2012).

Koskela, Bolviken, and Rooke (2013) identified the need to develop a taxonomy of waste sources specific to construction as the seven production wastes defined by Ohno do not reflect the specific nature of the production systems of this industry. From this, researchers developed a taxonomy oriented toward the management of construction projects, more suited for the construction industry (Emond, 2014). This taxonomy focuses on the same types of flows, but adds the human component as it plays an important role in every step of a construction project, whereas in production, most of the work is automated. Both taxonomies, however, do not take information flows into account. The same can be said of construction waste minimization approaches, techniques and tools, in which case research tends to focus on work and material flow wastes. For example, Z. Liu, Osmani, Demian, and Baldwin (2011) conducted a literature review on existing waste minimization tools, approaches and techniques in the construction industry, and how BIM could aid in waste reduction. Their aim was to identify existing BIM practices and tools to help design out waste in construction projects. However, they only focused on material waste. More recently, the same authors developed a BIM-aided construction waste minimization framework based on their literature review (Zhen Liu, Osmani, Demian, & Baldwin, 2015). The same observation can be made as they only focused on material waste when developing their framework. Several other research efforts have come up with ways to reduce waste in construction, such as using a combination BIM/Lean to develop a framework designed to eliminate waste in the design phase (Mollasalehi, Fleming, Talebi, & Underwood, 2016) or producing a taxonomy of waste based on the TFV theory, with a focus on work and material flows (Bolviken, Rooke, & Koskela, 2014). Dubler et al. (2010) provided an adaptation of Ohno's seven wastes of production in the information exchange process. However, information exchange is only a small part of the information flow, and the seven wastes of production do not cover all the sources of waste in construction, and especially in terms of information flow. More recently, Issa and Alqurashi (2020) proposed a model for evaluation causes of waste depending on Lean implementation in construction projects. The authors provide extensive results with 42 identified sources of waste and identify a correlation between the level of waste and Lean implementation levels. Similarly to previous research, the focus was made primarily and the work flows with only little mention of the information flows. A different approach was used by Khalesi et al. (2020), with a focus on one important consequence of waste that is rework. The authors then identified and categorized all the causes of rework to analyze how BIM technologies could benefit in processing and predicting them. The causes are categorized into seven categories but there is no category for the production, exchange, and management of information.

There is clearly a gap in the literature regarding waste in the information flow in construction. Indeed, a recent bibliometric analysis of the literature on BIM revealed that BIM research is mostly distributed in nine fields (Wen, Ren, Lu, & Wu, 2021). The notion of information flow is one of them, but the notion of waste is not mentioned. Another bibliometric analysis revealed that the research on BIM in structural engineering was directed towards information systems and information management between 2013 and 2015 but it is no longer the case (Vilutiene, Kalibatiene, Hosseini, Pellicer, & Zavadskas, 2019). The issue is that with the implementation of new techniques such as Lean construction or BIM, the amount of information generated in construction has drastically increased and changed information flows. The use of BIM processes, practices and tools shows potential as information flow is central to BIM implementation.

5.3.2 BIM dimensions

BIM plays a bigger and bigger role in construction with every passing day. A systemic review pointed out the increase in adoption of digital technologies such as BIM in off-site construction (M. Wang, Wang, Sepasgozar, & Zlatanova, 2020). The study also indicated a great potential to implement these technologies to improve the construction processes. However, these technologies also mean an increase in the amount of information and a need to improve information flows. In their paper, Jung and Lee (2015) illustrated the status of global BIM adoption from several perspectives. Despite the limited data on hand, the authors managed to show that BIM has been adopted worldwide, with the rate increasing steadily. The evolution of practices and technologies has also contributed to this revolution, particularly with the arrival of the different dimensions of BIM, also called nD modelling (Azhar, Khalfan, & Maqsood, 2012). Today, there are five BIM dimensions recognized in the construction industry, namely: BIM 3D (i.e., BEP & LOD), BIM 4D (scheduling), BIM 5D (estimating), BIM 6D (sustainability) and BIM 7D (facility management applications). Other dimensions exist but are not included in the present research because they are not officially recognized. Regarding information flow and the notion of waste, at the 3D level, Eastman et al. (2011) dedicate an entire chapter to the exchange of information between different actors without dealing with the concept of waste. The same thing can be observed in more recent research projects, which provide procedures or guidelines to improve information exchange through the BIM BEP (Gerçek, 2016; Hadzaman, Takim, & Fadhil, 2016) or to improve information transfer through BIM LOD (Y. Wu & Xu, 2014). These two recent research studies are based on increasing the level of standardization in BIM projects. The BEP is a report generated to implement BIM on a project that provides formalized protocols respecting the production and exchange of information and the identification of roles and responsibilities (Michaud et al., 2019). The LOD concept takes the form of a matrix to provide protocols on the amount of details injected into the BIM model at any point in the project. It also enables actors to improve the reliability of the models (Latiffi, Brahim, Mohd, & Fathi, 2015).

Regarding BIM 4D and 5D BIM, both are implemented during the design and construction phases of the project with the goal of ensuring better cost and scheduling controls. Indeed, BIM 4D is a process that allows the planning, scheduling and sequencing of the construction phase. BIM 5D is the process of adding the cost to the components of the information model. These dimensions can be distinguished from BIM 3D in that they are presented as solutions to problems in information flows. In their research Umar et al. (2015) described the impact of BIM 4D on Integrated Project Delivery (IPD). According to the authors, BIM 4D allows to enhance project planning and minimize resource waste, with an improved coordination and final product quality and a time and cost reduction. Moreover, Park, Cai, Dunston, and

Ghasemkhani (2017) presented a Web and databased-supported method allowing to improve information exchange of 4D BIM. Their goal was to improve the communication and coordination among stakeholders while reducing information delay and issues with consistency. The same observations can be made regarding the use of BIM 5D in construction projects. Indeed, Vigneault, Boton, Chong, and Cooper-Cooke (2020) developed an innovative framework of 5D BIM solutions through a systematic review for construction cost management.

Finally, for BIM 6D and BIM 7D, both dimensions are also implemented during the design phase with the goal of ensuring that the construction operation and maintenance phase proceeds smoothly. Indeed, BIM 6D is a set of simulation tools implemented to accurately predict energy consumption requirements, thus ensuring sustainability and cost efficiency. Farzaneh, Carriere, Forgues, and Monfet (2018) proposed a framework design to create a Building Energy Model (BEM) embedded in the BIM model to be used in the design phase by professionals. The framework would help implement the BIM 6D tools, in addition to providing more information within the BIM models. BIM 7D is an approach designed to track and bring together all information related to the facility management process within the BIM model. Both BIM 6D and BIM 7D are used to optimize the operation and maintenance of a building during its entire life. Tan, Zaman, and Sutrisna (2018)'s study identified information gaps during the transfer from the construction to the operation and maintenance of the building. For example, the authors identified issues between as-built drawings and actual structures due to modifications made in the designs, creating information gaps. Another gap identified was the lack of availability of the relevant O&M manuals. Through a qualitative research study, the authors proposed the development of an integrated knowledge sharing model to tackle these gaps. As is observed with BIM 6D, this study provides a solution to better implement BIM 7D in construction projects, but also requires the generation of more information within the BIM model. While 4D and 5D BIM use information from the 3D model to operate, 6D and 7D BIM add information to the 3D model to improve it. This is why the focus of this paper is on the 3D, 6D and 7D BIM dimensions.

5.3.3 Gaps in knowledge

Numerous analyses of the literature indicate that BIM has a positive impact on information flow. BIM is a disruptive approach to information production and exchange, in which a shared digital model is used for the creation of building drawings and visualizations. Moreover, BIM also significantly modifies all of the key processes used in a building construction (Sacks, Eastman, Lee, & Teicholz, 2018). Furthermore, due to the disruptive approach, there is a lack of knowledge regarding the design process in BIM project, as it was pointed out by Saoud, Omran, Hassan, Vilutiene, and Kiaulakis (2017), where the authors developed a method to predict the impacts of change with building information models. Their method provides one way of improving productivity, efficiency and quality in BIM construction projects.

However, the references studied during this review also identify gaps in knowledge regarding the identification of sources of waste within information flow. Furthermore, the current problem is that the identification of waste is based only on sources identified from the study of work and material flows. Indeed, the sources identified by Ohno (1988), with the taxonomy of waste on the management of material flow in production, and the sources identified Howell, Koskela, Macomber, Bodek (Emond, 2014), with the taxonomy of waste on the management of work flow in construction project management, do not take into account the sources of waste specific to the information flow. This is explained by the fact that the data studied in both flows are inherently different. In the work flow, the study of sources of waste is based on its activities and it is its state of fulfillment that predominates, whereas in the information flow, the study of waste is based on the utility and/or value of the information. To respond to this gap, this paper proposes a taxonomy of the sources of waste in the information flows of BIM processes. At this time, there is a significant differential between what is known in theory regarding information flow waste and what is observed in practice. This fact has been discussed in this literature review with the identification of barriers and issues in BIM implementation made by several studies. The taxonomy presented in this paper aims to provide professionals with sufficient knowledge on how to identify issues in their information flows in all their future projects.

5.4 Methodology

The research design used in this research is based on a collaborative design science research approach influenced by Simon's arguments for the science of the artificial, where the conclusion of the research would present as a new artefact or technological rules providing a framework on how a determined objective can be reached (Koskela, 2017). The collaborative component provided a method allowing researchers to work closely with the professionals in designing the artefact to contribute to the knowledge and solve practical issues at the same time (Otto & Österle, 2012). It is divided into two phases: firstly, semi-structured interviews to capture BIM practices within the different specialties involved in a BIM project, and secondly, use of the ShareLab approach to validate the sources of waste identified in the BIM information flows.

The first phase of the research took place with BIM consultants, one client and professionals from four different fields of the construction industry (architect, MEP engineer, general contractor and MEP contractor) and covered their BIM practices, the way they share information, their use and understanding of a BIM execution plan (BEP) and the level of development (LOD), and the issues they encounter with these tools in managing BIM information. This research was part of a larger study around the research theme of improving productivity in the construction industry through the optimization of the production, exchange and management of information. This allowed the use of data from several other research studies conducted within the laboratory. First, raw data from semi-structured interviews conducted as part of a research project covering the application of the BEP (Quenneville, 2019) was used for the 3D BIM dimension. Second, data from a thesis based on developing a BIM-BEM framework to support the design process (Farzaneh, 2019) was used for the 6D BIM dimension. Finally, the last portion of the data used for this research was obtained in part through 5 one and a half-hour long semi-structured interviews, and on the other hand, using raw data from semi-structured interviews realized in the context of a Master's thesis focused on the evaluation of a BIM model's LOD (Marchioni, 2018). Both data from other research and data collected during this research were analyzed following the three stages (Figure 5.1) proposed by Miles and Huberman (2003).

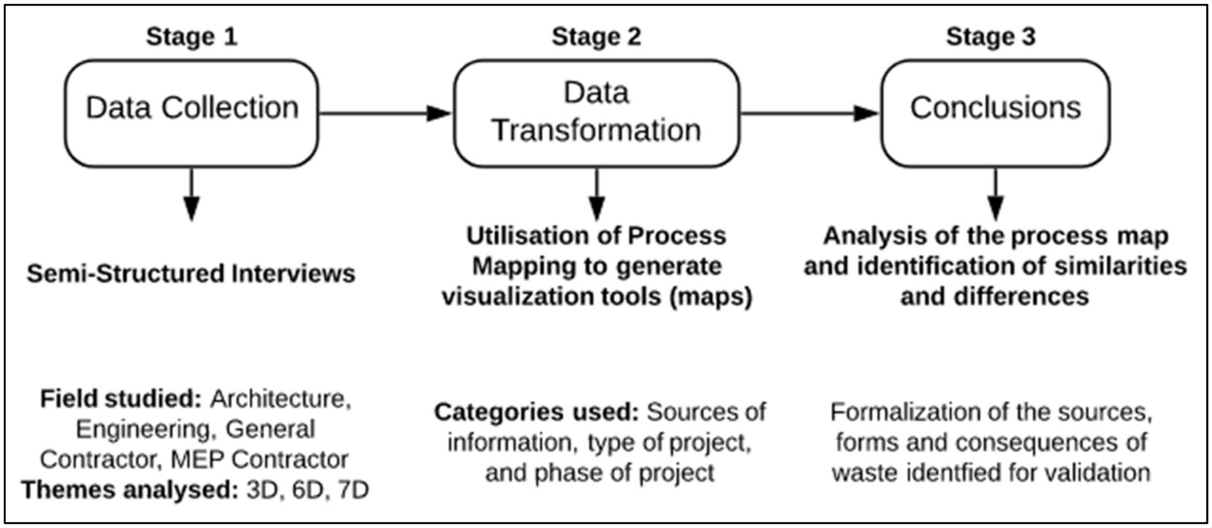

Figure 5.1 Stages of qualitative data analysis

Stage 1 - Data collection: In addition to data from other research, semi-structured interviews were used to collect additional data at this stage of the research. Several fields and dimensions were studied to obtain as complete a picture of the information flows in the design and construction processes as possible, as shown in Table 5.1.

Table 5.1 Sources of data and data collection

<table>
<tr><th>Stakeholders</th><th>Roles</th><th>Dimensions studies</th><th>Sources of data</th></tr>
<tr><td>BIM consultant</td><td>BIM Consultant</td><td rowspan="5">BEP</td><td rowspan="5">Semi-structured interviews' verbatims (Quenneville, 2019)</td></tr>
<tr><td>General Contractor</td><td>BIM Manager</td></tr>
<tr><td>Engineering</td><td>BIM Manager</td></tr>
<tr><td>Architecture</td><td>BIM Manager</td></tr>
<tr><td>Client</td><td>Client Representative</td></tr>
<tr><td>BIM Consultant</td><td>BIM/BEM Consultant</td><td>BIM/BEM 6D</td><td>(Farzaneh, 2019)</td></tr>
<tr><td rowspan="2">Architecture</td><td>Project Manager</td><td rowspan="5">BEP/LOD and Facility Management</td><td rowspan="5">Semi-structured interviews' verbatims (Marchioni, 2018) + Semi-structured interviews</td></tr>
<tr><td>Architect</td></tr>
<tr><td>Engineering</td><td>Project Manager</td></tr>
<tr><td>General Contractor</td><td>Project Manager</td></tr>
<tr><td>MEP Contractor</td><td>Project/BIM Manager</td></tr>
</table>

Stage 2 - Data transformation: The goal here was to identify contradictions and issues in information flows through the generation of visualization tools in the form of process maps using BPMN notation. Three categories were used during the mapping to aid in the analysis: (1) the source of the information (architects, engineers, general contractors, MEP contractors, BIM consultant or client); (2) the type of project delivery modes discussed (Design Build or Design Bid Build), as the information flow varies from one mode to another, potentially generating different sources of waste, and (3) the phase of the project (design or construction phase). A process map was generated for each actor, type and phase of project, for a total of 16 maps. The maps show the work flow between the different actors and the input and output of information for each activity for the design and the construction phases.

Stage 3 - Conclusions: The goal of this last stage was to analyze the interviews' verbatims and the process maps created to identify similarities, differences and issues between the actors' processes. This allowed the identification of sources, issues and consequences of waste in information flows.

For the second phase of the research, a ShareLab was used as a validation process for the artefact created. This approach was devised by the LUCID laboratory. The ShareLab cycle is composed of the following steps: build trust, establish common ground, define shared items and ensure synchronization (Ben Rajeb, Senciuc, & Pluchinotta, 2015). The main interest of the ShareLab approach in this context was to develop a consensus among involved professionals from various fields of the construction industry.

This ShareLab was divided into three steps (Figure 5.2). A one-day workshop was conducted, and included the first two steps. The visualization through process maps prepared during the first step of the research was used to help build a common ground on the understanding of the BIM information processing and potential sources of waste.

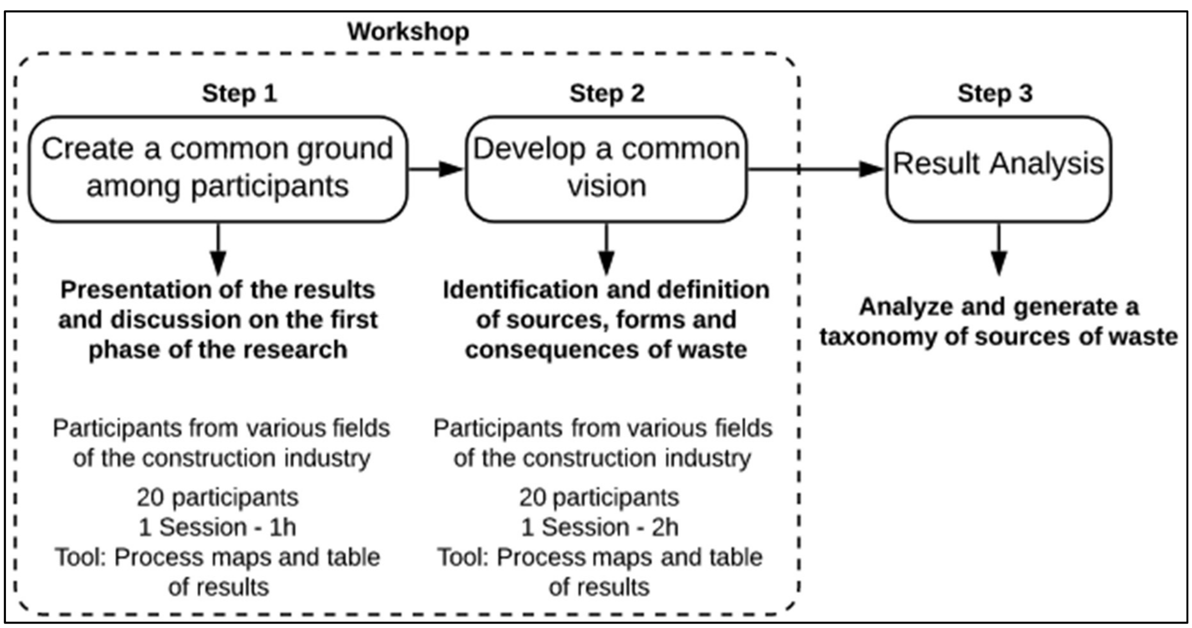

Figure 5.2 Steps of the ShareLab approach

Step 1 - Create a common ground among participants: this step consisted of gathering all the participants together to facilitate exchanges and discussions. A presentation of the results, including the process maps generated during the first phase of the research, was given. All the participants present during the workshop took part in the first phase of the research, at one point or another. There was a total of 20 participants, with five architects, five engineers, three general contractors and seven MEP contractors. The presentation allowed providing a reminder of the context, scope and goal of the research. The context of this research was to provide solutions to the need to improve productivity in the construction industry. The scope was focused on one of the needs of the industry, namely, redefining the design rules and methods by developing a framework to optimize the information flows and reduce waste in the production of information. Given the gap identified during the review of this paper and the context, the goal of the ShareLab workshop was to validate a taxonomy of sources of waste specific to the information flows of construction projects. At the end of the presentation, the participants were given the opportunity to exchange their respective opinions in order to identify similarities between their approaches for managing BIM information, and a consensus was reached among all 20 participants on the goal of the workshop.

Step 2 - Develop a common vision: the goal of this step was to identify and define the sources, issues and consequences of waste. During the workshop, each source, issue and consequence of waste was validated by the participants. By the end, the sources were ranked in order of importance through the participants' votes. This two-hour workshop brought together the same participants as the first session.

Step 3 - Result Analysis: the goal of this step was to analyze the results and generate a taxonomy of sources of waste in the information flows of construction projects.

These three steps of the ShareLab approach used during this research represent a form of validation of the results. Indeed, according to constructive research theory, a validation can be obtained through the approval and endorsement by professionals of the recommendations and/or conclusions presented (Lukka, 2000).

5.5 Results

The results are divided into two sections. The first section presents the data analysis that allowed the identification of the sources of waste within the information flows. The second section provides the validation of the analysis results with the creation of a taxonomy, using the ShareLab approach.

5.5.1 Data analysis

A qualitative data analysis process (first phase of the research) allowed to create an exhaustive list of waste sources in the information flows of design and construction processes. Table 5.2 below presents the list of issues identified during the data analysis, as well as the dimensions in which they were identified. These issues were identified through an analysis of the interviews' verbatims and of the process maps. The analyses also confirmed what is present in the literature, as most of the issues identified are mentioned in separate research works such as, issues with communication, lack of interoperability, resistance to change (Michaud et al., 2019), the lack of coordination (Zhang et al., 2018) or contractual relationships and unclear role (Fan, Chong, Liao, & Lee, 2019). However, it is important to note that all the issues presented in Table 5.2 were identified in the data collected during this study and are not derived from the literature. From these issues, a list of sources was created to provide a concise taxonomy. Some issues were regrouped into a single source of waste because of their strong link with each other. For example, a definition can easily regroup the type of project and contract into one source of waste. Finally, each source was placed in one of three categories of waste: human, process or technology. A definition of each source is given below.

Table 5.2 Sources of waste identified in the information flows through data analysis

LOD	BEP	6D	7D	Issues identified (data analysis)	Sources of waste	Category
X	X	X	X	Type of project	Type of project and contract	Process
X	X	X	X	Type of contract		
X	X		X	Lack of communication	Lack of communication and coordination	
X	X		X	Lack of coordination		
X			X	Unclear role		
X			X	Undefined responsibilities		
X	X		X	Semantics & language		
X	X			Lack of collaboration		
X	X	X	X	Lack of control quality processes	Lack of control quality processes	
X	X	X	X	Lack of standards	Lack of standards	
		X	X	Data presentation		
X	X		X	Organization		
X	X	X	X	Limitation of the tools	Limitation of the tools	Technology
		X	X	Lack of interoperability		
X	X	X		Technical issues (software)		
X	X		X	Lack of trust	Lack of trust	Human
X	X	X	X	Resistance to change	Resistance to change	
	X	X		Blinder		
X	X			Lack of motivation		
X	X	X	X	Lack of competence	Lack of competence and knowledge	
X	X	X	X	Lack of knowledge		

A total of 21 issues were identified during the data analysis. In terms of their nature, frequency, potential impact and/or link to others, the issues were grouped together within one of the eight sources of waste shown in Table 5.2. Indeed, some, such as the lack of communication and coordination, were complementary. Others described the same issue, but with a different formulation. Examples include the limitation of the tools and a lack of interoperability. Following the analysis and identification of the sources of waste, a definition was formulated for each source.

Each of the sources was observed in one or more of the BIM dimensions studied during the present research. The eight sources are divided into three categories, namely, (1) Human, (2) Process, and (3) Technology. These three categories were based on the literature and on the fact that together, they represent the main parts of an organization (Koskela & Dave, 2008). These categories help better understand the reasons and the impacts of each source of waste. Furthermore, they are useful for professionals as they narrow the identification of waste within their own processes. All issues were grouped together during the first phase of the research, and were part of the results presented during the ShareLab for validation.

The “Process” category groups together four sources of waste. First, the type of project and contract has a major influence on waste during information processing. Indeed, depending on the type of project (Design-Build, Design-Bid-Build, Integrated Project Delivery, etc.), the nature of the contract signed will differ. In a Design-Bid-Build or Design-Build project, there is fragmentation of contracts, and since each professional is linked only with the client as well as the general contractor, information sharing represents a risk, which leads to rework. For example, the sub-contractor must redo the models because the professionals do not want to provide them. Also, professionals will produce models to generate 2D plans because this is the format that acts as a contract to document the work to be done, and therefore, the model is not designed to be reused for construction. On the other hand, in an IPD project, a general contract links all actors, thus generating a common need and/or goal for the actors to gather around. The choice of project and contract will influence communication, coordination, the work flow and the processes. Second, the lack of communication and coordination is in part linked to the previous source, as the contract type will greatly influence the relationship between the parties involved. Moreover, the traditional silo working structure in the construction industry tends to limit communication and coordination between the parties involved. Third, the lack of quality control of the processes that can be explained by a lack of specific requirements regarding the identification, definition and communication of needs. Finally, the lack of standards is linked to a lack of rigor and an absence of work rules. The second category, “Technology”, is composed of only one source of waste, that is, tools limitation. Every year, BIM tools are developed and improved with the goal of optimizing BIM implementation. However, there are still problems of interoperability and a lack of maturity of BIM software. This results in problems with information transfer.

Three sources of waste were associated with the last category, “Human”. First, lack of trust, between stakeholders of a same process or project can be explained by several reasons, such as previous bad experiences or new encounters for which trust needs to be built. Second, resistance to change is linked to a fear of changing habits, of finding oneself in an uncomfortable situation. It also leads to a significant lack of motivation, withdrawal and a loss of investment. Third, lack of competence and knowledge is in part linked to the previous source, with a resistance to incorporating changes, but it can also be linked to a lack of formation.

The issues identified are discussed in the next section as they were used during the ShareLab workshop in the waste taxonomy validation process. The section presents the three stages of the ShareLab approach, as well as a discussion of the results obtained.

5.5.2 Validation of the taxonomy through ShareLab approach

The first step of the workshop allowed to obtain a consensus on the goal of the workshop among the participants following the presentation of the results and a period of exchange regarding their respective opinions. The second step followed, with the same 20 participants. A presentation of the list of sources, issues and consequences of waste identified was given. A definition of each source was presented, along with a list of issues and consequences (Figure 5.3).

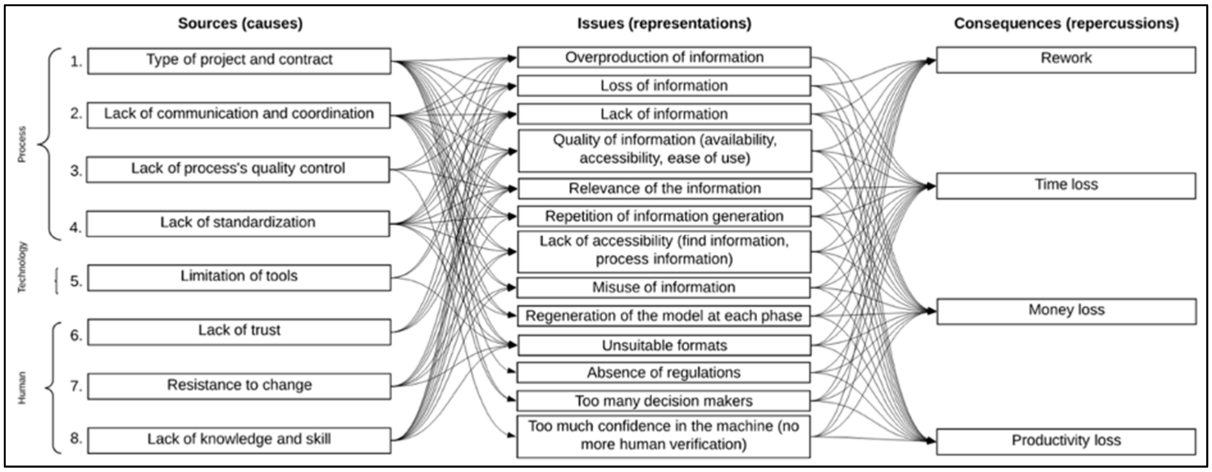

Figure 5.3 Link between sources, issues and consequences of waste in information flows

Figure 5.3 shows the links between the sources, issues and consequences of waste in the information flows. All the links presented in the figure were identified during the analysis of the verbatims of the interviews and/or the process maps generated from the interviews. Indeed, the figure is simply a representation of all the information given, identified or mentioned by the professionals during the data collection stage. Each source is not limited to just one issue. Indeed, it can be observed that each source can be represented by several issues, and that each issue is not limited to one source. This figure shows that the sources of waste identified are all interconnected. Of course, it is possible to reduce waste by tackling one or several sources. Using the Pareto principle - where 20 percent of the sources are responsible for 80 percent of the waste - and identifying and first tackling the sources with the most impact would decrease the amount of work needed to reduce waste within the information flows.

The last item of the workshop was to obtain a consensus among the participants on the results presented. The use of a questionnaire allowed to validate the eight sources of waste and also ranked them in order of impact on a project according to the professional's experience (Figure 5.4). This ranking allows using the Pareto principle on the most impactful sources of waste. In this questionnaire, an option was given to the participants to provide additional sources they felt could be part of the taxonomy and how would they be ranked. Four additional sources were proposed by all the participants: commitment from management, motivation, excessive expectations and too much confidence. However, after further discussion regarding the ranking, there was a consensus that these four propositions needed to be tackled before the start of a project, and could not be classified as sources of waste within the information flows.

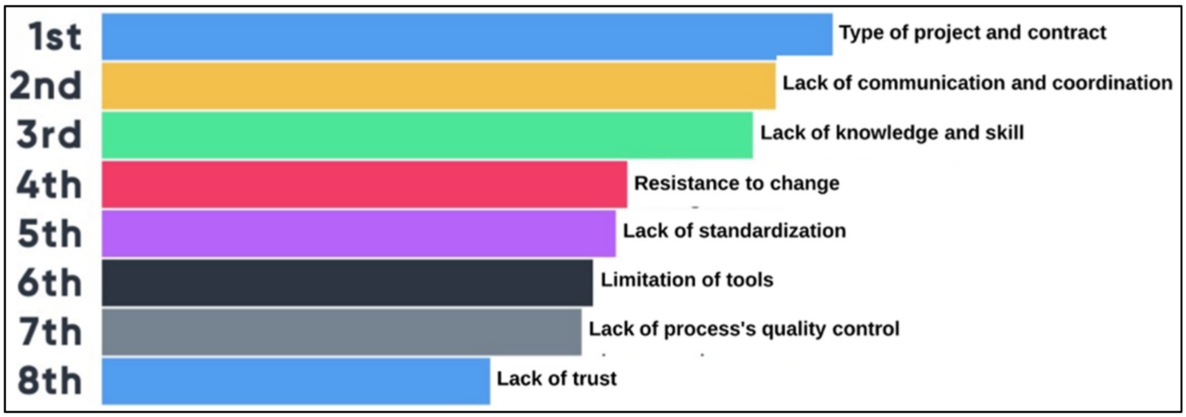

Figure 5.4 Ranking of the sources of waste validated in order of impact

This ranking provides vital information to the project and/or BIM manager when working with BIM to identify and eliminate sources of waste from their information flows. Indeed, the lack of time and/or resources does not always allow the project or BIM manager to tackle each source of waste within a project. With this ranking, the focus can be put on the most impactful sources of waste within a project. With more and more projects being carried out focusing on reducing waste, the BIM manager will be better able to tackle the sources of waste with a lower impact.

5.6 Discussion

Taxonomies have long been used for sources of waste in the production and construction industries. Tools, techniques, taxonomies and approaches mostly focus on improving work and materials flows. This discussion carries out a comparison of the proposed taxonomy with the one developed by Dubler et al. (2010), which is adapted from the manufacturing to the information exchange process in construction. Table 5.3 below provides a list of the sources of waste for both taxonomies. A major difference between the two is that the proposed taxonomy was developed specifically for the information flows in construction projects, whereas the other one was adapted from waste identified more than 30 years ago for material flows in the manufacturing industry. Indeed, over the last 30 years, new tools, technologies and approaches have been developed, and the amount of information in projects has increased drastically.

Table 5.3 Comparison of taxonomies

Proposed taxonomy of sources of waste in the information flow	**Taxonomy adapted from Ohno (1988) (Dubler et al., 2010)**
1. Type of project and contract	1. Overproduction
2. Lack of communication and coordination	2. Inventory
3. Lack of knowledge and skills	3. Extra processing steps
4. Resistance to change	4. Motion
5. Lack of standardization	5. Defects
6. Limitation of tools	6. Waiting
7. Lack of process's quality control	7. Transportation
8. Lack of trust	

In their adaptation, Dubler et al. (2010) adapted each source of waste from the manufacturing industry to the information exchange process in construction. Comparing each adapted source of waste with those from the proposed taxonomy of this paper, it can be seen that the latter considers each of the adapted sources and also provides two new ones. The following paragraph provides the meaning of the adaptation for each source of waste to the construction industry.

The overproduction source was transformed to producing more information than required and doing revisions to the model after release. This source is linked to four out of the eight sources of waste in the proposed taxonomy (1, 2, 5 and 7). The inventory source was converted to an early delivery of information and using Push instead of Pull – also meaning using what is provided. This source is linked to three out of the eight sources of waste in the proposed taxonomy (1, 2 and 5). The extra processing steps source was changed to generating a high level of details than necessary. This source is linked to four out of the eight sources of waste in the proposed taxonomy (1, 2, 5 and 7). The motion source was modified to not using a central location to share the model and transferring more often than necessary. This source is linked to three out of the eight sources of waste in the proposed taxonomy (1, 2 and 5). The defects source was adapted to providing inaccurate or wrong information. This source is linked to three out of the eight sources of waste in the proposed taxonomy (2, 5 and 7). The waiting source was converted to waiting for the delivery of information. This source is linked to three out of the eight sources of waste in the proposed taxonomy (1, 2 and 5). Finally, the transportation source was adapted to issues in transfer of information with an unsuitable format and version. This source is linked to two out of the eight sources of waste in the proposed taxonomy (5 and 6).

This research brings novelty to the field with the creation of this taxonomy as there was no existing taxonomy focusing on waste in the information flows. There is still a limited understanding of the waste in the production and exchange of information in the AEC industry, while the management of information has received much less attention than the management of the work and material flows. In addition to the taxonomy proposed by Dubler et al. (2010) and discussed in this section, Bajjou, Chafi, and En-Nadi (2017) proposed, more recently, an adaptation of the seven waste from Ohno (1988). However, this attempt does not focus on the information flows.

Regarding the solution aspect to the presence of waste in the information flows. There are currently several potential solutions in the form of tools, approaches or techniques that can be used to remove waste. However, a solution can only be implemented on an identified issue. Indeed, a few studies can be found in the literature with proposition of approaches to reduce waste in the information flows. Tribelsky and Sacks (2011) proposed to collect quantitative data on sources of waste to evaluate the quality of information flows. However, qualitative data is absent in this proposition while it plays a major role with information flows. Al Hattab and Hamzeh (2013) compared traditional and BIM-based information flows in design phases in an attempt to improve the information flow in BIM processes but only focused on one source of waste which was issues in sharing information. Lastly, Dubler et al. (2010), as discussed in this section adapted the seven waste from production to construction to improve the information flows of construction. However, their study did not consider the human dimension as a source of waste. Each study found in the literature on the subject lacks a complete picture of waste within the information flows. The proposed taxonomy is useful as it provides a description, identification and classification of the sources of waste present within the information flows, as well as a better understanding of these flows in construction projects.

5.7 Conclusion

The main contribution of this paper is the creation of a taxonomy of waste sources specific to information flows. The combination of data collected from several research studies conducted in the GRIDD laboratory provided a large database, allowing a more complete analysis. In addition, the perspectives of the different actors present in construction projects was gathered, in addition to a study of several BIM dimensions. Another way the paper contributes to knowledge is through its use of the ShareLab approach as a validation tool. This approach provides a new way to validate an artefact in a Design Science Research method. At the practical level, this paper’s main contribution is its provision of a defined frame allowing professionals to identify sources of waste within the information flows in construction projects. The use of this taxonomy is optimal when associated with a visualization tool such as Value Stream Mapping or Process Mapping. This tool in turn helps professionals reduce rework and work time, financial and productivity losses.

The presence of waste in construction is a widespread issue which impacts all the actors and the phases in a construction project. Given the ever-growing importance of information in construction, particularly in BIM projects, there is need for optimized information flows to tackle the related waste issues. Extensive research has been conducted, involving work and material flows in construction, with tools and approaches developed to improve them. A taxonomy of seven sources of waste was created more than forty years ago to tackle waste in the manufacturing industry. A few years ago, this was adapted to tackle waste in the construction industry, with a total of 10 sources. However, these taxonomies are not adapted to the waste found in the information flows.

The taxonomy developed in this research comprises a total of eight sources of waste. Three of them are linked to the human element: (1) Lack of trust, (2) Resistance to change and (3) Lack of knowledge and skill. Four sources are linked to the process: (4) Type of project and contract, (5) Lack of communication and coordination, (6) Lack of process's quality control and (7) Lack of standardization. Finally, one is linked to technology: (8) Limitation of tools. The use of a ShareLab approach allowed a validation of the findings with the participation of 20 professionals from various backgrounds. Through exchanges and discussions, the eight sources of waste identified were accepted via a consensus and ranked in order of impact on BIM projects. This research also demonstrated that all sources of waste are linked, and must be tackled as a whole.

The main conclusion that can be drawn after comparing both taxonomies in the discussion section is that the proposed taxonomy provides a new category of waste that was not considered in the previous one. Indeed, as mentioned in the results section, three categories represent the main parts of an organization, namely, human, process and technology. However, as shown in the comparison presented, no waste source in the existing taxonomy considers the human category. This can be explained by the fact that the sources of waste were first identified in the manufacturing industry, where the human category is less crucial than in the construction industry. Moreover, each source of the proposed taxonomy provides more information than does the existing one, as each of them covers more issues than the existing ones.

There are some limitations associated with this research. The data collected and the results generated are all linked to the construction industry in the region of Quebec, Canada. This means that the findings may be different in another country due to different practices. Moreover, the constant evolution of the AEC industry and the new construction projects starting every day can generate potential new data to expand this taxonomy as all construction projects are different and can generate unique cases and new issues.

It has been demonstrated in several research studies that all flows in construction projects are interrelated. In the future, research can be conducted to combine existing taxonomies of waste from other flows with the one created here to help reduce global waste in construction projects. Moreover, future research can focus on developing or identifying solutions for each source of waste in this taxonomy.

5.8 Acknowledgement

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CHAPTER 6

DISCUSSION

This chapter presents a discussion on the initial hypothesis, the research methodology and the findings of the research project. The implications of the results and their contributions to the research field and to practise are also discussed. This discussion provides a global dialogue of the research project.

The objective to develop this taxonomy originated from the theoretical framework proposed by Turk (2000) and discussed in the literature review of the thesis (Figure 1.1, p.9). In his proposition the author identifies the three main flows that are material, information and workflows and their relation to one another providing a clear interdependence. The framework provides a view of traditional projects, where the technology supports the processes, so the flow of information is dictated by the work and material flows. However, in recent years, with the development of new techniques, approaches and tools such as BIM or Lean, and the development of technology, the information needs, and production have skyrocketed and clearly plays a major role in every construction project. The results presented in this thesis call into question this theoretical framework. Indeed, with BIM being a disruptive technology, it acts as a driver to review the other flows. Davenport (1993) provides a potential solution with process reengineering as a powerful change approach that is able to provide major improvement in business processes. This thesis clearly demonstrates a lack of knowledge in regard to the information flows while providing answers to the gap in the literature regarding the presence of waste within these flows. Furthermore, the taxonomy created provides a first exploratory effort from the second article, to provide a better understanding and knowledge of the sources of waste within the information flows in the AEC industry in the last article. However, the taxonomy has not been validated in a real project. Thus, the challenge is to determine how to operationalize this taxonomy.

The research methodology presented in this thesis was organized around a collaborative design science research (CDSR) method. The aim was to answer a specific research question in relation to the information flows within BIM projects in order to help solve a problem in practice that was the presence of waste within these flows. The issue was the AEC industry's long-lasting problem with the lack of progress concerning productivity. The research question was stated as follows: How to identify the sources of waste in the production and exchange of information in the construction industry? Four objectives were formulated to answer this question and each of them has been answered through the production of three scientific articles. The CDSR methodology is a variation of the Design Science Research (DSR) methodology. However, compared to the DSR methodology, the one used for this thesis is less present in the literature. This thesis provides a new theoretical and practical example of its use with the presentation of two scientific articles using it as well as this thesis.

The studies done for this thesis provided a method to close the gap in literature regarding waste within the information flows of construction projects. The first article was developed to diagnose the information processing within a BIM project, conflicting and successful areas were identified, laying the groundwork for the rest of the thesis. On one hand, the conflicting areas identified were the issues of coordination of the work between stakeholders, the variety of software among stakeholders leading to interoperability issues, the difficulties in breaking traditional work patterns such as work in silos causing issues in coordination and communication and, issues with the supply chain integration and the lack of consideration to manufacturers and their potential role in the information processing strategy. One the other hand, the successful areas identified were the standardization of processes through the use of a BIM Execution Plan (BEP) and the advantages of long-term relationships when using an integrated supply chain, allowing the General Contractor (GC) to select firms based not only on the cost but also on more qualitative criteria such as the experiences and performances regarding previous collaborations. The second article was focused on the development of the method presented in this thesis. This method was developed in a particular context, within an architectural firm and the study of its internal processes. Moreover, the method developed can be generalized for the consultants and professionals of the construction industry.

The first contribution that is discussed here is linked to the methodology and is the proposition of a new approach to validate the artefact. The ShareLab approach used during this study was based on the approval and endorsement of the results by professionals of the field. This approach was implemented through the use of a workshop composed of participants from various fields of the AEC industry. The steps of the workshop were to create a common ground among the participants and develop a common vision before analyzing the results. Moreover, the CDSR methodology was also used as an enabler to co-develop a method of identifying and reducing sources of waste within the information flows of an architectural firm.

The second contribution is the taxonomy of the sources of information in the construction projects coupled with the proposed framework, which is a contribution to both the knowledge and the practice. There are many potential solutions to the presence of waste in the different industries. The issue in the AEC industry is the lack of understanding of the information processing. A potential solution can only be implemented to something known and understood. The taxonomy proposed in this thesis provides the knowledge and understanding necessary to know what and where to look to identify sources of waste within the information flows of construction projects. The Chapter 4 of this thesis provides an example on potential solutions to eliminate waste once it is identified. This taxonomy is useful for the theory as it provides a better understanding of the information flows in construction. As mentioned in the literature, the information processing has been little covered. In regard to the practice, the lack of understanding and knowledge of the information flows limit the positive. Impact to the solutions implemented to improve them. This taxonomy provides the professionals with a better understanding and help them pinpoint the sources of issues in their own projects. Furthermore, the proposed framework provides a way to implement the taxonomy.

Every study or research has limitations, some more important than others. Each article presented in this thesis are no exception to the rule. However, a key advantage of presenting a thesis is that some limitations that can be found in a single article, may be solved in the long run with a thesis. Indeed, the first and second articles showed limitations as each presented data and results from only one case study. The limitations included a limited amount of data available to develop and propose solutions resulting in the need for more cases in the expectations to generalize the conclusions made in the studies. However, the limitation was no longer an issue for the third one as several studies were done on the subject beforehand. The subject being the improvement of the production, exchange and management of information in construction projects through the identification and reduction of sources of waste. The same can be said for the general contributions and conclusions of this thesis. However, one limitation could not be solved using the scope of this thesis. Indeed, all the cases studied, data collected, and analysis were done with professionals and firms and construction projects from the region of Quebec, Canada. The issue here is that the findings are specific to this region and more case study are needed to assess if the findings can be generalized.

This discussion section allowed to identify two possible directions for future work after this thesis. First, future research may be focused on studying alternative or new version to the current paradigm of construction where information occupied the first role instead of the last in current construction processes. Second, the framework proposed in this thesis may be used in future work in different cities and countries in order to validate or expand the taxonomy proposed for the sources of waste in the information flows of construction projects.

CONCLUSION

In this thesis, a taxonomy of the sources of waste in the information flows of BIM projects was developed to answer this question: How to identify the sources of waste in the production and exchange of information in the AEC industry? This study aimed to address the issues and gaps identified in this area such as poor communication and information transmission, coordination or teamwork issues. The proposed method and taxonomy consider both the professionals and researchers' point of view in their applications. Any professional from any field of the AEC industry will be able to implement them during their design or construction process.

The method and taxonomy were created based on a Collaborative Design Science Research (CDSR) method that was oriented around the collaboration of professionals and researchers to address practical issues.

The main contribution of this research is the taxonomy of the sources of waste in the information flows of BIM projects and the method that is used to implement it:

- The contribution of this thesis to knowledge is the identification of problems in information flow and identifying potential solutions to these problems as only little had been done on this field. Also, another contribution was the demonstration of using VSM or PM as a visualizing tool to identify and eliminate sources of waste in the information flow. Moreover, the developed method and the proposed taxonomy contribute to knowledge by closing the gap regarding the presence of waste in the information flow as it was already done in the material and workflows. Finally, the use of the ShareLab approach as a validation method for an artefact adds knowledge to the CDSR methodology as it brings a new approach.
- The contribution to practice is a complete list of sources of waste with their definition and a way to identify them. With this knowledge and steps on how to implement it, the professionals are encouraged to improve their communication, coordination, teamwork and information transmission. Also, this study provides a way to develop a better understanding of the professionals' own processes as well as the ones of the other actors.

There are limitations associated with this research. The most important one is the fact that all the data collected, and all the professionals met during the research are part of the AEC industry of the region of Quebec, Canada. Practices may vary from one country to another, thus, there is a possibility to observe small variation in the identification of waste in the information flows. Another limitation is directly linked to the nature of the AEC industry, as all construction projects are different. The fact that several studies were made to complete this thesis limit this issue but as for the first limitation, new data can appear in the future and provide cause to expand the taxonomy proposed.

The combination of the method and the taxonomy represents a breakthrough for future work against the recurring issue that is the low productivity in the AEC industry. The way the method is constructed makes it possible to implement it using other taxonomies. Thus, in the future, researchers can combine existing taxonomies for the three main flows to help reduce waste as a whole in the design and construction phases. Another direction for future research might also be to adapt the method to implement it for the whole supply chain of construction projects. Another potential future work was identified in the discussion section of the thesis and is about developing an adaptation or a new paradigm for the AEC industry where the information flow is placed in front of the other flows in construction processes due to the crucial role the information acquired in the recent years.

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